

FACTORS INFLUENCING CO₂ EMISSIONS IN PETROL PASSENGER CARS: EVIDENCE FROM SLOVAKIA

Břetislav ANDRLÍK¹, Michal MÁDR²✉

¹Dept of Finance and Accounting, Faculty of Business and Economics, Mendel University in Brno, Czechia

²Dept of Economics, Faculty of Business and Economics, Mendel University in Brno, Czechia

Highlights:

- the study analysed 460000 Slovak passenger cars from technical inspection stations;
- 2 statistical methods (BMA and WALs) ensured the robustness of the results;
- WLTP testing disrupted traditional relationships between vehicle characteristics;
- actual emission measurements differ significantly from manufacturer technical certificates;
- maximum engine power and the latest emission standards can be used as a design element for taxation.

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Abstract. The aim of this article is to identify the factors that influence the evolution of CO₂ emissions in gasoline passenger cars. Specifically, the factors that can be obtained during emission measurements at technical inspection stations are analysed. This identification is used to determine the factors obtained by measurements at the technical inspection stations that should be used as a design element for the taxation of petrol road vehicles in order to reduce CO₂ emissions. The underlying source was data recorded by the vehicle technical inspection stations in 2019 and worked with passenger petrol cars of category M1. In total, almost 460000 passenger cars were analysed. 12 factors were used for each car, from which 7 variables were identified through 2 methods (BMA and WALs) as likely to have a statistically significant effect on the magnitude of CO₂ emissions. Subsequently, the effect of each factor was determined by OLS with robust Std. Err. Our results show that the maximum engine power and the latest emission standards can be used as design element for the taxation of gasoline road vehicles, as a positive relationship between the growth of this factor and the magnitude of CO₂ emissions of gasoline vehicles has been demonstrated.

Keywords: petrol passenger cars, externalities of transport, carbon dioxide, emission factors, Slovakia.

✉ Corresponding author. E-mail: xmadr@mendelu.cz

Notations

Abbreviations:

- BMA – Bayesian model averaging;
- BP/CW – the Breusch–Pagan/Cook–Weisberg test for heteroscedasticity;
- Coef. – regression coefficient;
- NEDC – new European driving cycle;
- OLS – ordinary least-squares;
- PIP – posterior inclusion probability;
- RDE – real driving emission;
- Std. Err. – standard error;
- WALS – weighted-average least-squares;
- WLTP – worldwide harmonised light vehicles test procedure.

Variables and functions:

- Age – age of the vehicle relative to 2019;
- Catalyst – catalyst type expressed as dummy (1 – petrol engine with lambda-probe controlled catalytic converter; 0 – petrol engine with lambda-probe controlled catalytic converter and OBD system);
- CO_{2_average} – the average of all four measurements of CO₂;
- CO_{2_first} – the first measured value of CO₂;
- CO_{2_min} – the lowest measured value of CO₂;
- Emission Standards 2 to 6 – highest emission standard the car meets expressed as dummy;

- Gearbox* – gearbox type expressed as dummy (1 – manual; 0 – automatic);
- Intercept* – the predicted value of the dependent variable when the independent variables are zero;
- Power* – maximum power of the vehicle in logarithmic functional form;
- Proxies* – list of independent variables (*Age, Catalyst, Emission Standards 2 to 6, Gearbox, Power, Speedometer, Volume, Weight*);
- Speedometer* – number of kilometres travelled in logarithmic functional form;
- Volume* – engine volume in logarithmic functional form;
- Weight* – maximum permissible total weight in logarithmic functional form;
- CO_{2i} – designation for individual dependent variables ($CO_{2_average}$, CO_{2_first} , CO_{2_min});
- $p(M_i)$ – the prior probability of model M_i ;
- $p(y|M_i)$ – the posterior probability for model M_i ;
- $p(M_j)$ – the prior probability of model M_j ;
- $p(y|M_j)$ – the posterior probability for model M_j ;
- λ_i – posterior inclusion probability;
- ε_i – error term;
- β_0 – intercept in the regression model;
- β_k – regression beta coefficients for independent variables (*Age, Catalyst, Emission Standards 2 to 6, Gearbox, Power, Speedometer, Volume, Weight*).

