

## Modeling the dynamics of changes in CO<sub>2</sub> emissions from Polish road transport in the context of COVID-19 and decarbonization requirements

### ARTICLE INFO

Received: 13 May 2023  
Revised: 8 July 2023  
Accepted: 17 July 2023  
Available online: 22 July 2023

*Emissions from transport account for 20–25% of anthropogenic global carbon dioxide emissions [17, 37], with more than 70% coming from road transport, making it an extremely important topic in the context of decarbonization. The aim of the article is to analyze the trend of CO<sub>2</sub> generated from road transport, taking into account various sources, and also to examine how reduced mobility during the pandemic affected the emissions at the time. For this purpose, a time series containing observations up to the pandemic outbreak and a time series containing additional observations from the pandemic period were analyzed. For each time series, a trend was determined and described by a polynomial and then verified to see if the pandemic phenomenon significantly affects a parameter of the proposed model, using appropriate statistical tests.*

**Key words:** transport decarbonization, CO<sub>2</sub> emissions, road transport, COVID-19 pandemic, polynomial model

This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>)

### 1. Introduction

Global warming, the main cause of which is the growing emission of carbon dioxide, causes drastic consequences for many ecosystems, bringing about irreversible changes in them [27, 36, 38]. The use of petroleum fuels in transport determines its significant share in greenhouse gas emissions, which is why this sector faces the greatest demands [5, 12, 23]. Meanwhile, the progressing globalization, population growth, increasing demand for goods, as well as the dynamic development of the tourism industry and the number of people travelling do not make this task easier, especially since it is estimated that by the 2050, the EU economy will more than double [10].

Emissions from transport account for 20–25% of anthropogenic global carbon dioxide emissions [17, 37], of which 71.7% are from road transport, but taking into account the production of cars and the construction of road infrastructure, this number increases to 37% of all emissions [7, 14, 16, 24]. Transport uses 30% of the world's energy. Although only 7% of the population owns cars, this translates into 40% of the world's petrol production.

Cars are considered the most polluting means of transport and at the same time the most unsafe [3, 4, 18]. They are also the largest emitter of toxic chemical compounds not subject to legal regulation, such as butadiene, benzene and others [22, 25]. The area necessary to build a road (30 to 40 m on average) is much larger than the requirements for railway traction (10 to 14 m) [25]. What's more, 30% of car journeys in the European Union do not exceed 3 km, and 50% – 6 km [39], so they could be successfully replaced by environmentally friendly natural forms of transport, such as bicycles.

The share of Polish road transport in the total emissions of the European Union is significant. Poland has been occupying leading positions for years [9]. Moreover, due to the intensive increase in passenger and transport activity, CO<sub>2</sub> emissions are constantly growing, increasing in 2020 by almost 150% compared to 2000, while emissions throughout the EU remain relatively constant [2].

The transport sector is therefore a challenge on the way to achieving climate neutrality, related to the reduction of greenhouse gases emissions, which is the result of the European climate policy. Currently, the European Parliament requires a 40% reduction in greenhouse gas emissions by EU countries by the 2030, compared to the level of 2005 [29]. This is a recent change (March 2023). The previous target was 30%.

Therefore, the article analyses the current dynamics of changes in CO<sub>2</sub> emissions from road transport, including various types of transport means. Mathematical identification of the examined time series and determination of the forecast was aimed at relating the current level of CO<sub>2</sub> emissions to the requirements imposed by the EU in this regard.

In addition, the article features an analysis of the impact of the COVID-19 pandemic on CO<sub>2</sub> emissions. Global movement restrictions, limited travel options and remote work, as well as fear of contagion, have strongly influenced changes in people's preferences in their choice of transport and travel in general. More people staying indoors or using safer forms of transport like cycling or walking may have reduced these emissions, as confirmed by studies by a number of authors [11, 13, 20, 32, 42]. On the other hand, the fear of coming into contact with an infected person has fostered a switch from public to private transport [1,6], and a number of authors believe that the decrease in emissions was too short-lived to have a relative effect [31, 33]. Therefore, the article also features an attempt to answer the question of how the COVID-19 pandemic in Poland affected the trend in CO<sub>2</sub> emissions, taking into account different modes of transport.

For this purpose, time series of CO<sub>2</sub> emissions from transport, published by the European Environment Agency, expressed in Gg [8], were analyzed. Time series with observations up to the outbreak of the pandemic and time series with additional observations from the pandemic period were analyzed.

For each time series, a trend was determined and described by a polynomial and then verified to see if the pandemic phenomenon significantly affects a parameter of the

proposed model, using appropriate statistical tests. A detailed survey procedure is presented in Chapter 2. The lack of confirmation of the significance of the impact of the pandemic on the model coefficients means that the hazard did not significantly affect CO<sub>2</sub> emissions.

## 2. Materials and methods

### 2.1. Determining the trend in a time series

The trend in the time series  $\{x_{\tau_i}\}_{1 \leq i \leq n}$  is identified as a polynomial [15, 41]

$$x_{\tau_i} = \beta_0 + \beta_1 \tau_i + \dots + \beta_k \tau_i^k + \varepsilon_{\tau_i} \quad (1)$$

where  $\{\varepsilon_i\}_{1 \leq i \leq n}$  is a sequence of independent random variables with a normal distribution  $N(0, \sigma^2)$  and  $x_{\tau_i} \stackrel{\text{def}}{=} x_{\tau_i}$ . The trend occurring in the series is identified using a  $k$  degree polynomial. The dependence (1) between the endogenous variable and the predictors (transformations of the variable  $\tau$ ) is linear. At the beginning we define objects:

$$X = \begin{bmatrix} 1 & \tau_1 & \dots & \tau_1^k \\ 1 & \tau_2 & \dots & \tau_2^k \\ \vdots & \vdots & & \vdots \\ 1 & \tau_n & \dots & \tau_n^k \end{bmatrix}, \quad Y = \begin{bmatrix} x_{\tau_1} \\ x_{\tau_2} \\ \vdots \\ x_{\tau_n} \end{bmatrix},$$

