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# Analysis of the influence of selected powertrain design parameters on fuel consumption in passenger vehicles

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*In view of increasingly stringent environmental requirements and global efforts to reduce greenhouse gas emissions, it is becoming increasingly important to identify the design factors of powertrains that directly affect fuel efficiency and carbon dioxide ($CO_2$) emissions. This study analyses the impact of selected technical parameters of passenger vehicles powertrains – in particular, engine displacement, number of cylinders, type of transmission and type of fuel – on fuel consumption in urban, highway and combined conditions, as well as on $CO_2$ emissions. The study used operational data covering the design parameters of selected passenger vehicle models on the market. The statistical analysis identified significant relationships between the drive system's design and its environmental impact. The results of the study can make a significant contribution to the development of forecasting tools to support the design of new-generation engines, as well as to decision-making and to the formulation of strategies for the sustainable development of low-emission transport technologies.*

Key words: *fuel consumption, multivariate regression, $CO_2$ emission, powertrain parameters*

## 1. Introduction

Reducing harmful emissions into the environment is one of the main objectives of climate policy. The regulations introduced by the European Union aim to reduce greenhouse gas emissions from the transport sector. The above results in stricter emission standards for newly designed and manufactured vehicles. Therefore, conducting research in the field of vehicle operation, especially powertrain systems, is an important element in meeting European standards, such as Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021, as well as United Nations SDGs (especially goal 13).

The clear need to optimize transportation energy efficiency is undoubtedly one of the main goals not only of climate policy but also of manufacturers' actions, as it simultaneously improves economic indicators. Identifying design solutions that will significantly reduce fuel consumption and, consequently, emissions is therefore a priority. At the same time, the result can be guidelines and recommendations for practice use by both manufacturers and end users, leading to the development of modern technological solutions to minimize operating costs, increase the competitiveness of automotive companies, and advance innovative zero-emission propulsion technologies.

The above elements made the analysis of selected design parameters of passenger vehicle powertrains in terms of their impact on fuel consumption in different modes of vehicle driving the purpose of the article. As the main research problem, the question was adopted: to what extent do individual factors shape the energy efficiency of motor vehicle powertrains? For the purpose of the study, a detailed analysis of a database consisting of 7,384 observations was carried out, which included measurements of engine displacement, number of cylinders, number of gears in the transmission and its type, fuel type and fuel consumption values in the urban cycle, highway driving and mixed cycle. The article uses a multivariate regression model, which enables selection of design parameters that significantly affect fuel consumption levels, as well as quantification of the interdependence between them and emission factors. Consequently, this type of analysis is an important contribution to the pursuit of sustainable development in the automotive sector and the reduction of the negative environmental impact of transportation.

## 2. Literature review

The impact of individual engine and transmission design parameters on fuel consumption has been widely studied in the literature, particularly amid increasing demands for energy efficiency and $CO_2$ reduction in the transportation sector. A review has shown that both engine and transmission parameters have a key impact on fuel consumption [4]. Among the design factors of passenger vehicle internal combustion engines, engine displacement, compression ratio, turbocharging, and the weight of the engine and the entire vehicle are listed as those that significantly affect fuel consumption and vehicle emissions [26].

Engine displacement is one of its key parameters, which determines the total volume of all cylinders [1]. It directly affects the performance characteristics of the power unit [35], including mainly torque, power and fuel consumption. Available in the literature, studies indicate that as engine displacement increases, more fuel is consumed, mainly because a larger amount of fuel-air mixture can be burned. Research results indicate that engines with smaller displacement (1.0 to 1.6 L) have fuel consumption up to 15–20% lower than those with 2.0 to 3.0 L [8, 24].

Other parameters mentioned in the literature that affect fuel consumption are compression ratio and turbocharging [6]. Zhu et al. indicate that increasing the compression ratio improves the engine's thermal efficiency, thereby reducing specific fuel consumption by 5–8% [33]. Turbocharging, on the other hand, is a technology that increases the amount of air supplied to the cylinders using a turbocharger [11]. This solution enables reducing the engine's capacity while maintaining its power, a process known as downsizing [28]. This makes it possible to reduce fuel consumption from 5% in gasoline engines [19] to 12% in compression-ignition engines [13], thereby reducing $CO_2$ emissions by 7% to 15% [3]. In contrast, combining a turbocharger with a properly adjusted compression ratio can improve fuel economy by up to 20% [18].