1. Introduction

The problem of studying and identifying the volume of production of harmful substances (emissions), or their impact on the environment, human health, but also the reduction of negative climate change is dealt with in the international environment, for example, the United Nations, the EU, but also the states as individuals individually. One of the most significant global agreements related to climate change is the 2015 Paris Agreement, which, according to the *United Nations Framework Convention on Climate Change* website, has been ratified by 190 countries to date (UN 2026), which speaks volumes about its importance. In line with the goals of the Paris Agreement on climate neutrality, the latest proposed targets of the European Council, which emerged from the October 2020 EU leaders' meeting, are also in line with the goals of the *Paris Agreement* on climate neutrality. In its conclusions, the European Council proposes a 55% reduction in emissions (European Council 2020). Regulations already adopted in the EU regulating emissions from motor vehicles are Regulation (EC) 2007/715 (EP, CEU 2007), which sets emission standards under EURO 5 and EURO 6 for light passenger and commercial vehicles, as well as Regulation (EU) 2019/631 (EP, CEU 2019), which sets CO_2 limits for new passenger cars and light commercial vehicles.

Currently, the most recent developments in the EU are the fit for 55 packages introduced on 14 July 2021, which

consists of an overarching Communication from the Commission on meeting the 2030 climate target towards climate neutrality – COM/2021/556 and 17 legislative and other proposals (EP, CEU 2021a). The package fulfils the *Green Deal for Europe* (the EU's decarbonisation policy framework presented in December 2019) and builds on the *EU's 2030 Climate Target Plan* and its impact assessment (September 2020). Legally, the Fit for 55 package fulfils the binding objectives of the *European Climate Legal Framework* – Regulation (EU) 2021/1119 (EP, CEU 2021b) to reduce greenhouse gas emissions by 55% by 2030 and to achieve emission neutrality by 2050. The interlinkages between instruments and policies can be identified, for example, Regulation (EU) 2019/631 (EP, CEU 2019) as regards the tightening of CO_2 emission performance standards for new passenger cars and new light commercial vehicles in line with the EU's more ambitious climate targets – COM/2021/556 (EP, CEU 2021a) and the links between CO_2 emission standards for light commercial vehicles and other instruments, most of which are either directly amended by the fit for 55 package or are expected to be proposed for amendment in 2021 (EURO 7 emission standard). The stated concrete efforts, even at the legislative level in the field of the European Union, aim to reduce CO_2 emissions produced by transport. However, it is clear that from a global point of view it is not sufficient to reduce the total volume of emissions produced by regulating only road transport. However, the elimination of this negative externality will definitely contribute to the volume of emissions produced in transport. The authors are also aware of the fact that the reduction of CO_2 emissions in transport may not be directly proportional to the improvement of the quality of the environment due to the existence of other transport emissions of air pollutants.

In addition to these legislative standards affecting newly manufactured road motor vehicles, EU Member States seek to control and subsequently exclude non-compliant older vehicles from road use, for example, through emission control stations, where an assessment is made as to whether or not a road motor vehicle is fit to continue to operate on the road. As the global economy grows, there is a natural increase in the demand for vehicles whether personal, commercial or other. There is no doubt that the size of the global fleet is increasing, because if we look only at the EU, the difference in the number of vehicles in use between 2014 and 2018 is an increase of 8.3%, which is approximately 23.5 million vehicles (ACEA 2019). In the case of the Slovakia, there has been an increase of 20.6% in registered vehicles between 2014 and 2019, that is 560711 vehicles (Ministerstvo vnútra Slovenskej republiky 2026). This article focuses specifically on the negative externalities in the form of CO_2 emissions from passenger road transport, which are contained in the exhaust gases of passenger cars.

According to Parry *et al.* (2007) noise, road congestion, accidents and, last but not least, the harmful impact on the environment, which includes air pollution, which will be discussed next. As Fiorito (2017) states in his article, there is an increase in greenhouse gases from transport due to

the ever-increasing use of motor vehicles. As Čechovič & Kendra (2019) report, in Slovakia the share of transport in total emissions is steadily increasing (16.44% in 2016), and the same is true for the EU as a whole (21.71% in 2016). Looking only at the transport sector in Slovakia, passenger vehicles are the highest emitters (48.54% in 2016), followed by trucks and buses (45.14% in 2016), according to Čechovič & Kendra (2019). It is thus evident that the road transport sector is a significant contributor to environmental pollution, air pollution.

