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ASSESSMENT OF THE INFLUENCE OF SELECTED FACTORS ON THE PUNCTUALITY OF AN URBAN TRANSPORT FLEET

Summary. Urban transport systems operate according to fixed, strict timetables, which requires high timeliness and technical readiness of the fleet. Therefore, this article proposes a detailed study of the punctuality of the public transport system using a multiple regression model for the main modes of transport (trams, buses, and Warsaw Metro). The analysis made it possible to go beyond the framework of the overall assessment and to identify the factors that have a significant effect on the punctuality index and to indicate the degree of this effect. The obtained results are a universal tool to assess the punctuality level of the urban transport fleet and to support decision making in the scope of organization of their work, which can be implemented in any similar transport system. The specification of the number of breakdowns, road accidents, or unauthorized stopping of a vehicle as the main causes of delays is the basis for taking corrective measures related to the improvement of the fleet operation system, or for preventive measures. The development of such models is practical in both public transport systems and similar companies providing transport services. For such institutions, the parameter of punctuality is extremely important and affects the quality of the services offered and the reputation of the company, which translates into the number of customers and potential profit. Therefore, it is important to investigate the factors that shape the punctuality of the tasks performed. It allows for shaping the processes of fleet control and management. It is also worth emphasizing the scientific aspect of the publication, which is the presentation of the possibilities of applying selected mathematical models in such analyses, indication of the conditions of their application, and presentation of possible results together with their interpretation.

1. INTRODUCTION

For public transport services to be a competitive alternative to private vehicle transport, high quality should be paramount. Quality of service means a set of criteria and their relevant measures for which the provider is responsible [10]. It is evaluated on the basis of eight main factors, including time, space and functional availability, information, fare, customer relations, comfort, safety, and the environment. Surveys available in the literature indicate that one of the key measures of customer satisfaction and reliability of public transport is the punctuality of the urban transport fleet [17].

Urban transport systems operate according to fixed, strict timetables, allowing for adequate planning and synchronization of different modes of transport (i.e., buses, trams, subways, and

railways). Therefore, a high level of reliability (timeliness and technical readiness of the fleet) and proper management are required. Punctuality is affected by a multitude of factors, a number of which is not recorded, limiting their controllability. Those that are monitored, however, enable assessment of the quality of operation of companies and their ability to react to potential incidents threatening the proper organization of transport operations. The aforementioned may be supported by the use of mathematical modeling methods that enable the analysis and identification of factors adversely affecting the functioning of the public transport system, and the identification of potential, innovative solutions to increase the punctuality of the rolling stock of transport companies. In addition, it can support the correct modeling of real-time vehicle schedule recovery methods of different modes by implementing changes to timetables on an ongoing basis depending on the presence of one or more disruptive factors, leading to the improvement of the quality of the services provided [2].

The aim of this article is to analyze and evaluate the punctuality of an urban transport fleet on the example of the capital city of Warsaw. The survey was conducted on the basis of aggregated data collected by the Public Transport Authority. The occurrence of adverse events, which may have a negative effect on the timeliness of tasks and the degree of their effect on the studied phenomenon, was analyzed. After the analysis, using the tools developed, short-term forecasts are presented, showing how the punctuality of public passenger transport can develop in the future.

2. THE STATE OF THE PROBLEM — LITERATURE ANALYSIS

Public transport is an alternative to private transport. It should therefore be competitive with the latter, mainly in terms of quality. This requires a high level of reliability in public transport, which should be understood as the ability to provide the service as planned. It is most often expressed as a percentage of the mileage “lost” as a result of negative factors, e.g., traffic volume or vehicle breakdowns [3]. Quantitative measurement of reliability of urban transport fleets is possible on the basis of punctuality index.

Punctuality is a feature of collective transport, which is expressed in the fact that a specific vehicle reaches, leaves, or passes a given point on its route in a predetermined time [13]. It means the conformity of the actual operation of vehicles with the adopted timetable. The results of passenger preference surveys available in the literature indicate that this is one of the most important factors influencing customer satisfaction [17]. Therefore, it is important to monitor, evaluate, and improve the indicators obtained.

Generally, authors focus on studying the punctuality index owing to the effect on the quality of service of transport companies. Frequently, achieving the assumed punctuality level of public transport results in a company being awarded a subsidy for its operation or charged with contractual penalties for failure to meet the adopted requirements. The first studies on the timeliness of public transport were conducted by Sterman and Schofer [18] or Turnquist [22] and are being developed to this day [8, 14, 21].

Bates presented a study showcasing basic practices for measuring punctuality based on a survey of 146 carriers. Their results indicate significant differences in the measurement techniques used in individual companies. However, it was noted that in the vast majority of the systems, the deviations of the departure time in the range of 1 minute ahead of schedule and 5 minutes of delay are considered to be compliant with the schedule [4].