$$\varepsilon = \begin{bmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \vdots \\ \varepsilon_n \end{bmatrix}, \quad \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{bmatrix}$$

therefore, the dependence (1) can be presented in linear form [21,24]:

$$Y = X\beta + \varepsilon \quad (2)$$

Using the Least Squares Method (LSM) [41] the values of the model parameters can be estimated using the formula

$$\hat{\beta} = (X^T X)^{-1} X^T Y \quad (3)$$

The vector of residuals  $\varepsilon \in \mathbb{R}^n$  can be presented as  $\varepsilon = Y - X\hat{\beta}$ . Coefficient of determination [41] is determined as follows

$$R^2 = 1 - \frac{\sum_{j=1}^n \varepsilon_j^2}{\sum_{j=1}^n (x_{\tau_j} - \bar{x})^2}, \quad (4)$$

where  $\bar{x} = \frac{1}{n} \sum_{j=1}^n x_{\tau_j}$  and the estimator of the variance of the residuals is equal

$$\hat{\sigma}^2 = \frac{1}{n - k - 1} \sum_{j=1}^n \varepsilon_j^2$$

Values of variance of structural parameters [41] are determined as follows

$$S^2 = (S_0^2, S_1^2, \dots, S_k^2) = \text{diag}(\hat{\sigma}^2 (X^T X)^{-1}).$$

Thus, each of the structural parameters  $\beta_j$  has a normal distribution  $N(\hat{\beta}_j, S_j^2)$  for  $0 \leq j \leq k$ . For each parameter  $\beta_j$  the significance of the influence of component  $\tau_i^j$  on the realizations of the series according to model (1) is tested. At the significance level  $0 < \alpha < 1$  for each structural parameter  $\beta_j$  we create a null hypothesis

$$H_0: \beta_j = 0$$

against an alternative hypothesis

$$H_0: \beta_j \neq 0.$$

The test statistic

$$t = \frac{\hat{\beta}_j}{\sqrt{S_j^2}} \quad (5)$$

has  $t$  – distribution with  $n - k - 1$  degrees of freedom [15,34,40]. The test probability is equal:

$$p. \text{val}_j = 2(1 - \Psi(|t|))$$

where  $\Psi(\cdot)$  is  $t$  – distribution function with  $n - k - 1$  degrees of freedom. If  $p. \text{val}_j < \alpha$  then for the parameter  $\beta_j$  the null hypothesis  $H_0$  is rejected in favor of the alternative hypothesis  $H_1$ . Therefore, the component  $\tau_i^j$  significantly affects the realization of the time series defined by formula (1).

The key in the analyzed mathematical equation is the choice of the degree of the polynomial. To select the appropriate polynomial, the Ramsey RESET test (linearity test) [21, 28] was used in the research. The degree of the polynomial is chosen as the lowest natural number for which the coefficient of determination is at a sufficiently high level and there are no grounds to reject the null hypothesis for the linearity test.

### 2.2. Study of the impact of COVID-19 on CO<sub>2</sub> emissions

First, a time series of CO<sub>2</sub> emissions is considered for pre-pandemic data, i.e., data covering the years up to and including 2019. Thus, for the series  $\{x_{\tau_i}\}_{1 \leq i \leq n-1}$  the model (1) is identified and, taking into account the linearity test of the models, the degree of the polynomial  $k \in \mathbb{N}$  is determined. Using LSM the structural parameters of the model and the variances of these structural parameters are determined, therefore  $\beta_i^{2019} \sim N(\hat{\beta}_i^{2019}, S_i^{2019})$  for  $0 \leq i \leq k$ .

Next, the time series of CO<sub>2</sub> emissions for data that includes the COVID-19 pandemic are analyzed, i.e., for data including the year 2020. Thus, for the series  $\{x_{\tau_i}\}_{1 \leq i \leq n}$  the model (1) for the degree of the polynomial  $k \in \mathbb{N}$  is identified. Using LSM the structural parameters of the model and the variances of these structural parameters are determined, therefore  $\beta_i^{2020} \sim N(\hat{\beta}_i^{2020}, S_i^{2020})$  for  $0 \leq i \leq k$ .

In the next step, for each  $j$  indices,  $0 \leq j \leq k$  at significance level  $\alpha = 0.05$  the null hypothesis is created:

$$H_0: \beta_j^{2019} = \beta_j^{2020} \text{ (no impact of pandemic on parameter } \beta_j)$$

against an alternative hypothesis:

$$H_1: \beta_j^{2019} \neq \beta_j^{2020} \text{ (significant impact of pandemic on parameter } \beta_j)$$

The test statistic

$$T = \frac{\hat{\beta}_j^{2019} - \hat{\beta}_j^{2020}}{\sqrt{\frac{S_j^{2019}}{n-k-2} + \frac{S_j^{2020}}{n-k-1}}} \quad (6)$$

has a normal distribution  $N(0,1)$  [15, 41]. The test probability is equal:

$$p. \text{val}_j = 2(1 - \Phi(|T|))$$

where  $\Phi(\cdot)$  denotes the standard normal distribution  $N(0,1)$ . If  $p. val_j < \alpha$  then the null hypothesis  $H_0$  is rejected in favor of  $H_1$ .

If there is such  $j$  index,  $1 \leq k$  for which  $p. val_j < \alpha$ , it is considered that the estimator of  $\beta_j$  parameter determined from observations up to the pandemic and observations with the onset of the pandemic are significantly different, and therefore the pandemic had a significant impact on the trend of CO<sub>2</sub> emissions. If for each  $j$  indices,  $1 \leq k$  the condition  $p. val_j \geq \alpha$  is satisfied, then for each structural parameter, the estimators obtained from observations up to the pandemic and observations with the start of the pandemic are not significantly different from each other, therefore the pandemic did not have a significant impact on CO<sub>2</sub> emissions.