Transport externalities and their minimisation are an important point of European policy and many Member States try to include these costs in their tax systems or in various forms of charges. An important aspect of tax and fee design in the EU should be that it removes the user-pays and polluter-pays externalities created as efficiently and effectively as possible, while at the same time incentivising their reduction. This principle was defined by Directive 2006/38/EC (EP, CEU 2006). These principles on transport taxation and charging aim to internalise negative externalities by including their amount in the taxes and road charges paid. The tax system of Slovakia applies a road tax for personal vehicles, the design parameter of which is the engine capacity and the higher the engine capacity, the higher the rate of taxation. In addition, a registration fee is collected for vehicle registration. The rate of the fee is based on the engine power in [kW], which is subsequently reduced according to the age of the vehicle.

The volume of emissions measured depends on various factors, one of which is the measurement method used. In order to harmonise the way emissions and consumption are measured, in 2017 the EU adopted Commission Regulation (EU) 2017/1151 (EC 2017), which adopted a test procedure WLTP applicable to new passenger cars and light commercial vehicles, replacing the then NEDC. The aim of this new method is to provide a more faithful representation of the actual emissions produced by vehicles in normal operation. In addition to the change in framework conditions, the driving cycle called WLTC, which falls under WLTP, has also changed (Pavlovic *et al.* 2018). The main difference between the 2 methods is that in the case of the NEDC these were measurements under laboratory conditions, whereas the WLTP is enriched by the RDE test. Since the earliest references to the change in emission and consumption measurement procedures, many studies have looked at the differences in emission measurements using the old and new methods (Bielaczyc *et al.* 2016; Marotta *et al.* 2015). Based on the change in driving cycle and conditions, a change in the magnitude of emissions and consumption was expected, namely WLTP shows higher values, which corresponds with the studies of Fontaras *et al.* (2017) and Pavlovic *et al.* (2016).

One of the important and often used tools for reducing CO₂ emissions in transport is the introduction of environmental charges or taxes. The aim of the article is to identify the factors influencing the development of CO₂ emissions of gasoline passenger cars in Slovakia. This identification is used to determine the factors obtained by measurements at the technical inspection stations that

should be used as a design element for the taxation of petrol road vehicles in order to reduce CO₂ emissions.

The article is structured as follows:

- current (Section 1) – an introduction;
- the literature review dealing with factors affecting CO₂ is provided in Section 2;
- the methodological framework is introduced in Section 3;
- in the Section 4, the empirical findings are presented and recommendations for adjusting the existing taxation of petrol vehicles are proposed;
- the concluding remarks are described in the Section 5.

2. Factors affecting CO₂ emissions

This section deals with the identification of potential factors that may influence the magnitude of CO₂ emissions from petrol road vehicles. Specifically, it deals with the technical characteristics of road motor vehicles, such as mainly engine-related characteristics, vehicle appearance and construction, and other selected technical characteristics. Petrol engines generally emit more CO₂ than diesel engines (EEA 2017; Tanaka *et al.* 2012). This is due to the generally higher fuel consumption of petrol vehicles (Waldron *et al.* 2006).

According to the existing literature, the key areas that have been shown to influence the amount of CO₂ emissions include fuel type and composition, engine characteristics (such as engine weight and volume, number of cylinders, but also the start-stop system) and its optimum performance, combustion process and improvements in engine technology, transmission efficiency and type, vehicle weight, rolling resistance, vehicle design and aerodynamic properties, and finally vehicle age and associated EURO emission standards (SRU 2005; Tsalikidis *et al.* 2020; Zachariadis *et al.* 2001; Ciuffo *et al.* 2016).

Tsalikidis *et al.* (2020) in their study describing the development of CO₂ emissions in newly registered vehicles between 2010 and 2018, stress and highlight the importance of these specific areas in particular, that is combustion technology and the engine technology itself leading to cleaner and also more efficient combustion, the appropriate type of transmission and improved design, including vehicle aerodynamics. These factors have been shown to influence the level of CO₂ emissions over the period studied, with improvements in conventional engines and on-road vehicle design highlighted as a primary point. On the other hand, according to the German Advisory Council of the Environment (SRU 2005), the greatest potential to reduce petrol consumption and thus CO₂ emissions lies in the weight of the vehicle.

