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A ROAD SAFETY EVALUATION MODEL IN THE CONTEXT OF LEGISLATIVE CHANGES

Summary. Road accidents are affected by various factors, but many of them are not monitored and collected, and some of them are not even known. Important factors that are often overlooked in research are legislative issues and legal changes regulating road safety, which are the subject of the study in this article. As it is extremely difficult to prove a significant influence of these factors and, therefore, to demonstrate that the impact of legislative changes on the number of road accidents is significant, this variable was considered while analyzing the impact of other variables, which, in the authors' opinion, were the most important and, above all, known over the period in question. Day of the week, month, and year are selected. It was decided that other factors influencing the decreasing number of accidents would be included in the trend. With this assumption, the analysis of an additional variable that marks the periods of changes in legal regulations and the confirmation of its significant impact on the number of accidents will allow us to conclude that it is an important element shaping road safety.

1. INTRODUCTION

Tragic statistics on road accidents around the world make them the subject of many scientific investigations aimed at improving road safety. Factors that have a decisive impact on road safety are the elements of the human-road-vehicle-technology system. This problem is very often explored in the literature. Particularly, many analyses are devoted to road users and the features that characterize them, such as sex and age, but also a tendency for risky behavior or the use of drugs or alcohol while driving. With regard to vehicles, the analyses are related to their characteristics and concern, for example, the type of vehicle, years of its operation or kilometers traveled, and its technical condition, especially with regard to the braking system. Research is also devoted to modern technologies and intelligent or autonomous cars. The road environment is also widely analyzed, including the road type, its geometry and characteristics, the type and condition of the surface [1-4], and factors related to the speed limit on a given road section and its marking. The availability of road safety-supporting elements, such as various barriers or speed-limiting elements, is also investigated [4]. Moreover, attention is paid to the road conditions prevailing during the accident; these conditions are related to visibility, weather conditions, and the season of the year [5, 6].

However, only a few authors have mentioned the necessity of introducing legislative changes as an important element of shaping road safety. Research in this area mostly concerns a distant time horizon. For example, in publication [7] in 2009, the authors emphasize awaiting legislative changes in the Australian state of Victoria. There are many studies on the impact of alcohol consumption on the number of road accidents and the corresponding mortality rate, while the impact of legislative changes in this area is no longer a common topic, although it is worth emphasizing that legal changes, if undertaken,

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are most often related to driving under the influence of alcohol [8]. In [9], the effectiveness of changes in regulations on drunk driving restrictions was analyzed using the example of Slovenia. It is worth emphasizing the wide time horizon, which covered the years 1980–2006. The analysis showed the effectiveness of only selected, implemented legislative solutions. In [10], the ineffectiveness of legal solutions was demonstrated. Legislative changes regarding the permitted blood alcohol concentration did not reduce the number of victims. On the other hand, opposing results were reported in [11], according to which lowering the allowed blood alcohol concentration limit had an impact on the number of fatalities in road accidents. Many studies on drunk driving have been done in the last century. In [12], the Australian experience is presented by assessing the frequency of fatalities and injuries in road accidents among passengers in the years 1955–1977, which confirmed the need to change the legislation on compulsory seat belt fastening as the most effective method of protecting vehicle passengers at that time, recommending that it should also be extended to children below eight years old. Considerations in the legislative area concerning seat belts most often date back to the 70s and 80s, when in many countries, there was an obligation to install and use them.

Much emphasis was placed in [13] on the need to determine the importance of political and socio-economic variables influencing the level of road accidents, where an overview of macro-models of road accidents has been presented. The authors postulate that identifying variables related to effective policies and interventions may present an opportunity for decision-makers to improve the level of road safety. The impact of legislative changes was also assessed in [14], where the influence of regulations concerning compulsory bicycle helmets on cyclists' head injuries was examined. Based on hospital admission data, a positive effect on the population level was confirmed. Similar results were obtained in [15].