### 3. Evaluation of the trend of CO<sub>2</sub> emissions in road transport

#### 3.1. Road transport

First, CO<sub>2</sub> emissions from road transport as a whole were evaluated without breaking them down by mode of transport. Figure 1 presents the time series under study (black curve).

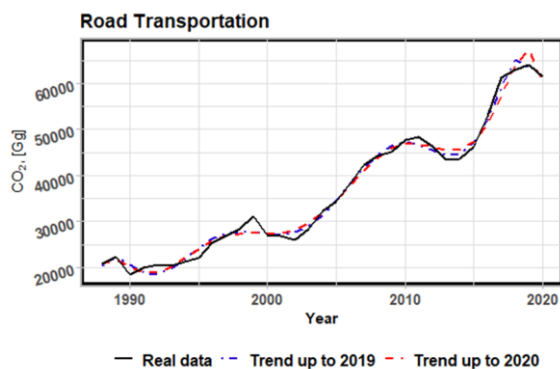


Fig. 1. CO<sub>2</sub> Emission for Road Transportation [8]

Then, for the time series presented, a model built only for the pre-pandemic period was proposed (blue line in Fig. 1). The estimators of structural parameters, standard deviations, t-statistic values and p-values are presented in Table 1.

Table 1. Structural parameters, standard errors, values of t-statistic and p-values for the trend to the pre-pandemic period

	Estimate	Std. error	t value	p-value
$\beta_0$	7115.71935	5166.94560	1.37716	0.18172
$\beta_1$	22985.07637	6162.91969	3.72958	0.00110
$\beta_2$	-12041.9597	2495.18762	-4.82607	0.00007
$\beta_3$	2769.26980	479.62213	5.77386	0.00001
$\beta_4$	-327.12113	50.15569	-6.52211	< 1e-5
$\beta_5$	21.43286	3.01362	7.11200	< 1e-5
$\beta_6$	-0.78550	0.10381	-7.56667	< 1e-5
$\beta_7$	0.01505	0.00190	7.90711	< 1e-5
$\beta_8$	-0.00012	0.00001	-8.15249	< 1e-5

The coefficient of determination is equal to 0.9907, and the standard deviation of the residuals is equal to 1524.28. At the significance level  $\alpha = 0.05$ , the  $H_0$  hypothesis was rejected in favor of  $H_1$  for the structural parameters of

$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$ , therefore the predictors of these parameters significantly affect the polynomial trend in the time series. The value of the statistic for the Ramsey RESET test is 1.6778, while the p-value is 0.2496.

In the next step, a model was built for data covering the period of the pandemic (red line in Fig. 1). Table 2 presents the estimators of structural parameters, standard deviations, values of t-statistics and p-values for the entire period.

Table 2. Structural parameters, standard errors, values of t-statistic and p-value for the trend to the entire period

	Estimate	Std. error	t value	p-value
$\beta_0$	12173.08505	5969.19873	2.03932	0.05258
$\beta_1$	15486.44602	6946.95856	2.22924	0.03542
$\beta_2$	-8500.03179	2739.16084	-3.10315	0.00485
$\beta_3$	2003.84146	512.08133	3.91313	0.00066
$\beta_4$	-239.32353	52.03960	-4.59887	0.00012
$\beta_5$	15.74571	3.03706	5.18452	0.00003
$\beta_6$	-0.57695	0.10158	-5.67979	0.00001
$\beta_7$	0.01102	0.00181	6.09446	< 1e-5
$\beta_8$	-0.00009	0.00001	-6.43854	< 1e-5

The coefficient of determination is equally high at 0.9873. The standard deviation of the residuals is equal to 1836.77. At the significance level  $\alpha = 0.05$ , the hypothesis  $H_0$  was rejected in favor of  $H_1$  for the parameters  $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$ . Thus, predictors at these parameters significantly affect the polynomial trend in the time series.

For the polynomials constructed above, their parameters were compared. Table 3 presents the calculated values of statistics (6) and p-values for the test of differences of structural parameters.

Table 3. T-statistic values and p-value for the tests of differences in structural parameters

	T	p-value
$\beta_0$	-3.10942	0.00187
$\beta_1$	3.91841	0.00009
$\beta_2$	-4.63753	< 1e-5
$\beta_3$	5.29107	< 1e-5
$\beta_4$	-5.88978	< 1e-5
$\beta_5$	6.44278	< 1e-5
$\beta_6$	-6.95724	< 1e-5
$\beta_7$	7.43869	< 1e-5
$\beta_8$	-7.89137	< 1e-5

At the significance level  $\alpha = 0.05$ , the  $H_0$  hypothesis was rejected in favor of  $H_1$  for all structural parameters. Thus, the parameters are significantly different for the polynomial trend determined for the CO<sub>2</sub> emission series up to the time of the pandemic outbreak and the polynomial trend determined for the CO<sub>2</sub> emission series containing the first year of the pandemic. Thus, the COVID-19 pandemic significantly affected the CO<sub>2</sub> emissions trend analyzed for road transport in Poland, as a whole.

In the next stage of the study, an analogous analysis was made, however, taking into account the different modes of transport. Passenger cars, light duty trucks, heavy duty trucks and motorcycles were studied.

### 3.2. Passenger cars

Passenger cars make up the majority of the vehicle market in Poland (more than 60% of the market). The latest available data shows that at the end of 2022, 26.675 million passenger cars were registered in the database of the Central Register of Vehicles and Drivers (CEPiK), 577,000 more than a year earlier [35]. In Fig. 2 CO<sub>2</sub> emissions (black line) are also on an upward trend.