The last-mentioned parameter related to engine characteristics is its weight. It is estimated that each 100 kg increase in vehicle weight results in a 0.3 to 0.6 liter increase in fuel consumption per 100 km [17]. For modern aluminum engines, which can reduce weight by 20–30 kg, fuel consumption decreases by 2–4% [34].

Other parameters that affect $CO_2$ emissions and fuel consumption are transmission parameters. A review of available research has shown that, in this area, the following should be specified [16]: the number of ratios (gears) and their span, the type of gearbox and its mechanical efficiency, as well as the driver's shifting strategy. Available research indicates that increasing the number of gear ratios results in a better match between engine speed and driving conditions, thereby allowing the engine to operate within its optimal range [30]. It is estimated that using a gearbox with 6 ratios (compared to a 4-speed) results in a fuel savings of about 3% (without affecting vehicle performance) [19]. The gear ratio value is also an important parameter. Lisowski points out that a higher ratio at the highest gear will lower engine rpm at constant speed, thus minimizing energy loss [15].

Studies also show that fuel consumption is affected by the type of transmission and its mechanical efficiency. Wang et al. indicate that manual transmissions have higher mechanical efficiency (up to 98%) than automatic transmissions (86% to 87%), which directly translates into lower fuel consumption [31]. Manual transmissions are also lighter than classic automatic transmissions. On the other hand, Al.-Saedi et al. note that modern solutions – such as direct-shift gearbox (DSG) transmissions, which are based on advanced electronics and precise shift control – can match or even surpass manual transmissions in terms of fuel economy, especially in urban conditions [19].

A variety of research methods are used in the literature to analyze the impact of specific vehicle design parameters on fuel consumption and $CO_2$ emissions [25]. These include experimental laboratory tests (dynamometers) [9] and real-world measurements during driving cycles [27]. Also popular are computer simulations, the use of artificial intelligence methods, including artificial neural networks, as well as mathematical modeling methods [12], including Markov processes [21] or multi-criteria algorithms [32].

In this study, the multivariate regression method was used to analyze the influence of selected design parameters of the vehicle's powertrain. Its application enabled answering the question of which recorded parameter values significantly affect fuel consumption and the extent of this influence. As part of the study, three models were built: for driving in an urban cycle, on the highway, and in a mixed cycle, which were further evaluated and compared.

## 3. Research method and results

### 3.1. Multivariate regression model

A multivariate regression model was used to analyze the impact of selected design parameters of passenger vehicle powertrains on fuel consumption and $CO_2$ emissions. This is a statistical method for modeling the relationship among multiple variables, enabling the testing of significance and the evaluation of the influence of selected factors on the phenomenon under study [10]. The multivariate regression model usually takes the form of an equation, which can be represented as the following relationship (1):

$$Y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_k x_k + \varepsilon, \qquad (1)$$

where: Y – dependent variable, $X_1, X_2, \ldots, X_k$ – independent variables, $b_i$ – parameters of the regression model (where i = 0….k), ε – random component.

The model parameters are estimated using least squares, which involves selecting the model coefficients to minimize the sum of squared residuals between the observed and predicted values [23].

Each time, the estimated model must be verified. The significance of the estimated parameters is evaluated to confirm their impact on the phenomenon under study, and the distribution of the model's residuals is analyzed to confirm that the model has been correctly built. The quality of the model, i.e., its fit to the empirical data, is determined by the coefficient of determination (R2).

A Student's t-test was used to test the significance of the model parameters, which tested the following hypotheses:

$H_{0:}\ \beta_i = 0$, no statistically significant effect of the explanatory variable $X_i$ on the variable Y,

$H_{1:}\ \beta_i \neq 0$. There is a statistically significant effect of the explanatory variable $X_i$ on the variable Y,

which were verified for the adopted significance level $\alpha = 0.05$.