The literature review shows several important guidelines and areas requiring analysis, which constitute a research gap:

1. The analysis of the factors influencing road accidents in the literature does not take into account legislative changes, while the decisions and orders formulated at the strategic level may significantly influence the number of such events.
2. Legislative changes concern important areas of the road-vehicle-human-technology system operation related both to organizational and technical conditions in relation to vehicles or road infrastructure, as well as restrictions and requirements for road users.
3. In the case of legislative changes, analyses dedicated to specific countries are extremely important. However, the obtained mathematical models can be implemented in other countries, and the identified dependencies and the results obtained will constitute the basis for global analyses and the creation of systems limiting the negative effects of road incidents at the global level.

In connection with the above, in this article, using Poland as an example, an analysis of legal acts and their most important changes was carried out. The underlying assumption was that there was an effective and significant reduction in the number of road accidents. Then, selected periods were used as variables in the model describing the number of road accidents.

Two main research hypotheses were adopted:

1. It is possible to use a mathematical model to assess the impact of legislative changes on the number of road accidents while taking into account other factors that affect them. The main problem concerns proving the significant impact of the independent variable defining the individual periods of validity of specific legal regulations on the independent variable (i.e., the number of road accidents).
2. The impact of legislative changes on the number of road accidents is significant and should be one of the main subjects of analysis in the process of shaping the level of road safety.

The authors have proposed a multiple regression model. This model takes into account the particular periods of legislative changes and the factors that were considered to be the most important in the long term. It was considered that such a model was sufficient to confirm the assumptions. Moreover, the literature review showed that in many cases, the most modern, complex models used to explain and predict road accidents do not meet expectations [13] and that their interpretation is difficult and complicated.

The structure of this article is as follows. In the introduction, a literature review was done, the existing research gap was indicated, and the aim of the research and the research hypotheses were provided.

Then, a detailed evaluation of changes to legal acts in the field of road traffic safety was performed, and the periods of validity of given regulations were selected, which were used as a variable in the model. In the next part, the parameters of the polynomial regression model were estimated, and the model was evaluated with reference to the assumed objectives of the study. The article ends with a summary of the analyses and final conclusions.

2. ANALYSIS OF PERIODS OF LEGISLATIVE CHANGES

The most important normative acts defining the legal order of road traffic in Poland and specifying the procedure and conditions for preparing drivers to drive on roads are represented by the laws and regulations regulating the matter in question. Their genesis is the Vienna Convention on Road, announced in 1968, which was an international treaty defining general road traffic rules in force in the signatory countries. Poland ratified the convention on February 24, 1998 [16]. Thus, significant changes in this area should be adopted and discussed after this date.

Based on the analysis of legal acts regulating road traffic in Poland, the time intervals presented in Tab. 1 were distinguished.

Table 1

Summary of the most important changes in the legal acts concerning road safety shaping in the years 1990 - 2020

Revision No.	Date of introduction	Description
Revision 0	Reference period	
Revision 1	October 1, 1991	Driving with safety belts on all road categories is compulsory for people in all vehicle seats.
Revision 2	May 1, 1993	Introduction of a penalty point system for road traffic offenses. Exceeding the permissible number of penalty points resulted in the withdrawal of the driving license.
Revision 3	January 1, 1998	Introduction of a ban on using a mobile phone while driving in a situation where it is necessary for the driver to hold it in their hand.
Revision 4	January 1, 1999	Introduction of the obligation to transport children up to 12 years of age (up to 150 cm tall) in safety seats.
Revision 5	May 1, 2004	Lowering the speed limit in the built-up areas between 5:00 and 23:00 to 50 km/h
Revision 6	March 21, 2007	The obligation to drive with dipped beam headlights on throughout the day was introduced. The use of daytime lights is also permitted.
Revision 7	December 31, 2010	Change in speed limits on motorways to 140 km/h and on expressways to 120 km/h. A driver error margin of 10 km/h has been introduced for recording equipment.
Revision 8	May 21, 2011	The so-called "Bicycle Act" introduced many significant changes regarding cyclists and drivers and their sharing of the road. The most significant change is the need for the driver, when turning into a crossroads, to give way to a cyclist riding in a bicycle lane along the road.
Revision 9	January 19, 2013	Introduction of new driving license categories: AM and A2. A change in the minimum age for drivers of selected categories: A cat. 24 years (previously 18), C cat. 21 (formerly 18), D cat. 24 (formerly 21).