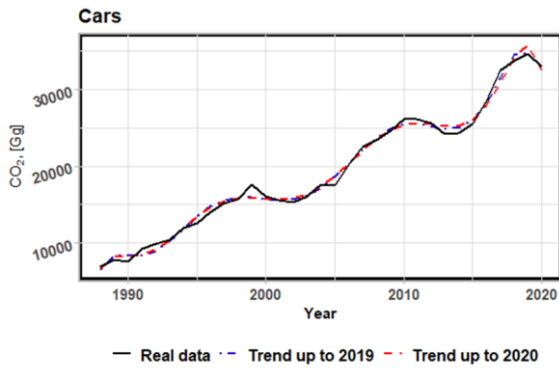


Fig. 2. CO<sub>2</sub> emissions for cars [8]

According to the adopted algorithm, the model was first built for the pre-pandemic period only (blue line in Fig. 2). Its structural parameters, standard deviations, t-statistic values and p-values are presented in Table 4.

Table 4. Structural parameters, standard errors, values of t-statistic and p-value for the trend to the pre-pandemic period

	Estimate	Std. error	t value	p-value
$\beta_0$	-902.69310	2570.25660	-0.35121	0.72863
$\beta_1$	12031.29715	3065.69611	3.92449	0.00068
$\beta_2$	-5793.93596	1241.21153	-4.66797	0.00011
$\beta_3$	1326.84643	238.58427	5.56133	0.00001
$\beta_4$	-156.72823	24.94956	-6.28180	< 1e-5
$\beta_5$	10.23508	1.49910	6.82748	< 1e-5
$\beta_6$	-0.37295	0.05164	-7.22225	< 1e-5
$\beta_7$	0.00710	0.00095	7.49445	< 1e-5
$\beta_8$	-0.00005	0.00001	-7.66937	< 1e-5

The coefficient of determination equals 0.993, and the standard deviation of the residuals equals 758.24. At the significance level  $\alpha = 0.05$ , the  $H_0$  hypothesis was rejected in favor of  $H_1$  for the structural parameters of  $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$ , therefore the predictors of these parameters significantly affect the polynomial trend in the time series. The value of the statistic for the Ramsey RESET test is 0.9118, while the p-value is 0.5895.

Consistently, in a further step, a model was built for data covering the time of the pandemic (red line in Fig. 2). Table 5 presents structural parameters, standard deviations of parameters, values of t-statistics and p-values for the entire period.

The coefficient of determination is equal to 0.9921, and the standard deviation of the residuals is 825.34. At the significance level  $\alpha = 0.05$ , the  $H_0$  hypothesis was rejected in favor of  $H_1$  for the  $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$  parameters. Thus, also in this case, the predictors at these parameters significantly affect the polynomial trend in the time series.

Table 5. Structural parameters, standard errors, values of t-statistic and p-value for the trend to the entire period

	Estimate	Std. Error	t value	p-value
$\beta_0$	801.28414	2682.23759	0.29874	0.76771
$\beta_1$	9504.78508	3121.59039	3.04485	0.00558
$\beta_2$	-4600.55486	1230.83189	-3.73776	0.00102
$\beta_3$	1068.95081	230.10187	4.64555	0.00010
$\beta_4$	-127.14660	23.38380	-5.43738	0.00001
$\beta_5$	8.31891	1.36469	6.09581	< 1e-5
$\beta_6$	-0.30269	0.04564	-6.63143	< 1e-5
$\beta_7$	0.00574	0.00081	7.06237	< 1e-5
$\beta_8$	-0.00004	0.00001	-7.40639	< 1e-5

For polynomials constructed for CO<sub>2</sub> emitted from passenger vehicles, their parameters were similarly compared. Table 6 presents the estimated values of statistics (6) and p-values for the test of differences of structural parameters.

Table 6. T-statistic values and p-value for the tests of differences of structural parameters

	T	p-value
$\beta_0$	-2.22406	0.02614
$\beta_1$	2.79922	0.00512
$\beta_2$	-3.30850	0.00094
$\beta_3$	3.76942	0.00016
$\beta_4$	-4.18986	0.00003
$\beta_5$	4.57649	< 1e-5
$\beta_6$	-4.93458	< 1e-5
$\beta_7$	5.26820	< 1e-5
$\beta_8$	-5.58048	< 1e-5

At the significance level  $\alpha = 0.05$ , the  $H_0$  hypothesis was rejected in favor of  $H_1$  for all structural parameters. The parameters are significantly different for the polynomial trend determined for the CO<sub>2</sub> emission series up to the pandemic and the polynomial trend determined for the CO<sub>2</sub> emission series containing the first year of the pandemic. Thus, in the case of passenger cars, the COVID-19 pandemic has significantly affected the trend in CO<sub>2</sub> emissions.

### 3.3. Light and heavy duty trucks

Trucks, which are the second largest group of vehicles registered in Poland [19, 26, 35] were then examined. As of the end of 2021, the number of registered trucks (including goods and passenger carrying vehicles) will reach 3.6 million [30], 3.0% more than a year ago. CO<sub>2</sub> emissions from light duty trucks (black line in Fig. 3) and heavy duty trucks (black line in Fig. 4) were analyzed.

