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INFLUENCE OF TIRE PRESSURE ON FUEL CONSUMPTION IN TRUCKS WITH INSTALLED TIRE PRESSURE MONITORING SYSTEM (TPMS)

Summary. In recent years, the development of IT systems for fleet monitoring was observed. Tire pressure monitoring systems are constantly improved. Decreased values in tire pressure can cause deformation of tires. Monitoring of tire pressure is an important function in oversized transport trucks. Tire pressure and rolling resistant influence fuel consumption. The purpose of this paper was to determine the impact of tire pressure on fuel consumption in a fleet of trucks with tire pressure monitoring system installed and to determine the impact of other factors that may affect fuel consumption, such as the vehicle weight, brake usage and cruise control usage. The results of the research were developed using a multiple regression model describing the above dependence.

Keywords: tire, pressure, monitoring, TPMS, fuel consumption

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1. INTRODUCTION

The development of technology, especially technology for measuring vehicle exploiting parameters, moving at the direction of increasing efficiency, reliability and reducing exploiting costs related to fuel consumption, thus reducing the emission of harmful pollutants. The basic parameter enabling the increase of usage properties in a tire is the selection of the proper tire pressure depending on the vehicle weight, ambient conditions (temperature, external pressure), and the mode of exploitation. The development of civil engineering and transport allows the use of increasingly better consumables, fuel mixtures and measurement systems of selected parameters to ensure higher reliability and efficiency [1-3].

Based on the literature review so far, it should be stated that tire pressure is an important factor affecting the passive safety of vehicles. First, it was noticed that depending on the tire pressure level, the tire is subject to greater or lesser deformations. Such deformations affect the stability exploiting of tires causing, for example, irregular tread wear [4-5]. Figure 1 presents tires with different pressure values.

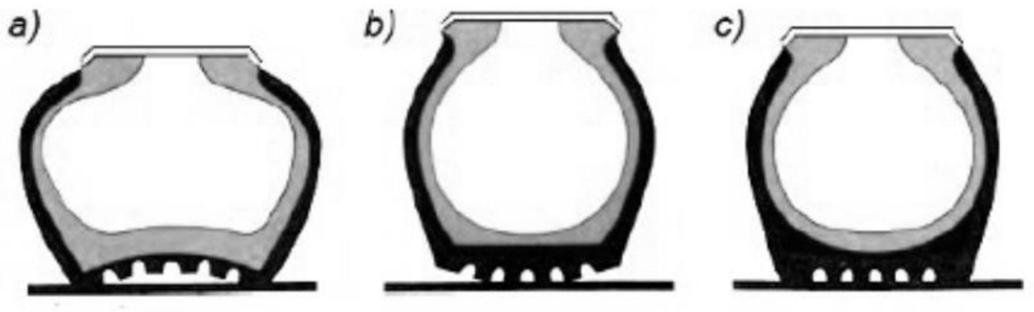

Fig. 1. Tire deformations in a) low pressure, b) high pressure, c) proper pressure [5]

Low tire pressure causes tire deformations from the inside in such a way that contact with the ground occurs only on the outer surface. Then there is a danger of the tire warming up quickly (increase of temperature) and damage its structure, which may lead to shorter tire life. Too high tire pressure values cause it to contact the ground only in the middle part.

In the third case, the tire pressure is correct. The tread consumption is regular, which affects the driving comfort and increases the tire life and shorter braking distances [5]. According to Mathai, correct tire pressure and temperature values allow for lengthening the life of the tire by 30%. The authors of the study [6] even indicate the value of 50%. In turn, Reiter et al. calculated that the exploiting of vehicles with lower tire pressure has the impact of shortening the tire life by up to 5% [7-8].

In recent years, the impact of tire pressure values on fuel consumption and rolling resistance has been analysed. The results of scientific and research work [12-21, 23] clearly indicate the relationship between these parameters. Tests carried out by Varghese and Schmeitz, indicate that as tire pressure increases, rolling resistance decreases with the same value of vehicle speed and weight [10-11]. In his scientific works, Jansen noted that the decrease in pressure in passenger car tires by 0.03 MPa caused an increase of 6% in rolling resistance while fuel consumption increased by 1% [11]. Similar relationships have been shown in publications [7-8, 22] where, with a drop in pressure in truck tires by 0.02 MPa, fuel consumption increased by 1.5%.

In turn, the work of Jasarevic and Reiter stated that the pressure drop of 0.05 MPa in the tires increased the rolling resistance by 15%, which determines an increase of fuel consumption in the range of 2-5% in vehicles [7-9]. Based on the analysis of the literature data, it can be stated that tire pressure is the basic factor affecting the efficiency of the use of vehicles, rolling resistance and the amount of fuel consumption. In addition, as demonstrated in a number of scientific and research works in Poland and around the world, the exploitation of vehicles at tire pressure other than recommended by manufacturers affects the condition of tires, causing premature wear.

The relationship between the decrease of tire pressure in passenger cars and the tire life has been investigated, among others by Wagner et al. [7-8].In these publications, the authors showed that the exploitation of vehicles with reduced tire pressure by about 7 kPa causes the tire life to be shortened by almost 2%. The published data of the research projects carried out confirmed this relationship. The results of scientific and research work indicate a reduction of tire life by 30% in the exploitation of vehicles with reduced tire pressure by 20% of the pressure recommended by manufacturers [7-8].