Revision No.	Date of introduction	Description
Revision 10	May 18, 2015	Tougher sanctions for drivers who commit the most serious offenses in road traffic, in particular in the case of drunk driving, causing a safety risk, grossly exceeding the speed limit, or driving the vehicle despite not having the appropriate permits to do so.
Revision 11	June 1, 2017	Jail punishment (not possible to be suspended) for a fatal accident if the driver was driving a car while using alcohol or other similarly acting intoxicants, a longer period of lapse of the offenses (three years instead of two), higher penalties for road accident perpetrators and drivers without authorization (imprisonment for two years, no driving for 15 years). Testing drivers for the presence of alcohol or other stimulants without their consent.
Revision 12	December 6, 2019	Compulsory creation of the corridor of life, compulsory slider driving (a driver who cannot continue driving in his lane due to difficulties or the disappearance of the lane will be able to enter the adjacent lane, which must be allowed by the driver from the adjacent lane).
Revision 13	June 1, 2021	The obligation for drivers to give way to pedestrians approaching a crossing. It is forbidden to use cell phones when crossing the road. Organizing the traffic of new vehicle categories: electric scooters and personal transport devices, as well as devices supporting movement (e.g., roller skates, skateboards).

According to the indicated acts, the most important changes in the field of road traffic in Polish legislation were made in 1992, 1997, 2001, 2005, 2009, 2011, 2016, and 2019; these periods were analyzed by the authors. The importance of long-term analysis in order to draw constructive conclusions has been emphasized by many authors and analysts [9].

3. THE PROPOSED APPROACH (MATERIALS AND METHODS)

Time series models are often used to predict road accidents [17, 18]. The analysis of time series allows us to describe the nature of the analyzed process, find the deterministic elements existing in it, and present the process as a function containing such components as development tendency, seasonal fluctuations, cyclical fluctuations, and random fluctuations. The identification of individual components and the internal dynamics of the time series allows future values of the time series to be predicted. In the present study, a multivariate linear regression model was used first, which is of the form [18,19]

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon_i, \quad (1)$$

where:
$\hat{y}$ – dependent variable,
x_k – independent variable,
β_k – model parameters, and
$\varepsilon_i = y_i - \hat{y}_i$- random element.

The regression coefficients β_k describe how much, on average, the value of the dependent variable y, changes if the value of the independent variable x_k to which they apply changes by a unit, assuming a fixed level of the remaining independent variables. The model was verified by evaluating the statistical significance of the estimated parameters, the determination coefficient, and the analysis of the model residuals.

The t test is used to evaluate the statistical significance of the estimated parameters. The null hypothesis assumes that the regression coefficients in the model are zero:

$$H0\colon \beta k = 0. \tag{2}$$

In view of the alternative hypothesis, assuming that the regression coefficients in the model are significantly different from zero:

$$H1\colon \beta_k \neq 0. \tag{3}$$

The test statistic expresses the equation:

$$t = \frac{\beta_k}{S(\beta_k)}. \tag{4}$$

The test statistic has the t-Student distribution with n-2 degrees of freedom. If the critical value of the test statistic is smaller than the calculated one, we reject the null hypothesis and adopt the working hypothesis.