Diagnosis of the model's residuals was carried out by testing the consistency of their distribution with the normal distribution using the chi-square test, for which the following hypotheses were formulated [14]:

$H_0: P(X = S_i) = p_i$ for $i = 1,2,\ldots,k$ – the studied characteristic X has a discrete distribution $(p_1, p_2, \ldots, p_k)$,

$H_1$: there is such a class j for which $P(X = S_i) \neq p_i$.

And autocorrelation, based on the Durbin-Watson test, based on the accepted hypotheses [14]:

$H_0: \rho = 0$ – the autocorrelation coefficient of the model residuals is statistically equal to zero,

$H_1: \rho \neq 0$ – the autocorrelation coefficient of the elements of the series is statistically different from zero.

The quality of the model fit was evaluated using the coefficient of determination $R^2$, which is estimated according to relation (2) [10]:

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad (2)$$

where: n – the number of observations, $y_i$ – empirical value of the variable Y, $\hat{y}_i$ – the theoretical value of the Y variable determined from the model, $\bar{y}$ – the arithmetic mean of the values of the Y variable.

This article analyzes the effects of selected design parameters of passenger vehicle powertrains on fuel consumption and $CO_2$ emissions. A database of 7,384 observations of selected parameters of passenger vehicle internal combustion engines was used for the study. The recorded data concerns passenger vehicles circulating in Canada, which were manufactured mainly in 2016 and 2017. Only passenger cars of different brands with similar total weight were analyzed. The values of the parameters of fuel consumption in the urban cycle, highway cycle and in the combined cycle were recorded, as well as engine displacement, type of transmission (automatic, manual), number of gears, type of fuel (diesel, premium gasoline, gasoline, ethanol 85%) and number of cylinders.

The study began with a detailed analysis of the selected explanatory variables, i.e. fuel consumption in urban mode, while driving on the highway and in combined mode (values measured both while moving in the city and on the highway). In the first step, basic values of descriptive statistics were calculated, including the mean and median (Table 1).

Table 1. Values of basic descriptive statistics

| Dependent variable | Mean | Median | Standard deviation | Skewness | Kurtosis |
|---|---|---|---|---|---|
| Fuel consumption in the urban cycle | 12.55 | 12.10 | 3.48 | 0.79 | 1.14 |
| Fuel consumption on highway | 9.03 | 8.70 | 2.21 | 1.07 | 2.00 |
| Fuel consumption in mixed cycle | 10.97 | 10.60 | 2.88 | 0.88 | 1.35 |

The results indicate that the highest mean of fuel consumption was recorded during urban driving, while the lowest was recorded during highway driving. Since the conformity of the tested distribution to the normal distribution was not confirmed (the obtained p-value in each group was 0.00), a nonparametric Friedman test (performed for the three groups simultaneously) was used to compare the significance of differences between mean values, followed by a Wilcoxon test performed individually between pairs. Figure 1 shows a box plot of the mean values in each group of observations.

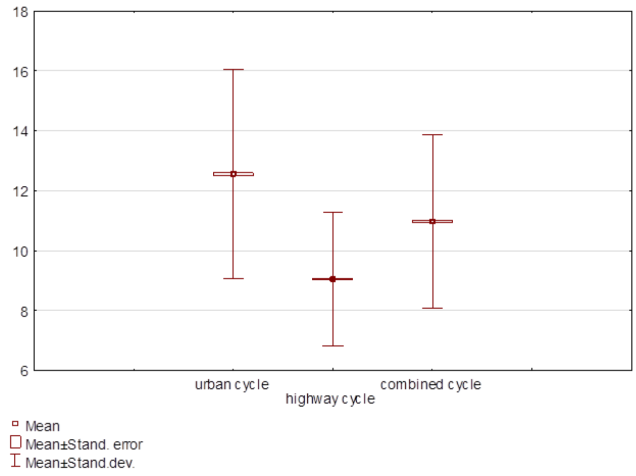

Fig. 1. Box plot of the mean values in each group of observation

Friedman's test tested the statistical hypotheses of equality of the sum of ranks for successive measurements:

$H_o: \theta_1 = \theta_2 = \ldots = \theta_k$,

$H_1$: not all $\theta_j$ are equal to each other for $(j = 1, 2 \ldots k)$.

where:

$\theta_1, \theta_2 \ldots \theta_k$ – medians of the studied feature in subsequent measurements in the studied population.