Rietveld et al. pointed to six main ways of measuring punctuality, such as follows:

- the probability that a train/bus arrives x minutes late,
- the probability of an early departure,
- the mean difference between the expected arrival and the scheduled arrival time,
- the mean delay of an arrival given that one arrives late,
- the mean delay of an arrival given that one arrives more than x minutes late, and
- the standard deviation of arrival times [12].

A number of studies indicating the effect of individual factors on the punctuality of the studied modes of transport is available as well [1, 4]. Chen et al. [5] considered three types of punctuality indices: a punctuality index based on routes (PIR), a deviation index based on stops (DIS), and an evenness index based on stops (EIS). They indicate the type of influence of four main factors, i.e. the length of the route, the distance between the bus stop and the turning loop, the time between subsequent courses of vehicles on a given route under study, and the division of a special lane for public transport on the values of the aforementioned indices.

Kho et al. presented a concept for examining the timeliness and efficiency of urban transport based on three types of punctuality indexes based on routes:

- P1 – index indicating the magnitude of time gap between actual arrival time and scheduled arrival time,
- P2 – index indicating the magnitude of time gap between actual headway and scheduled headway (regularity), and
- P3 – index indicating the magnitude of time gap between average headway of a day and each headway of successive buses (evenness).

In their study, they indicate the influence of a number of factors, such as traffic conditions, road conditions, route length and number of stops, evenness of passenger demand, transit preferential treatments, operations' control strategies, vehicle and staff availability, and differences in operator driving skills on the aforementioned indices [15].

Based on a study carried out in Portland, Strathman and Hopper indicate that the probability of not maintaining punctuality increases during the afternoon rush hours, as well as with the increasing time lag between measures on the route and the increasing number of passengers [19]. Similar conclusions were drawn by Napiah et al. in their study of the quality of urban transport services in Malaysia [7].

In contrast, Olson and Haugland studied (using correlation analysis) the effect of factors such as the number of passengers, occupancy ratio (passengers/seats), infrastructure capacity utilization, cancellations, temporary speed reductions, railway construction work, departure and arrival punctuality, and operational priority rules on the punctuality of Oslo suburban trains and Norland long-distance trains [9].

Literature analysis resulted in finding a small number of studies aimed at presenting an analysis of the effect of factors related to traffic safety on the punctuality of particular means of urban transport. For this reason, this paper, based on the multiple regression model, presents a study of the effect of adverse events on the reliability of urban transport fleet. The use of the multiple regression model will enable the identification of factors that statistically significantly affect the studied phenomenon, and also the degree of this influence. Additionally, the developed model will show how the studied phenomenon will change depending on the variability of the analyzed predictors.

3. MODEL OF FORECASTING PUNCTUALITY OF PUBLIC TRANSPORT USING MULTIPLE REGRESSION

The punctuality of the public transport system in the capital city of Warsaw was analyzed. The data were recorded between January 2017 and June 2019. It was carried out based on a division into the main types of transport means used: trams, buses, and Warsaw Metro subway trains [6].

The aim of the multiple regression method is to quantify the relationship between multiple independent variables and a dependent variable. The linear model takes the form of equation (1):

$$Y = \beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \dots + \beta_k \cdot x_k + \varepsilon_i \quad (1)$$

where Y – the expected value of the variable Y with the condition that the variable X_i takes the value of x_i ; β_j – model parameters (regression coefficients) and ε_i – random component.

The parameters of model β_j are estimated using the least squares method, based on the assumption that the estimation should be aimed at minimizing errors that are differences between the values observed y_i and the values predicted by the model \hat{y}_i .

The estimated regression function takes the form (2):

$$\hat{y}_i = b_0 + b_1 \cdot x_{i1} + b_2 \cdot x_{i2} + \dots + b_k \cdot x_{ik} + e_i \quad (2)$$

where $i=1, 2, \dots, n$ consecutive numbers of the observed elements; b_j – regression coefficients; e_i – residuals defined as the difference between empirical and theoretical values.

The model is verified by checking whether the following assumptions are met:

- significance of linear regression and partial regression coefficients, and
- normality of residuals distribution and lack of residuals autocorrelation [11].

The development of the model started with visual inspection of the graph (Fig. 1) and analysis of basic descriptive statistics (Table 2). The mean punctuality value in the period under study is 93.89% for trams, 93.13% for buses, and 99.70% for Warsaw Metro subway trains.