The diagnostics of the regression model concern the assessment of the consistency of the distribution of residuals with the normal distribution while examining the homogeneity of variance and the autocorrelation of residuals. The Kolmogorov-Smirnov test was used to test the consistency of the distribution of residues with a normal distribution. The Kolmogorov-Smirnov test uses the λ statistic, which is based on a comparison of the empirical and theoretical distribution function. At the significance level α, the null hypothesis assumes that

$$H0\colon F_{data}(x) = F_0(x), \tag{5}$$

where:
$F_{data\ (x)}$ – distribution function of the empirical distribution and
$F_{0\ (x)}$ – distribution function of the empirical distribution.

The test statistic (for a two-tailed test) is given as

$$D = sup|F_0(x) - F_{data}(x)\,|. \tag{6}$$

For a one-tailed test, the absolute values are omitted from the formula. If the value of D is greater than the critical value, then the null hypothesis is rejected. The homoscedasticity of variance was checked with the Breusch-Pagan test. The Breusch-Pagan test determines the linear model

$$y = \beta_0 + \beta_1 x + e, \tag{7}$$

and another linear model for the squares of residuals r^2 is determined as follows:

$$r^2 = \alpha_0 + \alpha_1 x + e. \tag{8}$$

The determination coefficient R^2 for the above model, multiplied by the number of observations n, is the test statistic for the above test. If the homoscedastic hypothesis H_0 is true (equivalently, the α coefficients are zero), then

$$nR2 \sim \chi^2_p,$$

where the number of degrees of freedom p is the number of explanatory variables.

The Ljung Box Test was used to test the autocorrelation of the series. It is a statistical test used to check if any of the groups of time series autocorrelation differs from zero. The null hypothesis (H0) assumes that the data are independently distributed, while the alternative hypothesis (H1) states that the data are not independently distributed. H1 exhibits series correlation:

$$Q = n(n+2)\sum_{k-1}^{h} \frac{r_k^2}{n-k}, \tag{9}$$

where:
r_k – the sample autocorrelation with k lag and
h – the number of lags.
At the significance level α, the null hypothesis is rejected if

$$Q > \chi^2_{1-\alpha,\ h},$$

where:
$\chi^2_{1-\alpha,\ h}$ – the (1-α) quantile of the chi-square distribution with h degrees of freedom.

Autoregressive and moving average models play an important role in drawing conclusions about actual stochastic processes [17]. For autoregressive model processes of the $p \in N$, order, abbreviated as $AR(p)$, there is a significant autocorrelation between the values of the forecast variable and the time-delayed values of this variable [17]. The construction of such a model is based primarily on the determination of the autoregression order (parameter $p \in N$). The autoregression model of the $p \in N$ order [20] is presented as

$$x_t = \alpha_0 + \alpha_1 x_{t-1} + \alpha_2 x_{t-2} + \dots + \alpha_p x_{t-p} + \varepsilon_t, \tag{10}$$

where $\{\varepsilon_t\}_{t\in N}$ is a sequence of independent random variables with the distribution $N(0, \sigma^2)$.

The above formula shows that the value of the time series at time t is the sum of the random component and the linear combination of the previous observations of this series.

In the case of the MA(q) moving average process, the value of the random component of a given observation is a linear combination of time-delayed external disturbances [20]. The construction of the MA model requires the determination of the parameter $q \in N$, which represents the order of lags included in the model. The elements of the time series for MA(q) are represented by the equation

$$x_t = \varepsilon_t - \beta_1 \varepsilon_{t-1} - \beta_2 \varepsilon_{t-2} - \dots - \beta_q \varepsilon_{t-q}, \tag{11}$$

where $\{\varepsilon_t\}_{t\in N}$ is a sequence of independent random variables with the distribution $N(0, \sigma^2)$.