The Friedman T statistic calculated by the test was 13,847.04, with a corresponding p = 0.00, which allows us to conclude that there are statistically significant differences in the medians between the listed three groups. In the next step, the groups were compared individually in pairs using the Wilcoxon test (Table 2). The test tested the following hypotheses [2]:

$H_o: F_1 = F_2$ (there is no significant difference in the distributions of the variables),

$H_1: F_1 \neq F_2$.

Table 2. Wilcoxon test results

| | Highway cycle | | Mixed cycle | |
|---|---|---|---|---|
| | T | p | T | p |
| Urban cycle | 11,529.5 | 0.00 | 10,014.0 | 0.00 |
| Highway cycle | | | 10,171.5 | 0.00 |

The obtained test statistic and its p-value confirmed the presence of differences in fuel consumption across all groups. On this basis, in the next step, an analysis of the impact of selected design parameters of the vehicle's powertrain on fuel consumption within the selected groups was carried out.

### 3.2. Analysis of the effect of selected powertrain design parameters on fuel consumption in the urban cycle

In the first step, a multivariate regression model was built from observations recorded during the urban cycle. Due to the collinearity of the parameters number of cylinders and engine displacement (correlation coefficient 0.97), it was decided to exclude the parameter number of cylinders from the model. The estimated values of the model parameters and the corresponding p-values are shown in Table 3.

Table 3. Estimated values of regression model parameters in urban cycle

| Independent variable | Level | The value of parameter | p |
|---|---|---|---|
| Intercept | | 5.63 | 0.00 |
| Engine displacement | | 1.91 | 0.00 |
| Transmission | A | 0.12 | 0.00 |
| Number of gears | | –0.08 | 0.00 |
| Fuel type | premium gasoline | 1.45 | 0.00 |
| Fuel type | gasoline | 0.94 | 0.00 |
| Fuel type | ethanol85 | 6.28 | 0.00 |

At the adopted level of significance ($\alpha = 0.05$), all selected variables have a significant impact on fuel consumption. Due to the inclusion of qualitative variables in the study, it was necessary to select a single reference level (class) for each variable. For the transmission type, manual transmission was used as the reference level, and for the fuel type, diesel. Based on the calculations, the following regression equation was formulated:

$$y = 5.63 + 1.91 \cdot \mathrm{E_d} + 0.12 \cdot \mathrm{T_A} - 0.08 \cdot \mathrm{G} + 1.45 \cdot \mathrm{F_{pg}} + 0.94 \cdot \mathrm{F_g} + 6.28 \cdot \mathrm{F_e}$$

where: $\mathrm{E_d}$ – engine displacement, $\mathrm{C_n}$ – number of cylinders, $\mathrm{T_A}$ – transmission type, G – number of gears, $\mathrm{F_{pg}}$ – fuel type, premium gasoline (98-octane and more), $\mathrm{F_g}$ – fuel type – gasoline (95-octane), $\mathrm{F_e}$ – fuel type – ethanol 85.

The next step was to verify the validity of the constructed model using residual analysis and assess the quality of the fit. It began by checking the distribution of residuals for conformity to the normal distribution. In the chi-square test, the calculated test statistic T = 218.04 and the corresponding p-value of 0.25 confirm normality of the random component (Fig. 2).