For petrol engines, there is a direct proportionality between the amount of fuel consumed and CO₂ emissions, so a reduction in fuel consumption in the case of a conventional petrol engine would have the effective output of a reduction in CO₂ emissions (SRU 2005; Kropiwnicki, Kneba 2013). It is therefore important to note that all of these factors are often associated with the consumption of petrol itself. Although there are already alternative fuels and

drives (hydrogen, electric current, CNG, etc.) helping to reduce CO₂ emissions, it is still necessary to think about conventional engines and their technological aspects affecting CO₂ emissions. Because they now represent an increasingly high percentage of new petrol vehicles and ways must be found to influence their fuel consumption. As these alternative fuels are a longer-term issue and the current dependence on fossil fuels is crucial (SRU 2005).

Closely related to the engine characteristics is a specific factor that directly influences CO₂ emissions, namely the engine's volume and weight. Smaller, more compact (both in terms of weight and cylinder volume) but equally powerful engines compared to larger engines can bring positive benefits in the form of a reduction in fuel consumption, resulting in a reduction in generated CO₂ emissions due to the direct correlation of generated CO₂ emissions to the amount of gasoline burned. But one of the reasons is also the number of cylinders, which is related to the lower displacement of the engine and the decrease in friction between the pistons, which is eliminated due to the smaller cylinder volume (Patil *et al.* 2017; Tsalikidis *et al.* 2020). Which is in line with the claim of Mickūnaitis *et al.* (2007) who point precisely to the relationship between increasing engine displacement and increasing CO₂ emissions. Similarly, a smaller engine size without as many cylinders is lighter in weight, leading to lower engine loads, better performance and, again, lower CO₂ emissions (Patil *et al.* 2017; Tsalikidis *et al.* 2020). Patil *et al.* (2017) concluded that this way can lead to a decrease in fuel consumption in the range of 10 to 30% depending on the type of combustion, which is of course associated with a relative decrease in CO₂ emissions.

Engine power itself, including maximum engine power, is also a factor in the amount of CO₂ emissions generated. This is a rather crucial aspect, which is closely linked to petrol consumption and thus CO₂ emissions, as increasing engine power is directly related to increasing fuel consumption. There has also been a gradual increase in the average [kW] output of newly registered vehicles over the years, which may be a potential problem in future reduction efforts (SRU 2005; Grelier 2018).

In terms of combustion technology and innovative engine technology, conventional engines differentiate between diesel and petrol engines. In the case of petrol engines, there are relatively significant combustion losses due to the effect of fuel injection and certain valve pressures resulting in higher petrol consumption. Compared to diesel engines, it can be shown how the better pressure ratio and direct fuel injection into the combustion chamber of each cylinder in diesel engines leads to lower diesel consumption and therefore lower CO₂ emissions, as demonstrated by the German Advisory Council of the Environment (SRU 2005). However, in recent years, direct injection has also started to be used more and more in petrol engines, taking advantage of better combustion control and increased fuel efficiency. There is therefore considerable room for improvement even within petrol engines (Tsalikidis *et al.* 2020).

Typically for petrol engines, one of the engine technologies is variable valve actuation. Specifically, either variable valve timing or variable valve timing including stroke. This technology, which helps to improve engine efficiency and exhaust gas recirculation, enables optimum valve timing (intake, exhaust), which results in the control of residual exhaust gases, including CO₂. It is therefore a means of improving engine performance and reducing fuel consumption (Posada, Façanha 2015).

Another factor is the quality and type of gearbox. Again, the amount of fuel used can be influenced, as with the other factors mentioned. It is about streamlining the process during the transmission system and thus reducing mechanical losses. It depends on whether it is a manual or automatic transmission, but also on the number of gears. The increasing number of gears contributes to more efficient operation and maximum efficiency (US EPA 2021; Tsalikidis *et al.* 2020). This is also linked to the fact that greater efficiency and more efficient operation, including lower fuel consumption and CO₂ emissions, are achieved with automatic transmissions compared to manual transmissions. Although the mechanical efficiency is similar to that of a manual gearbox, an automatic gearbox is associated with better optimisation of engine speed, as well as avoiding the internal resistance that arises with a manual gearbox (Tsalikidis *et al.* 2020). However, we also find the opposite claim, as evidenced by Mickūnaitis *et al.* (2007) whose research shows that automatic transmissions, on the other hand, consume more fuel and emit more CO₂. This contrary view can be explained by the link to the more complex mechanism and components that are used in the case of an automatic transmission for its proper functioning, such as sensors or electronic control units, which cause the vehicle to weigh more and therefore produce more emissions (Grelier 2018). It follows that even efforts in the context of technological progress to reduce emissions can ultimately have the opposite effect.