The purpose of this paper is to determine the impact of tire pressure on fuel consumption in a fleet of trucks with tire pressure monitoring system installed and to determine the impact of other factors that may affect fuel consumption, such as the vehicle weight, brake usage and the cruise control usage. The results of the research were developed using a multiple regression model describing the above dependence.

1. MATERIALS AND METHODS

In the considered transport company realising the transport of oversized cargo, the truck fleet consists of 50 vehicles including tractors and trailers. Among the vehicles, there are three types of tractors and six types of trailers. From among all available vehicles in the truck fleet, 10 vehicles consisting of three-axle tractors with 6x2 motor and Mega Tele type trailers were selected for basic tests, as it was found that for these vehicles, the exploiting conditions will be the closest in terms of route length, weight of transported loads, etc. In addition, these vehicles are the most used in the considered company.

Vehicles (tractor + trailer) are marked in sequence with letters A to E. The test material is truck tires. For the needs of the work, new tires were purchased (Michelin companies) and installed in all tested vehicles. Truck tires used for transport in the fleet of the considered company differ in size:

- 22.5 inches for tractors,
- 17.5 inches for trailers.

During the tests, the tires were not damaged, changed or transferred to another arrangement in the axles of the vehicle.

Remote tire pressure measurements were made using a tire pressure monitoring system. In the selected vehicles, a tire pressure monitoring system was installed while the vehicle was working, which made it possible to track the measured exploiting parameters continuously on the online platform, and every 30 days the data was transferred to the files for further analysis. On the basis of the obtained data, statistical calculations and graphs of fuel consumptions versus tire pressure were made.

The results of average fuel consumption measurements have been recorded on the Nawi24 website, which is used to monitor vehicles using GPS. The fuel quantities were controlled by CAN sensors, additionally, on the basis of the received data from the system, sections of the route were calculated, which allowed for relatively precise determination of the average of fuel consumption by the system. As part of the work, the average fuel consumption values were taken from the system in the form of files and then compiled and analysed.

Data collected from the Scania online platform concerned, for example, average fuel consumption in monthly summaries, and eco-driving, which is a modern and eco-friendly driver's style. All drivers have been trained on the impact of eco-driving on fuel consumption during vehicle exploiting. The factors controlled by the Scania Driving Service system include: using the cruise control [%], using the brake [number], the weight of the vehicle [Mg] and average speed [km/h]. Data collected from the Scania platform was compiled and then analysed in terms of their significance on the fuel consumption of tested vehicles.

2. RESULTS

3.1. Influence of tire pressure on fuel consumption

The influence of tire pressure on the average fuel consumption in vehicles with tire pressure monitoring system was examined. The measurements of average fuel consumption on the test day and the average pressure in all tires in the vehicle were compiled. Measurements of average fuel consumption were registered automatically in the system Nawi24, a platform for monitoring the truck fleet. Average fuel consumption values were taken into account in only those that concerned a route longer than 50 km. The obtained values were related to the main line. The CAN system uses a fuel probe to provide data from the amount of fuel consumed. The pressure values were recorded on the remote online platform of the tire pressure monitoring system, then averaged from each axis on each day of vehicle exploiting and averaged from all axles on a given day. The research was conducted from November 2017 to August 2018. The data from each month were compiled on a chart, the regression curve, the R^2 coefficient and the equation of this curve were derived. Linear regression was used in the studied relationship.

Analysis of the obtained data shows that the results of calculations of the average amount of fuel consumption in vehicles A-E and average tire pressure in a given day are arranged in diagrams linearly (Fig. 2-6), and the observed dependence is inversely proportional.

This means that as the tire pressure increases, the average fuel consumption in the tested vehicles decreases. For the linear regression model used, the determined R^2 coefficient is 0.67 for vehicle B, indicating a moderate correlation (Fig. 3). The R^2 coefficient was the lowest for the analysed vehicle. For vehicle A, the determined R^2 coefficient was 0.75, which also indicated a moderate correlation (Fig. 2). The R^2 coefficient determined (Figures 4-6) in the other analysed cases was about 0.80, which indicates a strong positive correlation between the analysed variables.