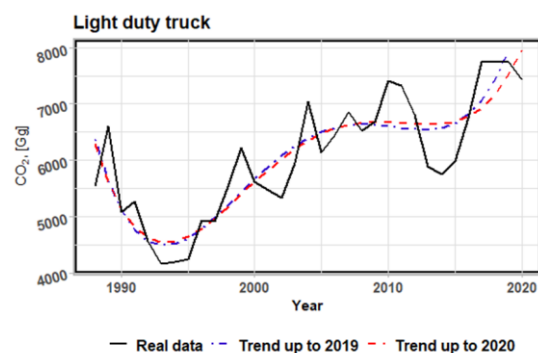


Fig. 3. CO<sub>2</sub> emissions for light duty truck [8]

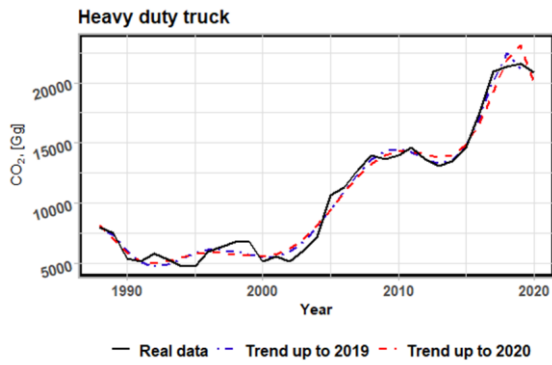


Fig. 4. CO<sub>2</sub> emissions for heavy duty trucks [8]

The models built for the pre-pandemic period (blue line in Fig. 3 and 4), their structural parameters, standard deviations of the parameters, values of the t-statistic and p-values are presented in Table 7.

Table 7. Structural parameters, standard errors, values of t-statistic and p-value for the trend to the pre-pandemic period

	Estimate	Std. error	t value	p-value
Light duty truck				
$\beta_0$	7347.38426	585.58715	12.54704	< 1e-5
$\beta_1$	-1103.45576	237.77329	-4.64079	0.00008
$\beta_2$	136.30530	28.67462	4.75352	0.00006
$\beta_3$	-5.78733	1.29616	-4.46498	0.00013
$\beta_4$	0.08198	0.01950	4.20497	0.00026
Heavy duty truck				
$\beta_0$	5669.98087	2480.91621	2.28544	0.03183
$\beta_1$	4898.82097	2959.13457	1.65549	0.11141
$\beta_2$	-3354.68039	1198.06785	-2.80008	0.01017
$\beta_3$	850.59185	230.29124	3.69355	0.00120
$\beta_4$	-106.96717	24.08233	-4.44173	0.00019
$\beta_5$	7.34736	1.44699	5.07767	0.00004
$\beta_6$	-0.27943	0.04984	-5.60608	0.00001
$\beta_7$	0.00552	0.00091	6.03490	< 1e-5
$\beta_8$	-0.00004	0.00001	-6.37530	< 1e-5

For CO<sub>2</sub> emissions from light duty trucks, the coefficient of determination is equal to 0.7679 and the standard deviation of the residuals is 542.63. At the significance level  $\alpha = 0.05$ , it was found that the structural parameters  $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$  are significantly different from zero (Table 7), thus, the predictors of these parameters significantly affect the polynomial trend in the time series. The value of the statistic for the Ramsey RESET test is 2.1032, while the p-value is 0.0877.

At the significance level  $\alpha = 0.05$  for heavy duty trucks, it was found that parameters  $\beta_0, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$  are significantly different from zero (Tab. 7), thus predictors at these parameters significantly affect the trend of CO<sub>2</sub> emissions. The value of the statistic for the Ramsey test is 1.4937, while the p-value is 0.305. The coefficient of determination is higher and equal to 0.9856. The standard deviation of the residuals, meanwhile, is 731.88.

The models built for the entire study period (red line in Fig. 3 and 4), their structural parameters, standard deviations, t-statistic values and p-values are presented in Table 8.

Table 8. Structural parameters, standard errors, values of t-statistic and p-value for the trend for the entire period

	Estimate	Std. error	t value	p-value
Light duty truck				
$\beta_0$	7166.73855	585.40978	12.24226	< 1e-5
$\beta_1$	-993.26539	230.94782	-4.30082	0.00019
$\beta_2$	119.85381	27.04951	4.43091	0.00013
$\beta_3$	-4.92894	1.18699	-4.15246	0.00028
$\beta_4$	0.06762	0.01733	3.90227	0.00055
Heavy duty truck				
$\beta_0$	8345.93187	2968.73528	2.81128	0.00967
$\beta_1$	931.14915	3455.01664	0.26951	0.78984
$\beta_2$	-1480.57710	1362.30067	-1.08682	0.28791
$\beta_3$	445.58876	254.67973	1.74960	0.09296
$\beta_4$	-60.51175	25.88150	-2.33803	0.02805
$\beta_5$	4.33818	1.51046	2.87209	0.00839
$\beta_6$	-0.16909	0.05052	-3.34697	0.00269
$\beta_7$	0.00338	0.00090	3.76141	0.00096
$\beta_8$	-0.00003	0.00001	-4.11824	0.00039

For CO<sub>2</sub> emissions from light duty trucks, the coefficient of determination for the entire study period is 0.7621 and the standard deviation of the residuals is 554.42. At the significance level  $\alpha = 0.05$ , thus all parameters of the model are significantly different from zero. For the trend model of CO<sub>2</sub> emissions generated by heavy duty trucks, the coefficient of determination is 0.9792, and the standard deviation of the residuals is 913.5. At the significance level  $\alpha = 0.05$ , it was found that the structural parameters  $\beta_0, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$  significant are different from zero, thus the predictors at these parameters significantly affect the trend occurring in the time series.

Comparing the two models with each other for each of the modes of transport analyzed, it can be seen again that the COVID-19 pandemic also affected the trend of CO<sub>2</sub> emissions from trucks. Table 9 presents the values of statistic (6) and p-values for the test of differences in the structural parameters. For light duty trucks at the significance level  $\alpha = 0.05$ , the  $H_0$  hypothesis was rejected in favor of  $H_1$  for the structural parameters  $\beta_2, \beta_3, \beta_4$ , while for heavy duty trucks the parameters  $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8$  are significantly different for the polynomial trend determined for the CO<sub>2</sub> emission series up to the pandemic and the polynomial trend determined for the CO<sub>2</sub> emission series containing the first year of the pandemic.