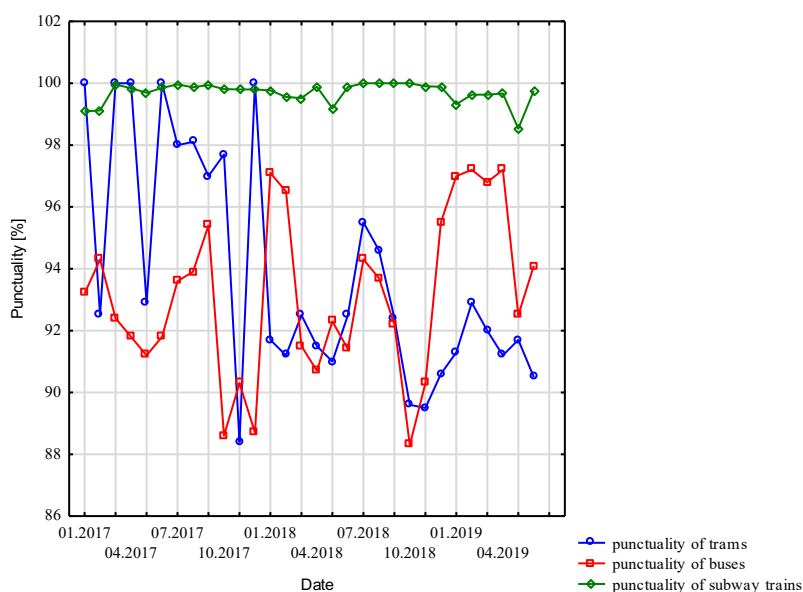


Fig. 1. Graph of punctuality variability of a given mode of transport over the survey period

Table 1

Basic descriptive statistics for the variable punctuality of a given mode of transport during the survey period

Punctuality	Number of observations	Mean [%]	Median [%]	Minimum [%]	Maximum [%]	Standard deviation [%]
trams	30	93.89	88.40	100.00	3.70	3.94
buses	30	93.13	88.30	97.20	2.66	2.86
subway	30	99.70	98.53	100.00	0.34	0.34

The analysis of the course of the examined variables indicates the existence of a trend in relation to the recorded punctuality values for trams. This is confirmed by the calculated correlation coefficients presented in Table 2. The calculated values indicate a high negative correlation between the variable *punctuality of transport* and the consecutive months of recording data (30 monthly observation during all conducted research). For buses and subway trains, the aforementioned relationship does not exist.

Table 2

Correlation coefficients between punctuality of transport and the consecutive months

Variable	Correlations N=30		
	punctuality		
	trams	buses	subway
Month	-0,66	0,29	-0,09

Based on the monthly data, the following exogenous variables were selected for further analysis: *occurrence of vehicle breakdowns, number of accidents, number of collisions, and traffic stoppages owing to other reasons*. For the purpose of the following study, the definition of punctuality was adopted as a percentage share of the number of departures from the checkpoint considered to be timely (with +1/-3 min. tolerance) in the total number of departures observed on a given day [6]. Three models were developed, respectively for buses, trams, and Warsaw Metro subway trains, and their parameters were estimated. The last step was to verify each model and compare the quality of the forecasting.

3.1. Multiple regression model for buses

The first model was developed for buses. The estimated parameters are presented in Table 3.

Table 3

Estimated values of parameters of the model for buses

Adjusted R ² = 0.34 F(4,25)=4.72 p<0.00 Std. error of estimation: 2.16 (bold values are statistically significant)				
N=30	b	Std. error	t(25)	P
absolute term	96.15	4.28	22.46	0.00
breakdowns	0.01	0.00	2.38	0.03
stopping traffic for reasons other than those mentioned above	0.00	0.01	-0.10	0.92
number of accidents	-0.12	0.03	-3.52	0.00
number of collisions	-0.02	0.01	-1.92	0.07

The *breakdowns* and the *number of accidents* variables are statistically significant. The adjusted coefficient of determination R² is 34%. Therefore, the model parameters were re-estimated, omitting the variables for which the *p*-value level is greater than 0.05 (no significance) (Table 4).

The regression equation takes the form (3):

$$y_i = 90.48 + 0.01 \cdot x_{breakdowns} - 0.12 \cdot x_{number\ of\ accidents} \quad (3)$$

Table 4

Estimated values of parameters of the model for buses

Adjusted R ² = 0.29 F(2,27)=6.94 p<0.00, Std. error of estimation: 2.23				
N=30	b	Std. error	t(25)	P
absolute term	90.48	2.91	31.14	0.00
breakdowns	0.01	0.00	2.36	0.03
number of accidents	-0.12	0.03	-3.63	0.00

The model was assessed on the basis of residuals analysis. These are characterized by a normal distribution, as confirmed by the Shapiro-Wilk test, for which the *p* value is 0.48 and indicates the lack of grounds for rejecting the null hypothesis talking about the normality of distribution (Fig. 2).