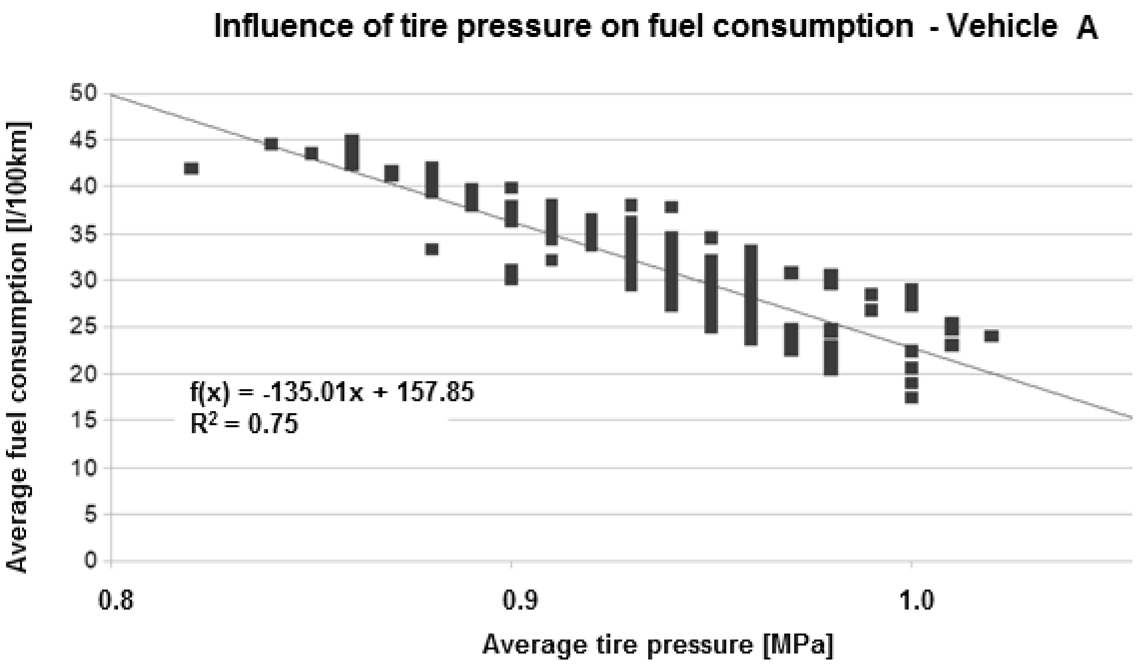

Fig. 2. Influence of tire pressure on fuel consumption – vehicle A

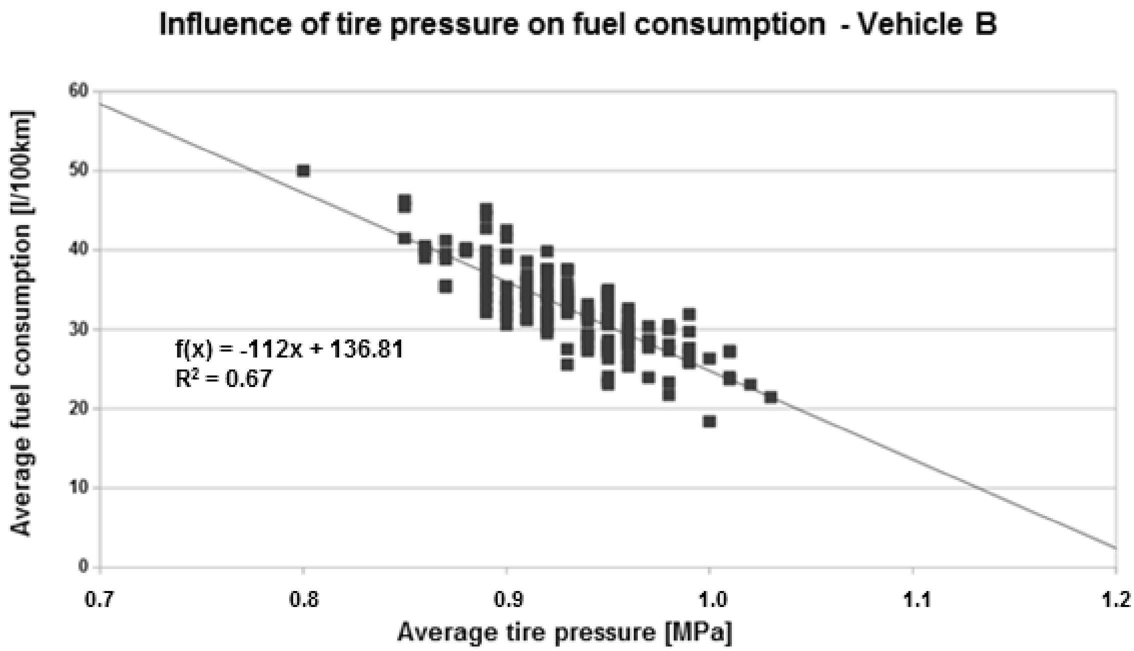

Fig. 3. Influence of tire pressure on fuel consumption – vehicle B

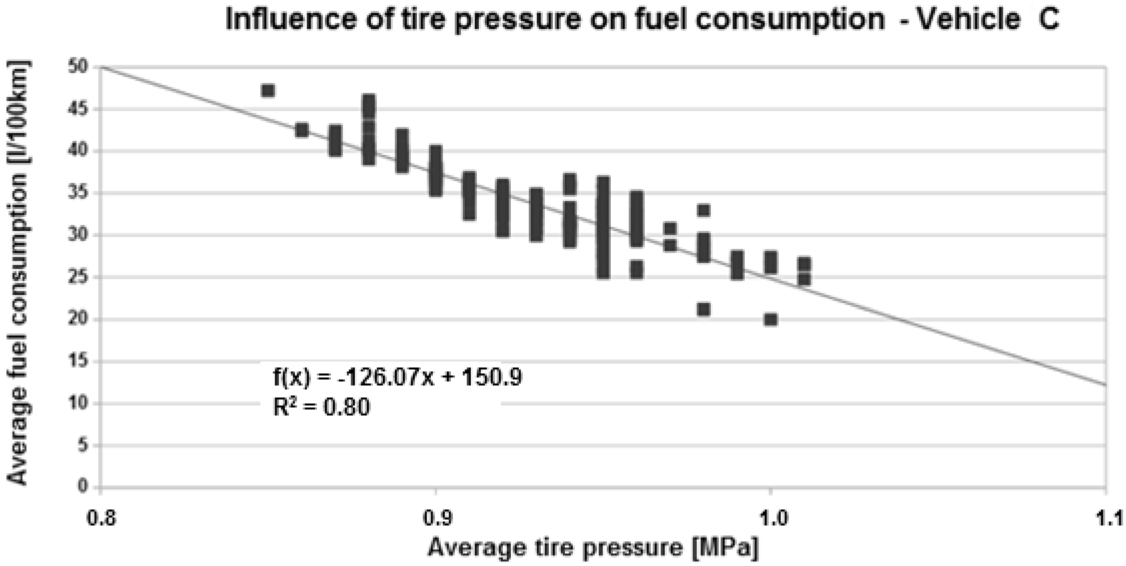

Fig. 4. Influence of tire pressure on fuel consumption – vehicle C

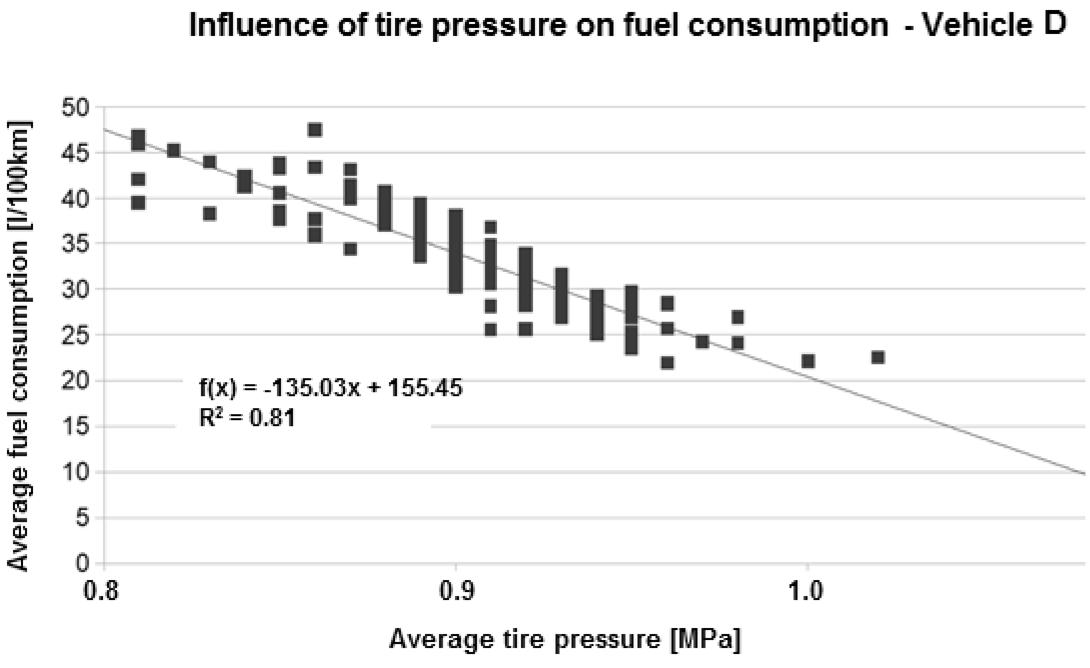

Fig. 5. Influence of tire pressure on fuel consumption – vehicle D

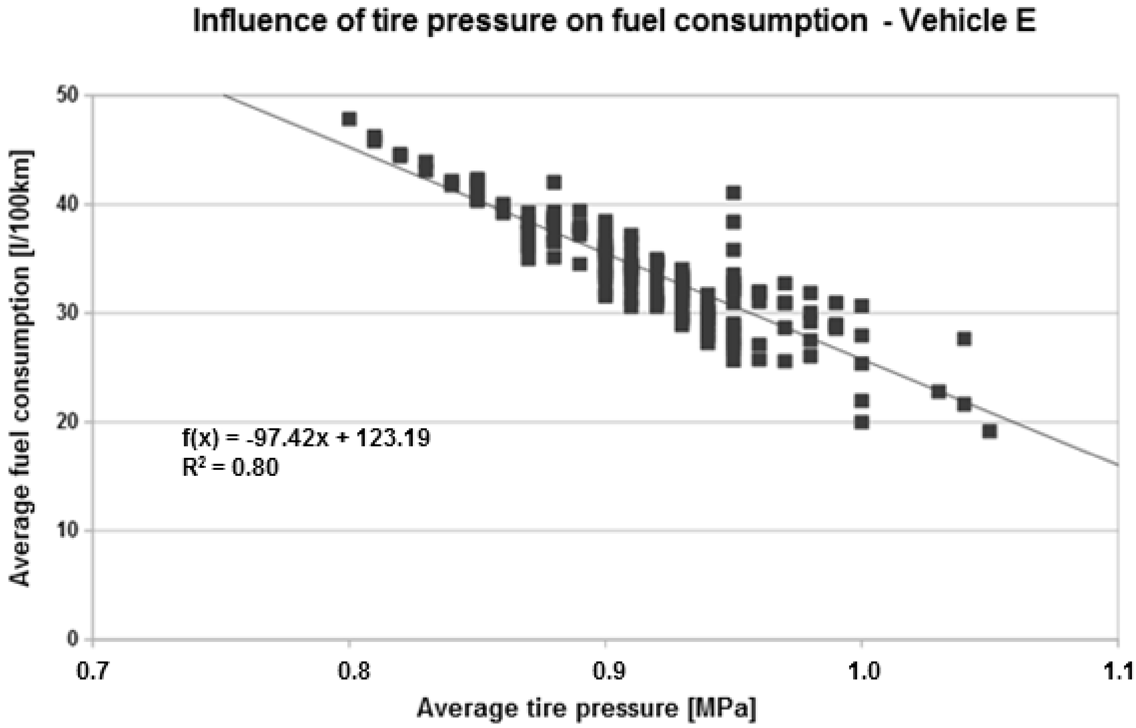

Fig. 6. Influence of tire pressure on fuel consumption – vehicle E

3.2. Influence of other parameters on fuel consumption

In order to identify other factors that may impact fuel consumption, the following measurements were compiled:

- weight of the vehicle (average weight of the truck; the vehicle together with the transported load) [Mg],
- brake usage (the number of brakes use over the distance of 100 km of the route) [number / 100 km],
- use of cruise control (percentage of cruise control) [%],
- average speed [km/h].

All measurements were registered by a special platform to manage the Scania Fleet Management truck fleet, where all monitored vehicle data were sent in an automated manner. The data of vehicles were downloaded from the platform in a file, ready for further analysis and comparisons.

The measurements and calculations were aimed at checking the impact of other exploiting parameters on fuel consumption in monitored vehicles and determining which of the parameters significantly affect the amount of fuel consumed. The analysis of the test results shows that the strongest correlation was demonstrated between these parameters: the weight of vehicle and fuel consumption (Fig. 7).

Along with the increase in the weight of vehicle, the fuel consumption in vehicles also increased (according to the linear law), which is consistent with the literature data. Determined R^2 coefficients in the analysed cases were from 0.60 to 0.73.

Slightly lower correlation was observed between such parameters as the registered number of braking and its effect on fuel consumption (Fig. 8) during vehicle exploiting and in the case of observation of the impact of the use of cruise control on fuel consumption.