Table 9. T-statistic values and p-value for the tests of differences of structural parameters

	T	p-value		T	p-value
Light duty truck			Heavy duty truck		
$\beta_0$	1.14388	0.25267	$\beta_0$	-3.35853	0.00078
$\beta_1$	-1.74252	0.08142	$\beta_1$	4.23413	0.00002
$\beta_2$	2.18704	0.02874	$\beta_2$	-5.01350	< 1e-5
$\beta_3$	-2.55875	0.01051	$\beta_3$	5.72280	< 1e-5
$\beta_4$	2.88339	0.00393	$\beta_4$	-6.37357	< 1e-5
			$\beta_5$	6.97556	< 1e-5
			$\beta_6$	-7.53647	< 1e-5
			$\beta_7$	8.06220	< 1e-5
			$\beta_8$	-8.55730	< 1e-5

### 3.4. Motorcycles

The analyses conducted ended with a study of motorcycles. Despite their growing popularity — 23,910 new motor-

cycles were registered in 2022, 10.8% more than in the previous year [30, 35]. It is clear that CO<sub>2</sub> emissions have been on a downward trend over the years (black line Fig. 5).

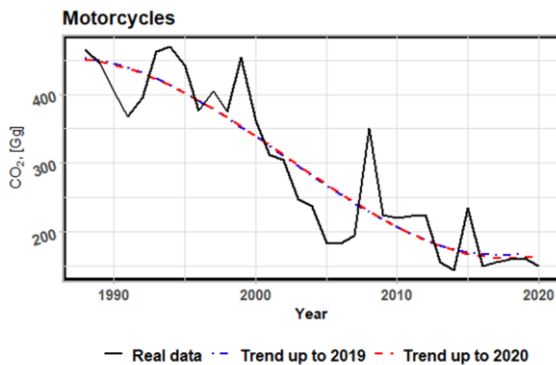


Fig. 5. CO<sub>2</sub> Emission for Motorcycles [8]

The estimators of parameters of the model constructed for the pre-pandemic period (blue line in Fig. 5), standard deviations of parameters, t-statistics and p-values are presented in Table 10.

Table 10. Structural parameters, standard errors, values of t-statistic and p-value for the trend to the pre-pandemic period

	Estimate	Std. error	t value	p-value
$\beta_0$	452.59779	17.62924	25.67313	< 1e-5
$\beta_2$	-0.94515	0.16588	-5.69780	< 1e-5
$\beta_3$	0.02087	0.00535	3.90082	0.00052

The coefficient of determination is 0.8293 and the standard deviation of the residuals is 48.66. At the significance level  $\alpha = 0.05$ , the  $H_0$  hypothesis was rejected in favor of  $H_1$  for the structural parameters  $\beta_0, \beta_2, \beta_3$ , thus the predictors of these parameters significantly affect the polynomial trend in the time series. The value of the statistic for the Ramsey RESET test is 1.3867, while the p-value is 0.2638.

The estimator of model parameters for the entire study period (red line in Fig. 5), standard deviations of parameters, t-statistics and p-values are presented in Table 11.

Table 11. Structural parameters, standard errors, values of t-statistic and p-value for the trend to the entire period

	Estimate	Std. error	t value	p-value
$\beta_0$	451.31832	17.10369	26.38718	< 1e-5
$\beta_2$	-0.91973	0.15152	-6.07003	< 1e-5
$\beta_3$	0.01992	0.00474	4.20027	0.00022

The coefficient of determination is 0.8368, and the standard deviation of the residuals is 47.97. At the significance level  $\alpha = 0.05$ , the  $H_0$  hypothesis was rejected in favor of  $H_1$  for the structural parameters  $\beta_0, \beta_2, \beta_3$ , thus the predictors at these parameters significantly affect the polynomial trend in the time series.

Comparing the parameters of the models for each period this time led to different conclusions. At the significance level  $\alpha = 0.05$ , there is no basis to reject the  $H_0$  hypothesis for all structural parameters. Thus, the parameters are not significantly different for the polynomial trend determined

for the CO<sub>2</sub> emission series up to the pandemic and the polynomial trend determined for the CO<sub>2</sub> emission series containing the first year of the pandemic. The trend parameters of the period up to the pandemic and the period with the onset of the pandemic are not significantly different, thus there was no significant effect on the trend. Table 12 presents the values of statistic (6) and p-values for the structural parameter difference test.

Table 12. T-statistic values and p-value for the tests of differences of structural parameters

	T	p-value
$\beta_0$	0.28281	0.77732
$\beta_2$	-0.61391	0.53927
$\beta_3$	0.72418	0.46895

This result of the study of CO<sub>2</sub> emissions from motorcycles is probably due to the fact that traveling on a motorcycle was not associated with an increased risk of danger, as all single-track vehicles were a safe means of transport from the point of view of virus infection. This is why the result is so different from other modes of transport.

#### 4. Conclusion

The primary objective of the study was to assess whether the COVID-19 pandemic significantly affected CO<sub>2</sub> emissions from road transport. A general analysis was made first, without distinguishing between different modes of transport, and then passenger cars, light and heavy-duty trucks and motorcycles were examined. It turned out that only in the case of motorcycles was the impact of the pandemic not significant. Thus, global mobility restrictions and probably the fear of becoming infected have influenced public behavior. Despite the woeful pandemic period, meaningful conclusions can also be drawn. The study shows that changes are possible regarding CO<sub>2</sub> emissions from transport, but they require comprehensive, systemic solutions.

The obtained results clearly prove that it is possible to implement mechanisms for controlling society on a global scale and to achieve the desired results in terms of harmful emissions. The solutions implemented in this area require the use of appropriate analysis methods that will allow for a reliable assessment of whether the implemented changes bring the expected results and whether the obtained effect is statistically significant. The method proposed in the article can be successfully used for such analyses. The algorithm proposed in the methodological chapter is universal and can also be applied to factors other than the COVID-19 pandemic. This is an additional advantage of the article.