The analysis of autocorrelation and partial autocorrelation graphs (Fig. 3) showed the lack of significant values of these functions. The confirmation is the Durbin-Watson test (Table 5). The calculated value of the statistics $DW=1.77$ is lower than 2, giving rise to a suspicion that the autocorrelation may be positive. For the analyzed sample ($n=30$, $k=2$, where n — number of

observations, k — number of model parameters), two critical values $d_L=1.28$ and $d_G=1.57$ are given. As $DW>d_G$, there are no grounds for rejecting the null hypothesis on the lack of autocorrelation [16].

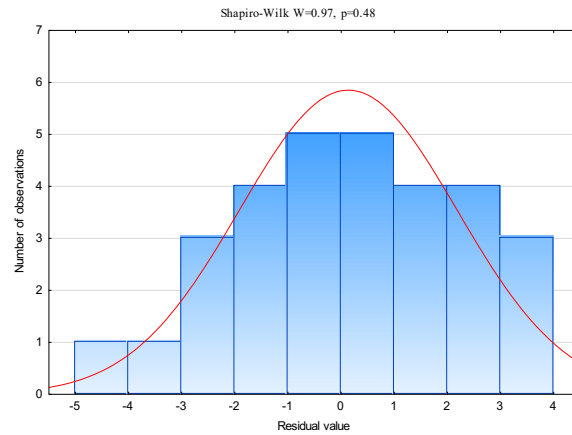


Fig. 2. Histogram of distribution of the residuals of the model for buses

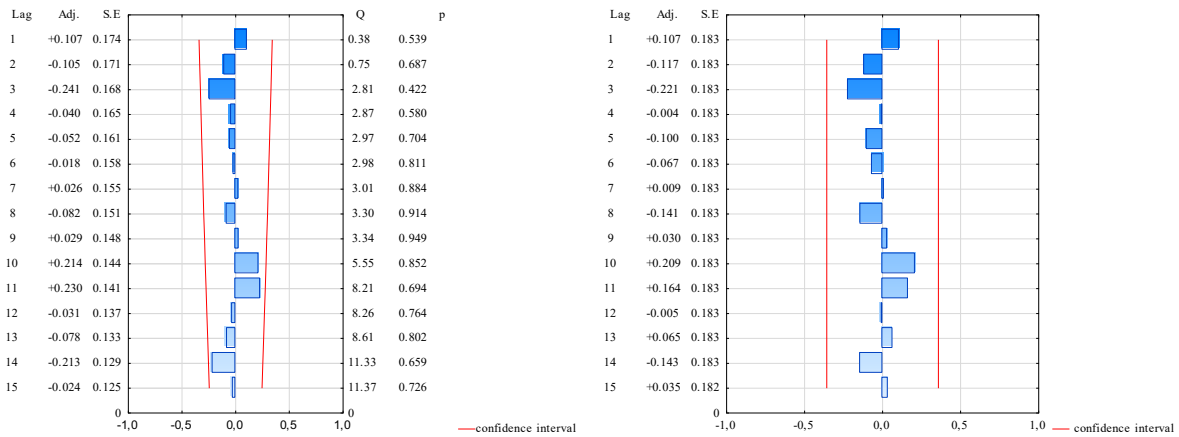


Fig. 3. Charts of autocorrelation and partial autocorrelation functions of the model residuals

Table 5

Durbin-Watson test values

	Durbin–Watson statistic d and serial correlation of residuals	
	Durbin–Watson statistic d	serial correlation
estimation	1.77	0.11

Fig. 4 presents a graph of empirical and predicted values, which shows that the developed model reflects the direction of development of the studied phenomenon well. However, a series of overestimations and underestimations of the forecast variable are noticeable. The adjusted coefficient of determination R^2 is 29%, indicating that there are factors that may affect the punctuality level and that were not used in the development of the model.

3.2. Multiple regression model for trams

The next model was developed for trams. To identify the development trend, an exogenous variable *trend* was added. Estimated regression parameters are presented in Table 6.

The *trend* variable is statistically significant. The adjusted coefficient of determination R^2 is 38%. Parameters were re-estimated eliminating the variables for which no significance was found (Table 7). The regression equation takes the form (4):

$$y_i = 98.20 - 0.28 \cdot x_{trend} \tag{4}$$

The analysis of the distribution of the model's residuals, carried out on the basis of the Shapiro-Wilk test, showed that they are characterized by a normal distribution (Fig. 5).