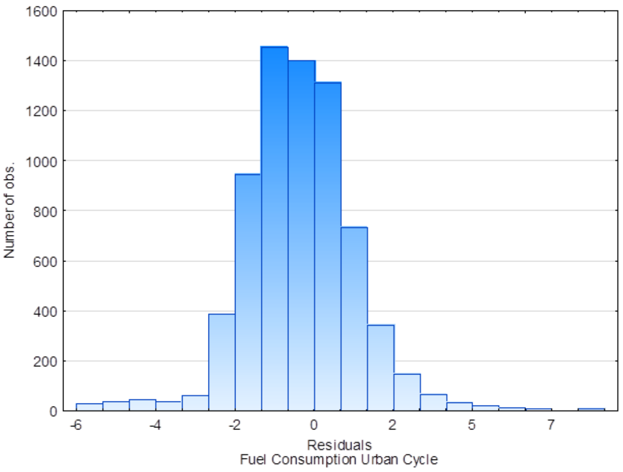

Fig. 2. Histogram of the residuals of the regression model for the urban cycle

In the next step, the Durbin-Watson test statistic for autocorrelation of residuals was calculated: DW = 1.96. It is assumed that in the absence of autocorrelation, the value of the statistic should be close to 2. In addition, the relationship between the test statistic and the threshold values dl and du from the Durbin-Watson table for k = 5 and n = 7000 was verified. The control values were dl = 1.95 and du = 2.04, respectively. The calculated value of the test statistic falls within the range <1.95;2.04>, which allows us to accept the null hypothesis and assume that there is no autocorrelation in the model residuals. The above conclusions indicate that the constructed model should be considered correct.

A coefficient of determination was calculated for the estimated model, which is $R^2 = 0.81$, meaning that as much as 81% of the variation in the observed values of the dependent variable is explained by it, which should be considered a satisfactory result.

Based on the results obtained, it can be concluded that both an increase in engine displacement by 1 L results in an increase in fuel consumption by 1.91 L/100. It should also be noted that, in the sample analyzed, an increase of 0.12 L/100 km in consumption was observed for vehicles with automatic transmissions compared to those with manual transmissions. In contrast, vehicles with more gears had lower fuel consumption. An increase of 1 in the number of available gear ratios resulted in a 0.08 L/100 km decrease in fuel consumption, due to the engine's ability to better adapt its operation to driving conditions. The last factor analyzed was the type of fuel. In relation to diesel-powered engines, the use of premium gasoline resulted in a 1.45 L/100 km increase in consumption, while regular gasoline resulted in a 0.94 L/100 km increase. For engines powered by ethanol fuel (85%) the sharp increase in fuel consumption of 6.28 L/100 km was observed.

### 3.3. Analysis of the effect of selected powertrain design parameters on fuel consumption in the highway cycle

As another, a multivariate regression model was built for the highway cycle. The estimated values of the model parameters and their corresponding p-values are shown in Table 4.

Table 4. Estimated values of regression model parameters in highway cycle

| Independent variable | Level | The value of parameter | p |
|---|---|---|---|
| Intercept | | 4.92 | 0.00 |
| Engine displacement | | 1.11 | 0.00 |
| Transmission | A | 0.34 | 0.00 |
| Number of gears | | –0.10 | 0.00 |
| Fuel type | premium gasoline | 0.95 | 0.00 |
| Fuel type | gasoline | 0.83 | 0.00 |
| Fuel type | ethanol85 | 4.53 | 0.00 |

For all estimated parameters, the p-values are 0.00, indicating they are statistically significant and affect fuel consumption. Based on the calculations, the following regression equation was formulated:

$$y = 4.92 + 1.11 \cdot \mathrm{E_d} + 0.34 \cdot \mathrm{T_A} - 0.10 \cdot \mathrm{G} + 0.95 \cdot \mathrm{F_{pg}} + 0.83 \cdot \mathrm{F_g} + 4.53 \cdot \mathrm{F_e}$$

In the next step, the model residuals and the fit quality were again verified. In the chi-square test, the calculated test statistic was T = 201.55, with p = 0.10, confirming the normal distribution of the random component (Fig. 3).

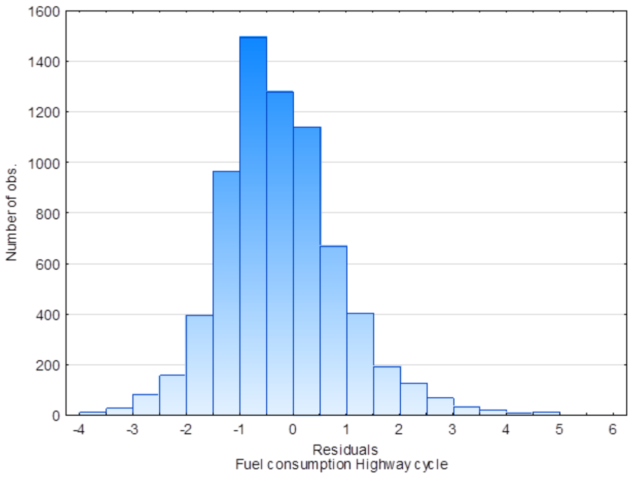

Fig. 3. Histogram of the residuals of the regression model for the highway cycle

In the next step, the value of the Durbin-Watson test statistic was calculated, which was DW = 1.97. The calculated value of the test statistic falls within the range <1.95;2.04>, which indicates that there is no autocorrelation in the model residuals. On this basis, again, the constructed model should be considered correct.