A combination of the above is the autoregressive moving average (ARMA) model, which is given by the formula [20]:

$$x_t = \alpha_0 + \alpha_1 x_{t-1} + \alpha_2 x_{t-2} + \dots + \alpha_p x_{t-p} + \varepsilon_t \beta_0 + \varepsilon_t - \beta_1 \varepsilon_{t-1} - \beta_2 \varepsilon_{t-2} - \dots - \beta_q \varepsilon_{t-q}, \tag{12}$$

where $\{\varepsilon_t\}_{t\in N}$ is a sequence of independent random variables with the distribution $N(0, \sigma^2)$. We usually model stationary series using ARMA class models. In the case of non-stationary models, we differentiate the k∈N series uniformly and such differentiated series $\{\Delta^d x_t\}_{t\in N}$ by satisfying the stationarity condition identified by means of ARMA (p, q). The model obtained in this way is the ARIMA (p, d, q) model.

4. MATHEMATICAL MODEL

This article employs a linear regression model using qualitative (binary) variables. A limited number of variables was used to build the model, as the method of defining and measuring some factors has changed over the years, which means that their impact in selected periods cannot be compared. Therefore, only variables with indisputable definitions were used whose impacts on accidents are unique and have been confirmed both in this article and in many studies [5, 21]. The factors related to the time of the event were selected (i.e., year, month, and day of the week). Additionally, the model takes into account a variable that divides the analyzed period into ranges for the validity of a given act.

The data concerned road accidents from 1990–2020 and were collected on a daily basis. The data comprised 11,324 observations. The calculated coefficients are presented in Tab. 2.The influences of practically all of the calculated parameters are statistically significant, as evidenced by the obtained p-values (Tab. 2). The adjusted coefficient of determination was R^2 = 62%, test statistic F = 696.8, and $p < 2.2\ 10^{-16}$. The Akaike criterion was AIC = 107211. The analysis of the distribution of residuals was performed in accordance with the methodology adopted in Chapter 3. The Kolmogorov-Smirnov test and Kolmogorov-Smirnov test with Lilliefors correction were used to test the consistency of the distribution of residues with the normal distribution. None of them confirmed the normality of the distribution. The test statistic of the Kolmogorov-Smirnov test was D = 0.477 (p-value < $2.2\ 10^{-16}$), while Lilliefors' D = 0.039 ($p - value < 2.2\ 10^{-16}$). The homoscedastic city of variance was also not confirmed. The Breusch-Pagan test statistic was BP = 1014.8, df = 26 ($p - value < 2.2\ 10^{-16}$).

The autocorrelation of the residual distribution was also not confirmed. The Box-Ljung test statistic was X-squared = 2510 ($p - value < 2.2\ 10^{-16}$). The existence of the autocorrelation of residuals is clearly visible in the ACF(Autocorrelation Function) plot (Fig. 1). The lag values fade slowly, and there is a visible seasonality.

The main problem caused by the diagnosed autocorrelation of the model residual distribution is that statistical significance tests such as the F-test and Student's t-test cannot be fully reliably used to determine whether the regression coefficients are significant. Errors in the standard regression coefficients are not reliable, either.

Table 2

Estimated values of the regression model parameters

Term	Estimate	p-value	Term	Estimate	p-value
(Intercept)	98.296	0.000	Change 1	-6.045	0.000
Monday	16.382	0.000	Change 2	13.667	0.000
Tuesday	9.627	0.000	Change 3	25.815	0.000
Wednesday	11.188	0.000	Change 4	4.260	0.001
Thursday	13.298	0.000	Change 5	-10.306	0.000
Friday	34.047	0.000	Change 6	-20.542	0.000
Saturday	17.099	0.000	Change 7	-33.662	0.000
January	1.556	0.226	Change 8	-39.159	0.000
March	2.656	0.039	Change 9	-46.223	0.000
April	17.307	0.000	Change 10	-54.176	0.000
May	34.818	0.000	Change 11	-57.999	0.000
June	49.496	0.000	Change 12	-77.784	0.000
July	47.683	0.000			
August	50.715	0.000			
September	48.873	0.000			
October	50.871	0.000			
November	33.370	0.000			
December	30.558	0.000			