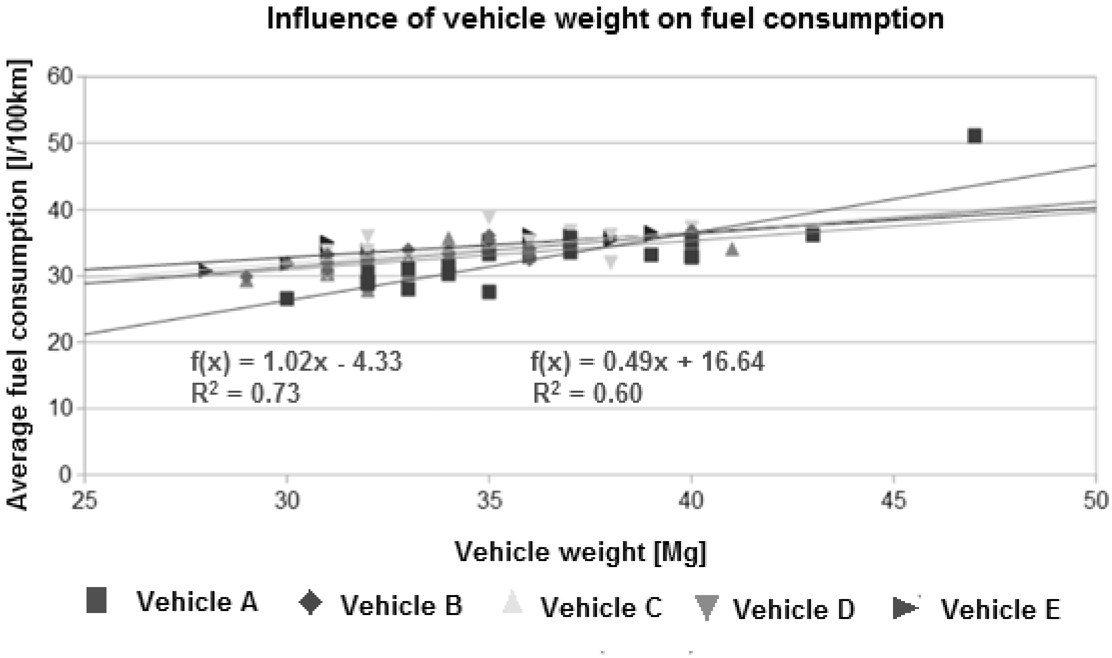

Fig. 7. Influence of vehicle weight on fuel consumption

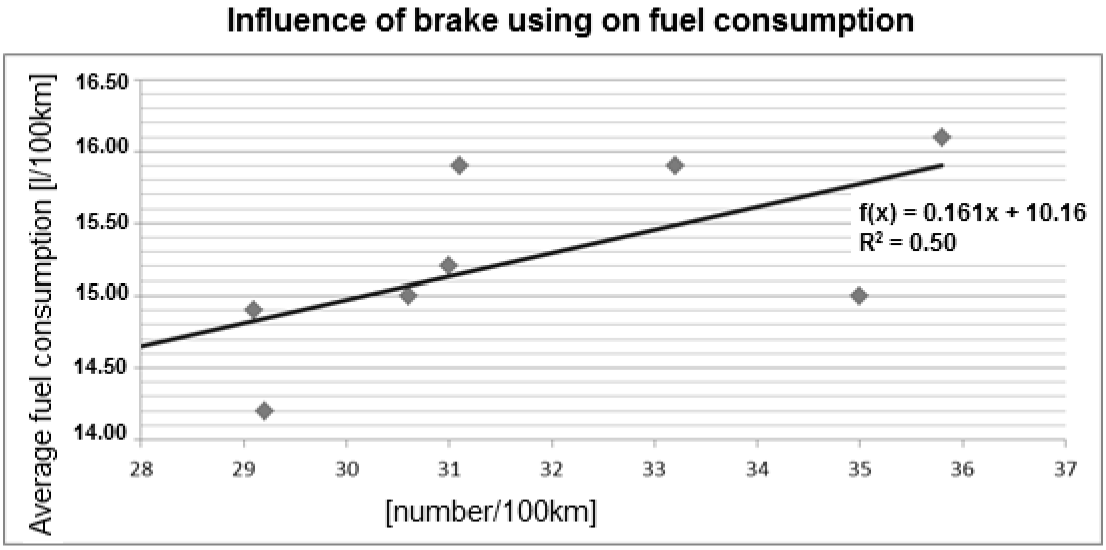

Fig. 8. Influence of brake usage on fuel consumption

In both cases, the low linear correlation coefficient of the independent variable with the dependent variable (the amount of fuel consumption) was recorded. However, these results do not determine the removal of these variables from the set of predictors. In order to make an unambiguous assessment of the impact of each of the explanatory variables on the variability of the explained variable (fuel consumption), statistical analyses should be carried out, determining partial and semi-partial correlation coefficients. Observed results indicate that the percentage use of cruise control in vehicles was high, in the range of 57 to 91%.

Considering the data analysis, it could be concluded that in addition to the tire pressure, the most significant impact on the amount of fuel consumption during the exploration of the trucks is affected by the following: the vehicle weight, brake usage and use of cruise control. For these variables, linear regression was assumed. The correlation was considered to be strong for the dependence between the parameters: vehicle weight and average amount of fuel consumption, while the average or weak correlation was recorded in the case of the analysis of the dependence of the registered number of brake and cruise control usage on the average amount of fuel consumption.

In the first step, linear relationships between variables were examined to determine whether: fuel consumption depends linearly on other variables (explanatory) given that explanatory variables do not depend strongly on each other.

Table 1 summarises the values of basic statistics and Pearson's linear correlation coefficients for the considered variables.

The presented values of the correlation coefficient (Table 1) indicate a strong, statistically significant, negative relationship between fuel consumption and tire pressure(-0.73) and also a statistically significant positive relationship between fuel consumption and vehicle weight.

Among the explanatory variables, there were also several statistically significant linear relationships (marked in red in the table). The strongest is the negative relationship between brake usage and use of cruise control, which has a causal effect. This means with increase use of cruise control on the route, the number of brake usage decreases.

It should be noted that the low linear correlation coefficient of the independent variable with the dependent variable does not determine the deletion of the variable from the predictor set. In order to make an unambiguous assessment of the impact of each of the explanatory variables on the variability of the explained variable (fuel consumption), the coefficients of partial and semi-partial correlation should be determined. Partial correlation expresses correlation between a given independent variable, taking into account its correlation with all other variables (dependent and independent). This is the correlation between the rest after considering all independent variables. The partial correlation represents the unique contribution of a given independent variable when predicting the value of the dependent variable. On the other hand, semi-partial correlation determines the correlation of a given independent variable, given its correlating with all other variables and the dependent variable (without considering its correlation with other variables).

Statistically significant at the level of $\alpha = 0.05$ Pearson's linear correlation coefficients were marked in red.

Thus, partial semi-correlation is the correlation of the residuals of a given independent variable after considering the influence on other variables with the dependent variable without taking into account the influence of other variables.

In the analysed case, the semi-partial correlation coefficient is a better indicator of the "actual impact" of the predictor than the partial correlation because it scaled (referred to) the total variability of the dependent variable (fuel consumption). Values of partial correlation coefficients and semi-partial correlation coefficients are presented in Tab. 2.

The values of partial semi-correlation coefficients indicate the greatest impact of the pressure and vehicle weight on the variability of fuel consumption. The effect of brake and cruise control is similar. The value of Pearson's correlation coefficient (high positive relationship between these variables) indicates their redundancy (tolerance coefficient equal to 0.19 and 0.21, respectively – Tab. 3).