A coefficient of determination was also calculated for the estimated model, which is $R^2 = 0.72$, meaning that as much as 72% of the variation in the observed values of the dependent variable is explained by it, which should be considered a sufficient result.

Based on the results obtained, the following conclusions were drawn. In highway driving, increasing engine displacement by 1 liter results in a 1.11 L/100 km increase in fuel consumption. It should also be noted that in the sample analyzed, an increase of 0.17 L/100 km in consumption was observed for vehicles with automatic transmissions compared to those with manual transmissions. In contrast, vehicles with more gears had lower fuel consumption. An increase of 1 in the number of available gear ratios resulted in a 0.11 L/100 km decrease in fuel consumption. In the case of the variable fuel type, it can be concluded that In relation to diesel-powered engines, the use of engines powered by premium gasoline, gasoline and ethanol fuel (85%) resulted in an increase in consumption of 0.95 L/100 km, 0.83 L/100 km and 4.53 L/100 km, respectively.

### 3.4. Analysis of the effect of selected powertrain design parameters on fuel consumption in the combined cycle

Lastly, a mixed-mode multivariate regression model was built. Again, the model's parameter values were estimated, and the corresponding p-values are shown in Table 5.

Table 5. Estimated values of the regression model parameters in the combined cycle

| Independent variable | Level | The value of the parameter | p |
|---|---|---|---|
| Intercept | | 5.31 | 0.00 |
| Engine displacement | | 1.55 | 0.00 |
| Transmission | A | 0.22 | 0.00 |
| Number of gears | | –0.09 | 0.00 |
| Fuel type | premium gasoline | 1.22 | 0.00 |
| Fuel type | gasoline | 0.88 | 0.00 |
| Fuel type | ethanol85 | 5.49 | 0.00 |

For all estimated parameters, the p-values are 0.00, indicating they are statistically significant and affect fuel consumption. The regression equation has the following form:

$$y = 5.31 + 1.55 \cdot C_c + 0.22 \cdot T_A - 0.09 \cdot G + 1.22 \cdot F_{pg} + 0.88 \cdot F_g + 5.49 \cdot F_e$$

In the next step, the model residuals and the fit quality were again verified. In the chi-square test conducted, the calculated value of the test statistic was T = 211.32 and the corresponding p = 0.45, confirming the fit to the normal distribution of the random component (Fig. 4).

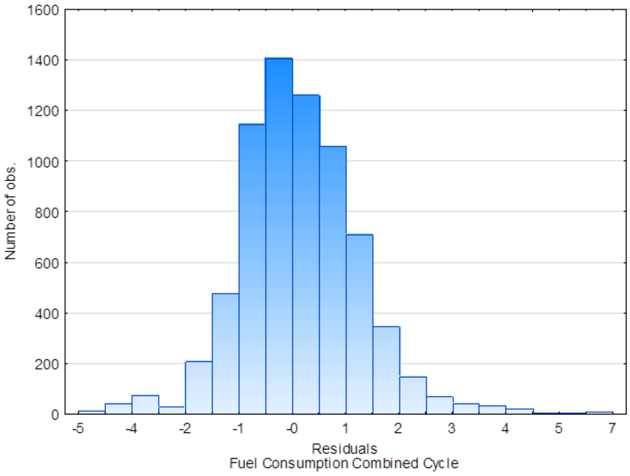

Fig. 4. Histogram of the residuals of the regression model for the combined cycle

In the next step, the Durbin-Watson test statistic was calculated, yielding DW = 1.96. The calculated value of the test statistic falls within the range <1.95;2.04>, which indicates that there is no autocorrelation in the model residuals. On this basis, again, the constructed model should be considered correct.