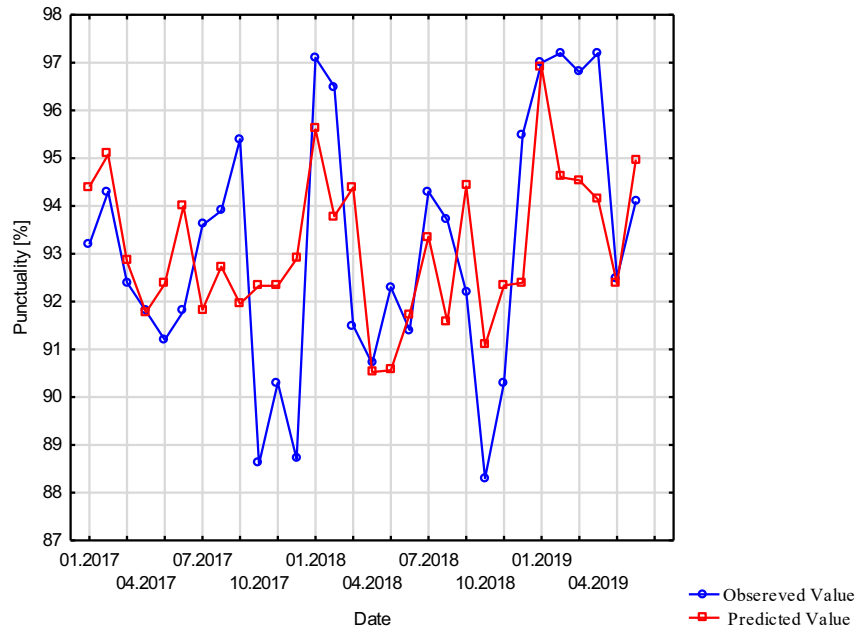


Fig. 4. Graph of empirical and observed values for the bus model

Table 6

Estimated parameters of the model for trams

	Adjusted R2= 0.38 F(5,24)=4.57 p<0.00 Std. error of estimation: 2.91 (bold values are statistically significant)			
N=30	b	Std. error	t(25)	p
absolute term	104.15	4.50	23.13	0.00
Trend	-0.28	0.08	-3.61	0.00
Breakdowns	-0.01	0.01	-0.56	0.58
stopping traffic for reasons other than those mentioned above	-0.03	0.13	-0.26	0.80
number of accidents	-0.05	0.06	-0.94	0.36
number of collisions	0.00	0.04	-0.12	0.90

Table 7

Estimated parameters of the model for trams

	Adjusted R2= 0.41, F(1,28)=27.73 p<0.00, Std. error of estimation: 2.83			
N=30	b	Std. error	t(25)	p
absolute term	98.20	1.06	92.81	0.00
trend	-0.28	0.06	-4.66	0.00

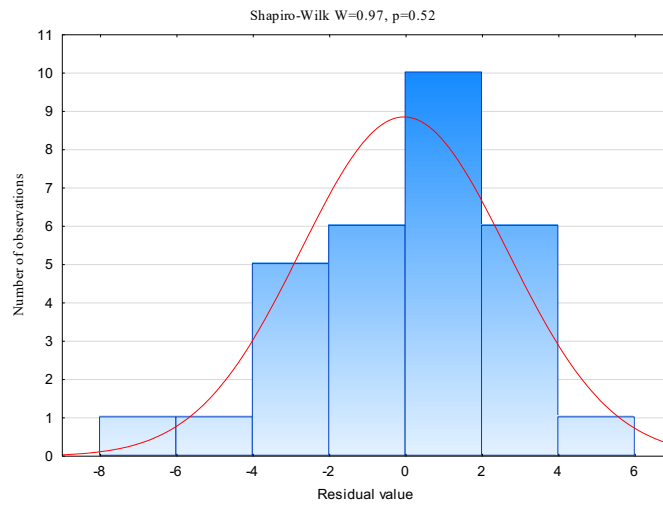


Fig. 5. Histogram of the residuals of the model for trams

The analysis of autocorrelation and partial autocorrelation graphs (Fig. 6) showed the lack of significant values of these functions. The Durbin-Watson test suggests that for the calculated value of the *DW* statistic, the autocorrelation may be negative (Table 7). For the sample analyzed ($n=30, k=1$), two critical values $d_L=1.35$ and $d_G=1.49$ are given. The *DW* statistic value is in the $\langle 4-d_L, 4-d_G \rangle$ range, which is the so-called “non-conclusive range”, which means that no decision can be made to accept or reject the null hypothesis on the lack of autocorrelation.