In early 2023, the European Parliament approved new targets to reduce CO<sub>2</sub> emissions produced by new passenger and goods carrying vehicles by 100 percent by 2035 compared to 2021. With regard to the results presented, these assumptions seem difficult to implement. Over the entire period studied, for every mode of transport except motorcycles, the research presented shows an upward trend. Only the COVID-19 pandemic caused small declines but only for passenger cars and heavy duty trucks. Thus, changes in this area are necessary. Given the short time left for Poland and the European Union as a whole to achieve climate neutrali-

ty, it is necessary to introduce the principles of sustainable development and take a holistic view of the environmental impact of individual modes of transport.

In the article, the study was conducted at a general level, observing global trends and considering whether they are possible to change. This provides the basis for more detailed analyzes and the search for relationships between specific solutions and CO<sub>2</sub> emissions.

In addition, due to the fact that the publication of emissions data is delayed, so the authors have not had the opportunity to make a study based on complete historical data, it is necessary to continue research and analyze trends. However, this will be the direction of further research planned in this area.

## Bibliography

- [1] Advani M, Sharma N, Dhyani R. Mobility change in Delhi due to COVID and its' immediate and long term impact on demand with intervened non motorized transport friendly infrastructural policies. *Transport Policy*. 2021;111:28-37. <https://doi.org/10.1016/j.tranpol.2021.07.008>
- [2] Antosiewicz M, Gorzałczyński A, Rabiega W. The role of public transport in Poland in the pursuit of climate neutrality (in Polish). 2023. <https://managerplus.pl/rola-transportu-publicznego-w-polsce-w-dazeniu-do-neutralnosci-klimatycznej-54351> (accessed on 30.04.2023).
- [3] Borucka A, Kozłowski E, Oleszczuk P, Świdorski A. Predictive analysis of the impact of the time of day on road accidents in Poland. *Open Engineering*. 2021;11(1):142-150. <https://doi.org/10.1515/eng-2021-0017>
- [4] Borucka A, Pyza D. Influence of meteorological conditions on road accidents. A model indexed by: for observations with excess zeros. *Eksplot Niezawodn*. 2021;23(3):586-592. <https://doi.org/10.17531/ein.2021.3.20>
- [5] de Blas I, Mediavilla M, Capellán-Pérez I, Duce C. The limits of transport decarbonization under the current growth paradigm. *Energy Stratag Rev*. 2020;32:100543. <https://doi.org/10.1016/j.esr.2020.100543>
- [6] Eisenmann C, Nobis C, Kolarova V, Lenz B, Winkler C. Transport mode use during the COVID-19 lockdown period in Germany: The car became more important, public transport lost ground. *Transp Policy*. 2021;103:60-67. <https://doi.org/10.1016/j.tranpol.2021.01.012>
- [7] European Environment Agency, Air quality in Europe 2022. <https://www.eea.europa.eu/publications/air-quality-in-europe-2022>
- [8] European Environment Agency. National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism. <https://www.eea.europa.eu/en/datahub/datahubitem-view/3b7fe76c-524a-439a-bfd2-a6e4046302a2>
- [9] Global Carbon Atlas. CO<sub>2</sub> Emissions |Global Carbon Atlas. [Globalcarbonatlas.org](http://www.globalcarbonatlas.org/en/CO2-emissions). 2020. <http://www.globalcarbonatlas.org/en/CO2-emissions>
- [10] Going climate-neutral by 2050. A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy. *2050 long-term strategy (europa.eu)*
- [11] Gössling S, Humpe A, Fichert F, Creutzig F. COVID-19 and pathways to low-carbon air transport until 2050. *Environ Res Lett*. 2021;16(3):034063. <https://doi.org/10.1088/1748-9326/abe90b>
- [12] Graba M, Bieniek A, Praznowski K, Hennek K, Mamala J, Burdzik R et al. Analysis of energy efficiency and dynamics during car acceleration. *Eksplot Niezawodn*. 2023;25(1):17. <https://doi.org/10.17531/ein.2023.1.17>
- [13] Griffiths S, Furszyfer Del Rio D, Sovacool B. Policy mixes to achieve sustainable mobility after the COVID-19 crisis. *Renew Sust Energ Rev*. 2021;143:110919. <https://doi.org/10.1016/j.rser.2021.110919>
- [14] Groll W, Sowiński B, Konowrocki R. Study of transitional phenomena in rail vehicle dynamics in relation to the reliability and operational state of the continuous welded rail track in terms of rail joints. *Eksplot Niezawodn*. 2023;25(1):7. <https://doi.org/10.17531/ein.2023.1.7>
- [15] Hamilton JD. Time series analysis, Princeton University Press. 1994. <https://doi.org/10.1515/9780691218632>
- [16] IEA. Net Zero by 2050 – Analysis. IEA. 2021. <https://www.iea.org/reports/net-zero-by-2050>
- [17] International Energy Agency. CO<sub>2</sub> Emissions in 2022. <https://iea.blob.core.windows.net/assets/3c8fa115-35c4-4474-b237-1b00424c8844/CO2Emissionsin2022.pdf>
- [18] Kozłowski E, Borucka A, Świdorski A, Skoczyński P. Classification trees in the assessment of the road–railway accidents mortality. *Energies*. 2021;14(12):3462. <https://doi.org/10.3390/en14123462>
- [19] Kukulski J, Lewczuk K, Góra I, Wasiak M. Methodological aspects of risk mapping in multimode transport systems. *Eksplot Niezawodn*. 2023;25(1):19. <https://doi.org/10.17531/ein.2023.1.19>
- [20] Le Quéré C, Jackson RB, Jones MW, Smith AJP, Abernethy S, Andrew RM et al. Temporary reduction in daily global CO<sub>2</sub> emissions during the COVID-19 forced confinement. *Nat Clim Change*. 2020;10(10):1-7. <https://www.nature.com/articles/s41558-020-0797-x>
- [21] Lee TH, White H, Granger CWJ. Testing for neglected nonlinearity in time series models. *J Econometrics*. 1993;56(3):269-290. [https://doi.org/10.1016/0304-4076\(93\)90122-L](https://doi.org/10.1016/0304-4076(93)90122-L)
- [22] Li B, Wang J, Wang J, Zhang L, Zhang Q. A comprehensive study on emission of volatile organic compounds for light duty gasoline passenger vehicles in China: Illustration of impact factors and renewal emissions of major compounds. *Environ Res*. 2021;193:110461. <https://doi.org/10.1016/j.envres.2020.110461>
- [23] Mączak J, Więclawski K, Szczurowski K. New approach of model based detection of early stages of fuel injector failures. *Eksplot Niezawodn*. 2023;25(1):6. <https://doi.org/10.17531/ein.2023.1.6>
- [24] Melnik R, Koziak S, Dižo J, Kuźmierowski T, Piotrowska E. Feasibility study of a rail vehicle damper fault detection by artificial neural networks. *Eksplot Niezawodn*. 2023;25(1):5. <https://doi.org/10.17531/ein.2023.1.5>
- [25] National Cluster of Innovative Enterprises, Poland 3.0 – A response to modern transport needs (in Polish: Ogólnopolski Klaster Innowacyjnych Przedsiębiorstw, Polska 3.0 – Odpowiedź na współczesne potrzeby transportu). 2016. <http://klasterip.pl/polska-3-0-odpowiedz-na-wspolczesne-potrzeby-transportu-jedyny-spojny-projekt-infrastrukturalny-w-polsce/>
- [26] Oszczypała M, Ziółkowski J, Małachowski J. Semi-Markov approach for reliability modelling of light utility vehicles. *Eksplot Niezawodn*. 2023;1:25(2). <https://doi.org/10.17531/ein/161859>