Tab. 1

Basic descriptive statistics and Pearson's linear correlation coefficients

Variable	Variable					
	Average speed [km/h]	**Use of Cruise control [%]**	**Brake usage [number/100km]**	**Vehicle weight [Mg]**	**Pressure [MPa]**	**Fuel consumption [l/100km]**
Average	59.20	71.80	23.0	34.20	0.93	32.93
Standard deviation	4.87	16.90	11.1	3.18	0.03	2.40
Fuel consumption [l/100km]	0.01	-0.09	0.11	**0.57**	**-0.73**	1.00
Pressure [MPa]	-0.14	0.10	-0.01	**-0.41**	1.00	
Vehicle weight [Mg]	0.16	0.07	-0.09	1.00		
Brake usage [number/100km]	**-0.35**	**-0.88**	1.00			
Use of cruise control [%]	0.25	1.00				
Average speed [km/h]	1.00					

Tab. 2

Partial and semi-partial correlation coefficients of variables considered in the model

Variable	Partial correlation coefficients	Semipartial correlation coefficients
Pressure [MPa]	-0.69	-0.55
Vehicleweight [Mg]	0.44	0.28
Brake usage [number/100km]	0.24	0.14
Use of cruise control [%]	0.21	0.13
Average speed [km/h]	-0.13	-0.08

Tab. 3

The values of the Pearson correlation coefficient for a variables set

Variable	Actual variable in equation; DV: Fuel consumption [l/100 km]			
	Partial correlation	**Semi-partial correlation**	**Tolerance**	**R^2**
Pressure [MPa]	-0.69	-0.55	0.79	0.21
Vehicle weight [Mg]	0.44	0.28	0.73	0.27
Brake usage [number/100km]	0.24	0.14	0.19	0.81
Use of cruise control using [%]	0.21	0.13	0.21	0.79
Average speed [km/h]	-0.13	-0.08	0.82	0.18

Therefore, only one of them can be included in the model as an explanatory variable. Due to the higher Pearson's correlation coefficient between brake usage and fuel consumption, it was decided to introduce this variable into the model. The average speed and use of cruise control were considered to have a slight impact on the variability of fuel consumption and were not included in the model. For a set of variables in the model, the semi-correlation and tolerance values were again determined to verify the correctness of the selection. The results are summarised in Tab. 4.

Tab. 4

Semi-correlation values after been removed from the set of redundant variables

Variable	Partial correlation	Semi-partial correlation	Tolerance
Pressure [MPa]	**-0.67**	**-0.54**	**0.83**
Vehicle weight [Mg]	**0.46**	**0.31**	**0.82**
Brake usage [number/100km]	0.21	0.13	0.99

The tolerance coefficients indicate that none of the variables is redundant, so the set of explanatory variables is correctly specified.

The linear model equation was determined by the multiple regression method with the minimisation of the error functions using the least squares method:

$$\boldsymbol{fuel\ consumption} = \mathbf{71.334} - \mathbf{51.512} * \boldsymbol{pressure} + \mathbf{0.2580} * \boldsymbol{vehicle\ weight} + \mathbf{0.0284} * \boldsymbol{brake\ usage}$$

The standard error of the estimation of this model is 1.479 l / 100 km. The R^2 coefficient is 0.64. The correctness of the model was assessed on the basis of the distribution of residuals, that is, the differences between the actual (empirical) and model values. For a well-constructed model, the rest should have a normal distribution. The correctness of the model presented in the work confirms the distribution of residuals shown in Fig. 9.

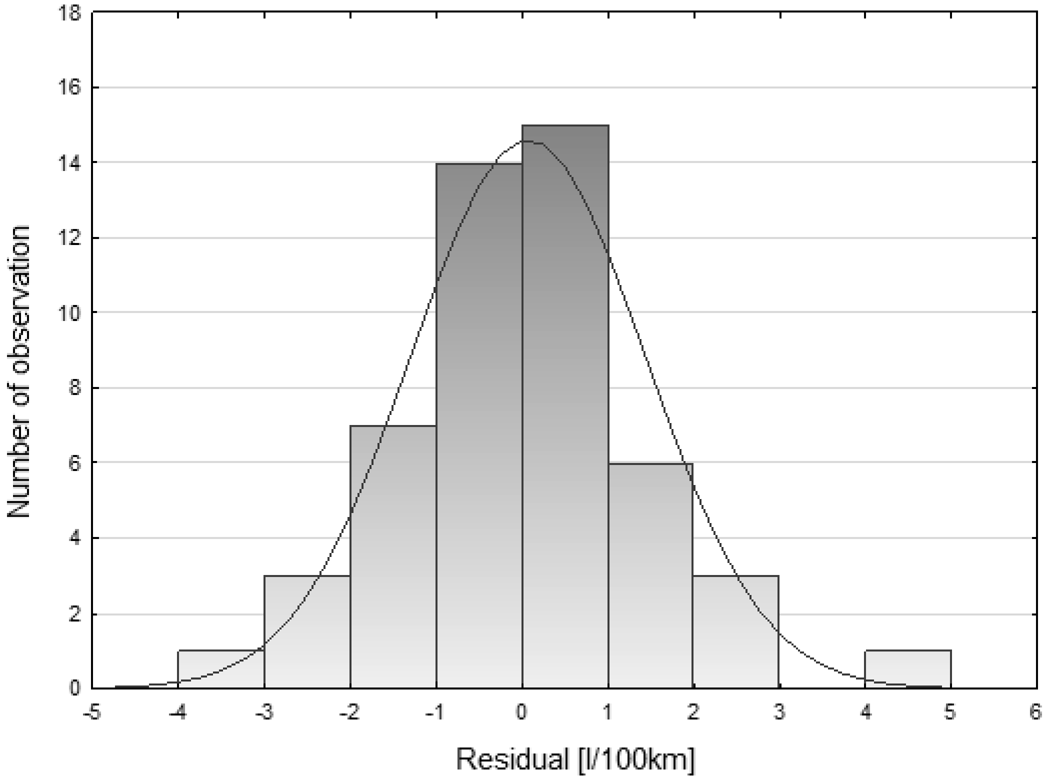

Fig. 9. Residual histogram for the model (pattern number)