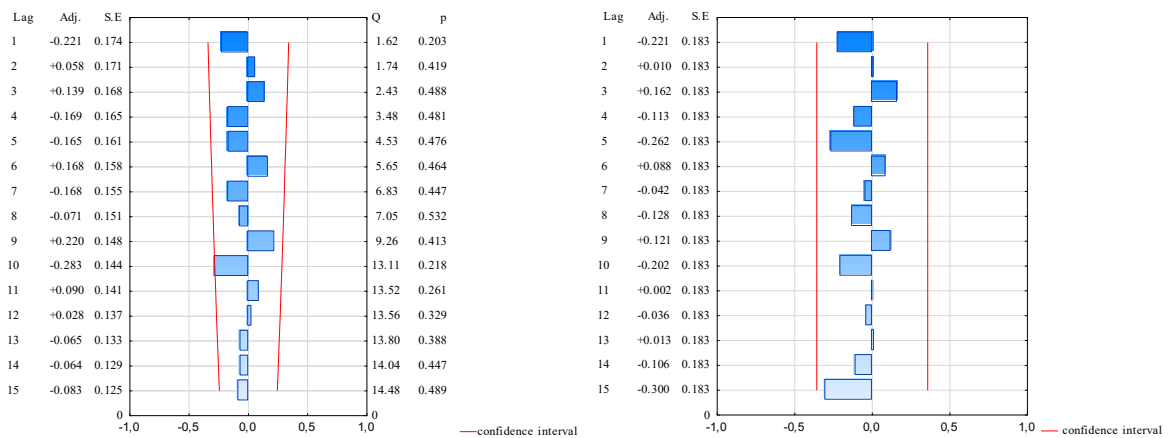


Fig. 6. Graphs of autocorrelation and partial autocorrelation functions of the model residuals

Fig. 8 shows a chart of observed and predicted values, which shows that the model reflects only the occurring trend of the studied phenomenon, without providing correct forecast values, both for high and low indications. It results from insufficient number of exogenous variables used for its construction (for most of the studied factors, the p-value showed their lack of significance).

Table 8

Durbin-Watson test values

	Durbin–Watson statistic d and serial correlation of residuals	
	Durbin–Watson statistic d	serial correlation
estimation	2.42	-0.22

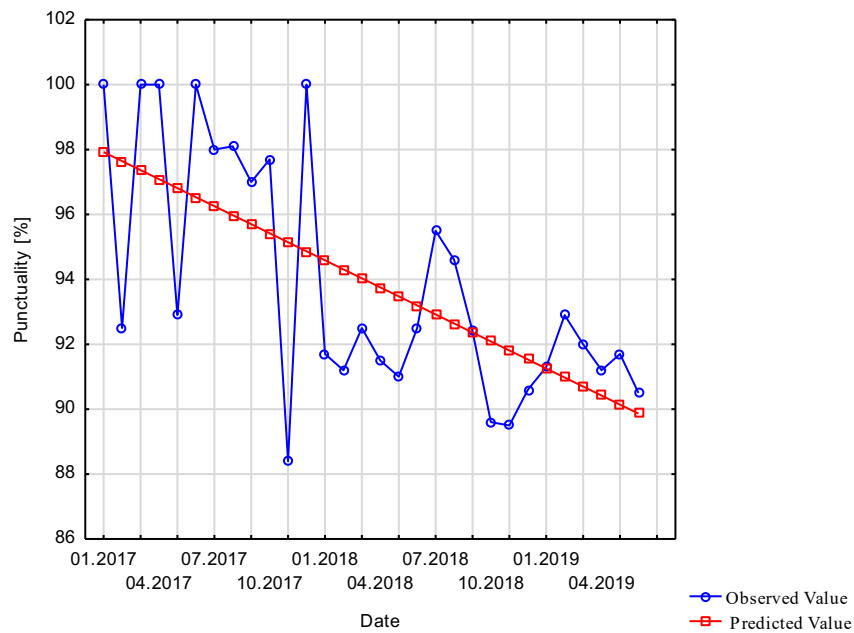


Fig. 7. Graph of empirical and observed values for the bus model

3.3. Multiple regression model for the Warsaw Metro subway trains

The third model to be estimated was for the subway trains. Estimated parameters are presented in Table 9.

Table 9

Estimated parameters of the model for subway trains

Adjusted R2= 0.20 F(2,27)=4.70 p<0.00 Std. error of estimation: 0.30 (bold values are statistically significant)				
N=30	b	Std. error	t(25)	p
absolute term	99.47	0.21	477.45	0.00
Breakdowns	0.00	0.00	0.52	0.61
stopping traffic for reasons other than those mentioned above	0.03	0.01	2.83	0.01
number of accidents	-0.18	0.07	-2.64	0.01
number of collisions	-0.19	0.11	-1.65	0.11

The *stopping of traffic for reasons other than those aforementioned* and the *number of accidents* variables are statistically significant. The adjusted coefficient of determination R² is 24%. Parameters were re-estimated excluding variables for which no significance was found (Table 10).

The regression equation takes the form (5):

$$y_i = 99.55 - 0.14 \cdot x_{number\ of\ accidents} + 0.03 \cdot x_{stopping\ traffic} \tag{5}$$

The analysis of model's residuals, carried out on the basis of the Shapiro-Wilk test, showed that they are characterized by a normal distribution (Fig. 8).