- [27] Papalexioiu SM, Montanari A. Global and regional increase of precipitation extremes under global warming. *Water Resour Res.* 2019;55(6):4901-4914. <https://doi.org/10.1029/2018WR024067>
- [28] Ramsey JB. Tests for specification errors in classical linear least-squares regression analysis. *J Roy Stat Soc B Met.* 1969;31(2):350-371. <https://www.jstor.org/stable/2984219>
- [29] Regulation of the European Parliament and of the Council amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement. <https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX:52021PC0555>
- [30] Road transport in Poland in the years 2020 and 2021 (in Polish), Główny Urząd Statystyczny Warszawa, Szczecin 2023.
- [31] Rojas C, Muñoz I, Quintana M, Simon F, Castillo B, de la Fuente H et al. Short run “rebound effect” of COVID on the transport carbon footprint. *Cities.* 2022;131:104039. <https://www.sciencedirect.com/science/article/pii/S0264275122004784>.
- [32] Rojas-Rueda D, Morales-Zamora E. Built environment, transport, and COVID-19: a review. *Current Environmental Health Reports.* 2021;8(2):138-145. <https://doi.org/10.1007/s40572-021-00307-7>
- [33] Schulte-Fischedick M, Shan Y, Hubacek K. Implications of COVID-19 lockdowns on surface passenger mobility and related CO<sub>2</sub> emission changes in Europe. *Appl Energ.* 2021; 300:117396. <https://doi.org/10.1016/j.apenergy.2021.117396>
- [34] Shumway RH, Stoffer DS. Time series analysis and its applications, Springer International Publishing, 2017.
- [35] Statistics | Information Portal of the Central Register of Vehicles and Drivers (in Polish). [www.cepik.gov.pl/statystyki](http://www.cepik.gov.pl/statystyki)
- [36] Thompson JR, Gosling SN, Zaherpour J, Laizé CLR. Increasing risk of ecological change to major rivers of the world with global warming. *Earth's Future.* 2021;9(11):1-20. <https://doi.org/10.1029/2021EF002048>
- [37] United Nations. Fact Sheet Climate Change. [https://www.un.org/sites/un2.un.org/files/media\\_gstc/FACT\\_SHEET\\_Climate\\_Change.pdf](https://www.un.org/sites/un2.un.org/files/media_gstc/FACT_SHEET_Climate_Change.pdf)
- [38] Wang J, Guan Y, Wu L, Guan X, Cai W, Huang J et al. Changing lengths of the four seasons by global warming. *Geophys Res Lett.* 2021;22:48(6). <https://doi.org/10.1029/2020GL091753>
- [39] Weiss M, Paffumi E, Clairrott M, Drossinos Y, Vlachos T, Bonnel P et al. Including cold-start emissions in the Real-Driving Emissions (RDE) test procedure. Publications Office of the European Union. 2017. <https://publications.jrc.ec.europa.eu/repository/bitstream/JRC105595/kjna28472enn.pdf>
- [40] Woodward WA, Gray HL, Elliott AC. Applied time series analysis with R, CRC Press. 2017. <https://doi.org/10.1201/9781315161143>
- [41] Wooldridge JM. Introductory econometrics: a modern approach, South Western Educ Pub. 2019.
- [42] Zhang R, Zhang J. Long-term pathways to deep decarbonization of the transport sector in the post-COVID world. *Transp Policy.* 2021;110:28-36. <https://doi.org/10.1016/j.tranpol.2021.05.018>

Anna Borucka, DSc., DEng. – Faculty of Security, Logistics and Management, Military University of Technology, Poland.  
e-mail: [anna.borucka@wat.edu.pl](mailto:anna.borucka@wat.edu.pl)



Edward Kozłowski, DSc., DEng. – Faculty of Management, Lublin University of Technology, Poland.  
e-mail: [e.kozlovski@pollub.pl](mailto:e.kozlovski@pollub.pl)