This, in turn, makes the confidence intervals of the regression coefficients and the model predictions unreliable. In effect, this makes the linear regression model practically useless. In such a situation, the solution may be a regression model with ARMA errors, which not only allows the use of a regression model but also copes with the problem of the correlated residuals of the model. At the same time, it gives a chance to obtain a reliable answer regarding the significance of individual variables, which is the main goal of this publication. Therefore, in a further stage of the study, the parameters of the linear regression model with ARMA seasonal errors were estimated for the tested time series. The ARMAX model (3,0,2) was obtained. The results of the estimation of individual parameters are presented in Tab. 3. The model consists of three autoregressive (AR) components; two components of a moving average (MA); and a set of regressors corresponding analogously to the day of the week, month, and legislative change. The residuals of the model estimated in this way were re-examined to see if autocorrelation was eliminated. The preliminary diagnosis of the ACF diagram (Fig. 2) shows that there are no autocorrelations.

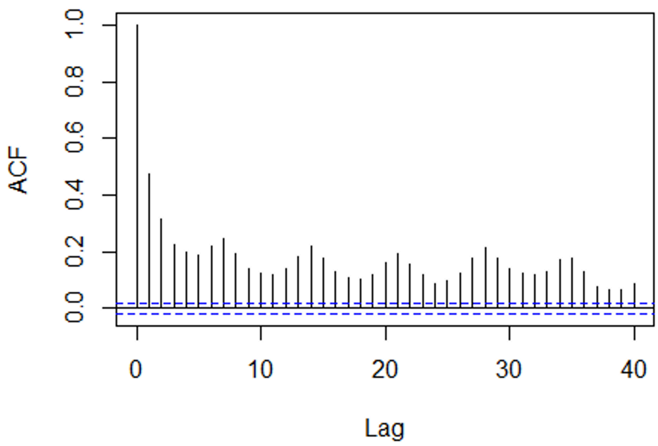

Fig. 1. Autocorrelation graph of the linear regression model residuals with binary variables

Table 3

Estimated values of the ARMAX (3,0,2) model parameters

Term	Estimate	p-value	Term	Estimate	p-value
ar1	0.832	0.000	Change 1	-7.543	0.299
ar2	0.347	0.138	Change 2	10.603	0.126
ar3	-0.193	0.001	Change 3	13.790	0.129
ma1	-0.455	0.013	Change 4	3.425	0.613
ma2	-0.452	0.007	Change 5	-12.329	0.094
intercept	104.827	0.000	Change 6	-23.090	0.001
Monday	16.408	0.000	Change 7	-33.365	0.001
Tuesday	9.665	0.000	Change 8	-36.003	0.000
Wednesday	11.234	0.000	Change 9	-48.494	0.000
Thursday	13.343	0.000	Change 10	-57.040	0.000
Friday	34.058	0.000	Change 11	-62.232	0.000
Saturday	17.094	0.000	Change 12	-72.547	0.000
January	0.320	0.878			
March	4.569	0.029			
April	18.128	0.000			
May	25.898	0.000			
June	39.334	0.000			
July	39.043	0.000			
August	44.854	0.000			
September	44.082	0.000			
October	46.308	0.000			
November	25.300	0.000			
December	23.679	0.000			