The analysis of the autocorrelation and partial autocorrelation function confirmed the lack of significant values of these functions, allowing to consider the distribution of residuals as a white noise process (Fig. 9). The confirmation is the Durbin-Watson test (Table 11). The calculated value of the

statistic $DW=1.75$ is lower than 2, giving rise to a suspicion that the autocorrelation may be positive. For the sample analyzed ($n=30, k=2$), two critical values $d_L=1.28$ and $d_G=1.57$ are given. As $DW>d_G$, there are no grounds for rejecting the null hypothesis on the lack of autocorrelation.

Table 10

Estimated parameters of the model for subway trains

	Adjusted R ² = 0.20 F(2,27)=4.70 p<0.00, Std. error of estimation: 0.30			
N=30	b	Std. error	t(27)	p
absolute term	99.55	0.11	867.55	0.00
stopping traffic for reasons other than those mentioned above	0.03	0.01	2.57	0.02
number of accidents	-0.14	0.07	-2.18	0.04

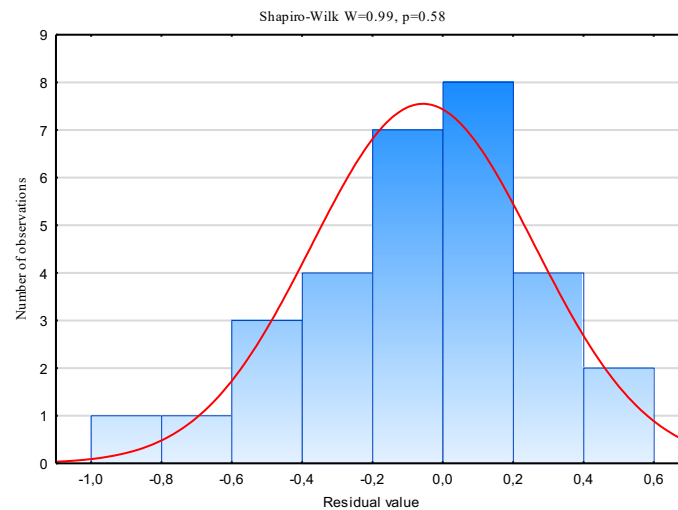


Fig. 8. Histogram of the residuals of the model for Warsaw Metro subway trains

Fig. 10 presents a graph of empirical and forecast values. The adjusted coefficient of determination (R^2) is 20%. The model reflects the trend of the studied phenomenon well. Nevertheless, there are indications for which theoretical values determined on the basis of the developed tool differ significantly from the value of the punctuality index recorded during the studied period.

3.4. Comparison of the quality of predictions of the developed models and indication of the possibility of their use

Table 12 presents a comparison of the quality of predictions of the models developed. The smallest forecast error was recorded for the model for the Warsaw Metro subway trains. The lowest accuracy of the forecast was obtained in the model for trams, which results from the adopted exogenous variables.

On this basis, the models for buses and Warsaw Metro subway trains can be considered satisfactory. For trams, other exogenous variables should be sought to examine their effect on the punctuality of the mode of transport in question.

The analysis of the quality of the developed models confirms the high efficiency of their prediction. Thanks to this, they can be used as a tool to support decision-making processes in fleet management in enterprises providing public transport services. They enable the identification of factors (mainly related to road safety) that significantly reduce the level of punctuality of transport and indicate the moments when the indicator falls below the adopted satisfaction threshold. In addition, they can be a

reference point when planning long-term strategies for scheduling public transport traffic or social campaigns dedicated to drivers and passengers, aimed at improving their awareness of traffic safety in urban agglomerations.

Table 11

Durbin-Watson test values

	Durbin–Watson statistic d and serial correlation of residuals	
	Durbin–Watson statistic d	Durbin–Watson statistic d
estimation	1.75	0.08