A coefficient of determination was also calculated for the estimated model: $R^2 = 0.79$, indicating that 79% of the variation in the observed values of the dependent variable is explained by the model, which should be considered a satisfactory result.

Based on the results obtained, the following conclusions were drawn. In highway driving, increasing engine displacement by 1 L results in a 1.55 L/100 km increase in fuel consumption. It should also be noted that, in the sample analyzed, an increase of 0.22 L/100 km in consumption was observed for vehicles with automatic transmissions compared to those with manual transmissions. In contrast, vehicles with more gears had lower fuel consumption. Increasing the number of available gear ratios by 1 resulted in a 0.09 L/100 km decrease in fuel consumption. For variable fuel types, it can be concluded that, compared with diesel-powered engines, engines powered by premium gasoline, gasoline, and ethanol (85%) resulted in increases of 1.22 L/100 km, 0.88 L/100 km, and 5.49 L/100 km, respectively.

## 4. Conclusions

Understanding which design parameters affect passenger vehicle fuel consumption is crucial for both individual users and the transportation sector as a whole. Knowledge of these relationships enables better management of operating costs by increasing vehicle fuel efficiency and optimizing the driver's driving style. On the other hand, the relevance of this issue stems from the ongoing efforts to achieve a sustainable transformation of transportation. Lower fuel consumption means lower $CO_2$ emissions into the environment. It should be noted that there is a linear relationship between $CO_2$ emissions and fuel consumption. Per 1 liter of fuel consumed, the approximate $CO_2$ emissions are 2.3 kg for gasoline, 2.66 kg for diesel, and 1.5 kg for ethanol [7, 29]. Therefore, in the above study, a multivariate regression model was used to analyze the significance and strength of the effect of vehicle powertrain parameters, such as engine displacement, number of cylinders, type of transmission, number of gears and type of fuel on fuel consumption recorded during urban, highway and mixed cycle driving.

Based on the results, it can be concluded that the studied phenomenon is influenced by all selected design parameters. In each recorded mode, increasing engine displacement increases fuel consumption. It should also be noted that, based on the sample studied, this increase is evident in vehicles with automatic transmissions. It should also be noted that as the number of gear ratios increases, consumption decreases, mainly because the engine performs more optimally under given driving conditions. In addition, for compression-ignition engines, an increase in fuel consumption is observed for spark-ignition engines (regular and premium gasoline) and for vehicles fueled with 85% ethanol.

The above studies can be used in practice by individual users to reduce vehicle operating costs, provide support in vehicle selection, and increase their awareness of environmental protection. They can also serve as a support for automotive concerns during vehicle design, providing information on optimal configurations of the studied design parameters (for example, combining a smaller displacement with a higher number of gears).

From the perspective of individual users, the results clearly show which configuration choices can help reduce operating costs. Choosing vehicles with smaller engine displacement, more gear ratios, and appropriately selected transmission types can contribute to measurable reductions in fuel consumption and, consequently, $CO_2$ emissions. At the same time, awareness that certain fuel types (e.g. high-ethanol fuel) may require higher volumetric consumption encourages a more informed assessment of real operating costs and environmental effects rather than relying solely on nominal fuel price.

For automotive manufacturers, the study provides quantitative evidence supporting the design direction of combining downsized engines with advanced multi-gear transmissions. Such configurations enable acceptable performance while reducing fuel consumption in real driving conditions.

The environmental context is also important. Given the linear relationship between fuel consumption and $CO_2$ emissions, every reduction in fuel demand translates directly into lower greenhouse gas emissions over the vehicle's life cycle. This is particularly relevant in the context of sustainable transport policies and tightening emission standards, where improving the efficiency of conventional powertrains remains an important complement to the development of electromobility.

The study thus fits into the broader research and regulatory trend to decarbonize road transport. By confirming and specifying relationships described in the literature, it strengthens the empirical basis for guidelines on vehicle design and for recommendations addressed to drivers (e.g. choice of vehicle specification adapted to usage profile). Ultimately, the results obtained are consistent with and confirm those of available studies in the literature.

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