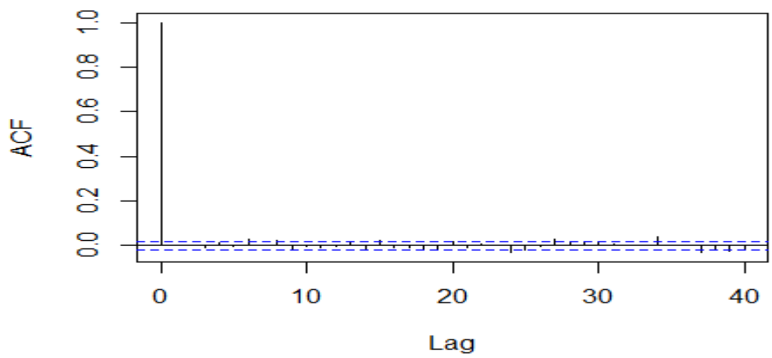

Fig. 2. Autocorrelation diagram of the ARMAX (3,0,2) model residuals

This conclusion was confirmed by performing the Box-Pierce test. The test statistic X-squared = 2.7 10^{-05} (p-value = 0.9958). Thus, there are no grounds to reject the null hypothesis of no autocorrelation. Moreover, the Akaike criterion for the ARMAX (3,0,2) model is more favorable and amounts to AIC = 103788.4. The forecast errors presented in Tab. 4 are also smaller for the ARIMAX model than Linear regression model.

Table 4

Calculated forecast errors for the linear regression model and the ARMAX (3,0,2) model

	RMSE	MAE	MPE	MAPE	MASE
Linear regression model	27.454	20.704	5.191	-18.622	0.58
ARMAX (3,0,2)	23.592	17.711	-3.917	15.508	0.74

Therefore, the ARMAX (3,0,2) model can be considered better than Linear regression model at identifying the number of road accidents in the analyzed period.

5. DISCUSSION

The influence of the vast majority of the calculated parameters is statistically significant, as evidenced by the obtained p-value (Tab. 3). Therefore, it was confirmed that the number of accidents depends on the day of the week. This is mainly due to the weekly life cycle of society and the associated traffic volume, which varies between weekdays and weekends. The reference point for the estimated variables in this case was Sunday, for which the mean value of accidents was the lowest. Therefore, all parameter values are positive. The estimated values for Friday, Saturday, and Monday are the highest, which means that these days have the greatest impact on the number of accidents. Friday has a particularly high value. This is probably due to migration related to moving from a distant place of work to home (which is a popular phenomenon, especially in large cities) but also from recreational weekend trips, which are usually planned on Fridays. In the case of variables describing individual months, the highest values were achieved from July to September (i.e., for the holiday months, when numerous holiday trips take place).

The most important element of the study, however, is the analysis of estimated parameters for the variable representing the periods of operation of individual legal acts. The reference point in this case was the first base period. Almost all other changes had a negative value, which further decreased with the introduction of subsequent adjustments. This means that the introduced changes have a positive impact on reducing the number of accidents. Only the values of the second, third, and fourth changes are positive, but these are statistically insignificant (p-value > 0.05). The overall evaluation of the estimated parameters is satisfactory, confirming that legal regulations have a significant impact on the number of accidents and that each change reduces them. This shows that these activities affect road safety.

6. CONCLUSIONS

In the analysis of road accidents and their causes, the issues directly related to the incident concerning the driver, vehicle, or the environment are most often taken into account. The authors of this article indicated that indirectly influencing factors, which are often ignored in road safety research, are also important. The linear regression model with binary variables was used to show that the foundation in the form of an effective legal system and restrictive regulations are an important element influencing the number of road accidents. Subsequent amendments to the applicable legal acts, the implementation of restrictions and requirements for road users, increases in the fines that can be imposed in the penal proceedings and the inevitability of the penalty, and increases in the level of education and training for drivers bring tangible results in the form of a lower number of road accidents.

In the developed model, only the most important factors (in the authors' opinion) that had an influence during the analyzed period were identified. However, despite a certain level of generalization, it was possible to confirm the research hypotheses and achieve the research objective. As part of further research, detailed analyses relating to narrower territorial areas, taking into account shorter research periods, are possible. This will also make it possible to use other variables that will be archived and interpreted in a given time interval.

The present analysis was carried out using Poland as an example, but the proposed method can be successfully applied in any other country. The dependencies found in various territorial areas will constitute the foundation of comprehensive (global) analyses and the creation of integrated systems limiting the number of road accidents at the global level, which may lead to the improvement of road safety, thereby minimizing financial and social costs.

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