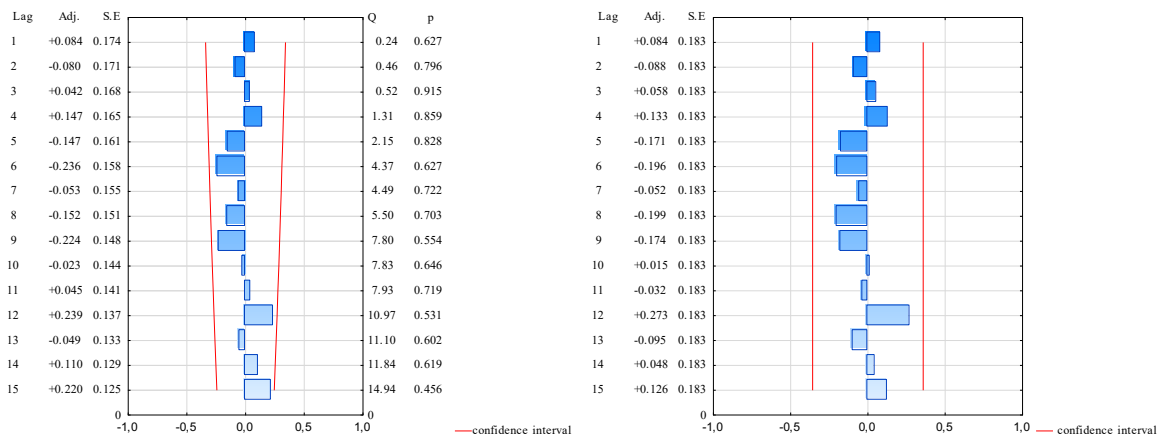


Fig. 9. Graphs of autocorrelation and partial autocorrelation functions of the model residuals

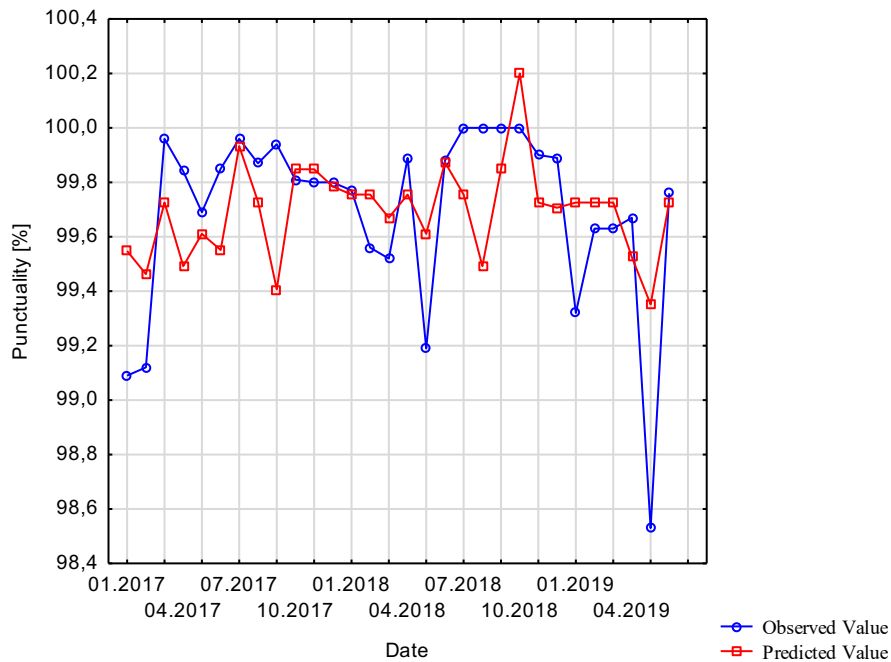


Fig. 10. Graph of empirical and observed values for the bus model

4. CONCLUSIONS

Punctuality analyses carried out by the Warsaw Transport Authority are mainly based on collective evaluations of the number of delayed transports. On this basis, general indexes are formulated which are a fraction of the punctual or non-punctual transport tasks. They only give a general view of the functioning of these systems and do not make corrective measures possible, as they do not indicate the causes of the irregularities found.

Therefore, this article assesses the effect of selected factors on the punctuality of the public transport system. The study was carried out based on the example of the means of urban transport of the capital city of Warsaw, but the developed method is universal and adaptable to other similar systems as well.

Table 12

Assessment of the forecast quality of individual model

Date	Bus		
	Empirical value	Forecast value	Forecast error [%]
07.2019	93.95	94.49	-0.57%
08.2019	93.80	94.25	-0.48%
Date	Tram		
	Empirical value	Forecast value	Forecast error [%]
07.2019	96.75	89.52	2.67%
08.2019	96.35	89.24	2.80%
Date	Warsaw Metro subway trains		
	Empirical value	Forecast value	Forecast error [%]
07.2019	99.98	99.85	0.13%
08.2019	99.94	99.62	0.32%

In addition, the aim of the article was also to indicate the multiple regression method as a tool supporting decision making in the field of proper organization of transport. The models developed make it possible to assess the punctuality of public transport on the basis of the road and rail safety factors recorded. In addition, they indicate situations when its value may fall below the assumed quality level (e.g., 90%). They are the basis for setting directions for improving the organization of transport through, inter alia, preventive actions in the fleet maintenance and repair system aimed at reducing the number of breakdowns, conducting training for drivers in road safety, or carrying out campaigns aimed at minimizing the number of vehicles stops resulting from the fault of improper behavior of passengers.

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