According to figure (Fig. 9), all residue values are arranged according to the frequency of normal distribution. For a more accurate assessment of the compatibility of the distribution of residues with the normal distribution, a normality diagram of the residuals is shown (Fig. 10). It can be seen that all points representing the rest of subsequent cases are arranged on a line representing the normal distribution.

In Fig. 10, one point is visible, for which the rest is significantly higher than expected. This is the last measurement of the last vehicle. This value may result from measurement error but we cannot verify this hypothesis, therefore we left the result of this measurement in the data set. The presented results confirmed a strong relationship between these parameters.

However, the limitations of inference based on the proposed and presented model should be considered. The tire pressure value is limited in advance by the maximum value specified by the manufacturer. According to the literature data, if the tire pressure is too high, the tire wear pattern also changes. Too high tire pressure causes the contact of tires with the ground only in the middle part. Such deformations may lead to irregular use of the tread, which may also lead to a shorter time of safe tire use [5].

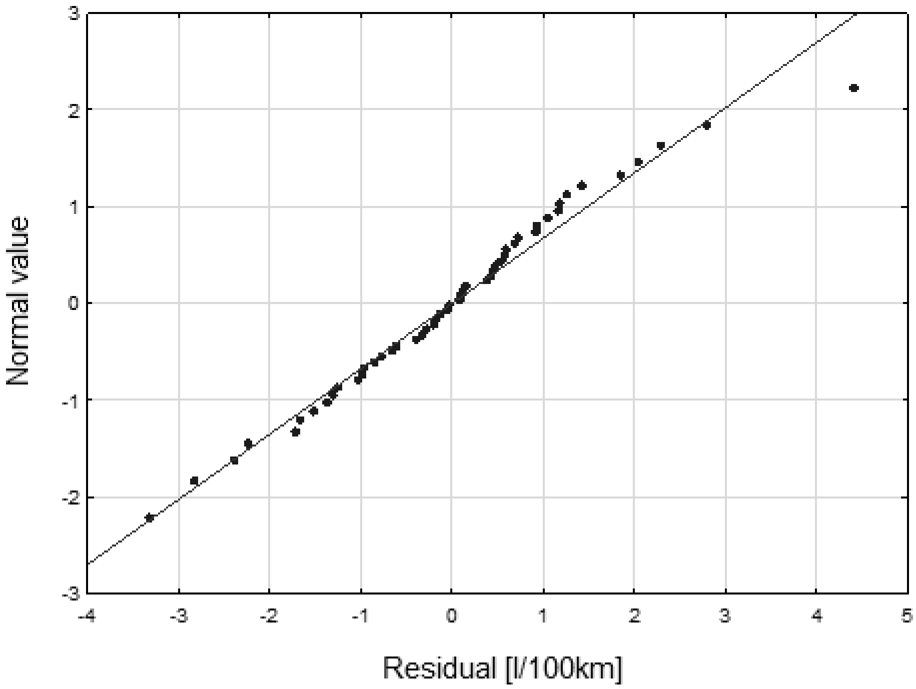

Fig. 10. Normality diagram of residuals

3. CONCLUSION

In recent years, scientific research clearly indicated a strong relationship between rolling resistance, tire pressure and fuel consumption. Moreover, low and high values of tire pressure can create the deformation of the tire. In this paper, the influence of tire pressure on fuel consumption was investigated. Model regression was used in data analysis of other parameters which can affect fuel consumption. Analysis of the results obtained for other vehicles confirms that the adopted linear regression model was correct. It can, therefore, be noted that:

- the influence of tire pressure on fuel consumption was observed,
- dependence of fuel consumption on tire pressure was inversely proportional; with the increase of tire pressure in the tested range (0.7-1.1 MPa), fuel consumption decreased.

It can, therefore, be asserted that maintaining tire pressures at appropriate values has an impact on lower fuel consumption.

It should be noted that in all examined vehicles, inversely proportional dependence of fuel consumption on tire pressure was performed. Thus, already at this stage of the research, it is justified that with the increase of tire pressure, the value of average fuel consumption decreases. Values of R^2 correlation coefficients indicated in some cases a moderate relationship between the parameters examined, while in the majority of cases a strong correlation was observed.

In conclusion, the tire pressure [MPa] has the greatest impact on the reduction of fuel consumption. With the pressure increase by 0.1 MPa, fuel consumption decreases by an average of 5.15 l / 100 km. Presence of a tire pressure monitoring system can help in initiating a rapid response when values of tire pressure decrease.

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