With all the technical aspects of the vehicle, such as the size and weight of the engine, the tank, the individual vehicle components, the equipment or materials used are closely related to another crucial factor, which is the total (operating) weight of the vehicle. The operating weight according to Ciuffo *et al.* (2016) consists specifically of several parts. The 1st component is the weight of the vehicle itself; the 2nd component is the amount of fuel in the tank and finally the weight and number of passengers, which means that it is possible to influence the individual weight components separately.

Vehicle weight is important for conventional engines, that is also for petrol engines, and is related to the amount of CO₂ emitted (Grelier 2018). In the examined sample of the time series comprising 16 years (2001 to 2016), an increasing trend in the average weight of new vehicles can be seen for all major manufacturers in the automotive industry – Skoda, Volkswagen, Audi, Ford, BWM and others. This trend can be explained by the increasing demand for comfort, vehicle versatility, higher performance and also safety, which in most cases will require more powerful and

heavier engines, possibly together with a larger fuel tank capacity, which will result in a higher overall vehicle weight (SRU 2005; Grelrier 2018). Light weighting vehicles with appropriate materials, along with other design optimizations, would therefore contribute to better CO₂ emissions in the form of these innovations, which would break the vicious cycle of increasing vehicle weight due to the constant demand for improvements and better features mentioned above (SRU 2005; Grelrier 2018). Concrete evidence of this phenomenon may be the result of the growing popularity of SUVs and hence the greater number of these vehicles on the road, which are heavier than conventional passenger vehicles and hence have different emission levels. These larger and heavier vehicles produce an average of 132 g CO₂/km compared to the average mid-range vehicle, which produces 118 g CO₂/km (Grelrier 2018). Or this fact is further illustrated by Kok (2013) using the example of consumer behaviour favouring smaller and lighter vehicles resulting in lower CO₂ emissions. It is clear from the research carried out that more powerful and heavier vehicles have an impact on fuel consumption, which translates into a larger and more significant carbon footprint.

Another factor that is often given attention is the age of the vehicle, including another related factor, the EURO emission standards, as older vehicles generate more pollutants in general. As a general rule, the older the vehicle, the lower the EURO emission standard, which sets less stringent limits on the emission parameters of road vehicles. This link between vehicle age and the amount of pollutants is generally confirmed by many expert studies, as shown for example, by Andrlík (2013) or Zachariadis *et al.* (2001). Older vehicles therefore meet less stringent EURO emission standards and, as Paltsev *et al.* (2015) demonstrates, stricter EURO standards have been shown to reduce pollutant emissions.

3. Methodology

The source of the input data set is the company responsible for the operation of emission control stations *S-EKA, Ltd* (S-EKA 2026). The input file contains data on vehicles of categories M, N and T from emission control stations in Slovakia for the year 2019. It contains a total of 1219398 vehicle records, which means that the emission control was carried out for 38% of the Slovak vehicle fleet (3169187 vehicles were registered in 2019 – CEIC 2026). Input data set provides 20 different technical information related to them (for example engine capacity, category, mileage), if recorded in the system. Part of this input set are also real measured values of emissions of CO, CO₂, HC in the conditions of idle engine speed (hereinafter IS) as well as high engine speed (hereinafter HS), which serve as the main basis for further processing of the cell. Thus, the examination outputs of this article are based on the actual measured values during the emission control and not on the values stated in the technical certificate, which are set by the vehicle manufacturer.

M1 category vehicles with petrol engine were selected from the input set, provided that the condition of containing HS CO₂ data was met. The M1 category was chosen because it is the most common type of vehicle in Slovakia (955853 out of 1219398 vehicle records in 2019, it means 78.4%). Petrol vehicles were selected here for 2 reasons: 1st, they account for a dominant share of the Slovak car market (diesel vehicles have only an 8% share, other types have a marginal share; EEA 2019) and 2nd, the analysed set contains CO₂ emissions measurements for petrol vehicles only. Such a narrowed data set, containing M1 and petrol-powered vehicles with the HS CO₂ condition met (458954 vehicles), serves as a basis for further analysis.

The article focuses on CO₂ emissions, specifically those produced at higher speeds. Vehicle Technical Inspection takes a total of 4 measurements. 3 expressions were created from these 4 measurements, CO_{2-*average*}, CO_{2-*first*} and CO_{2-*min*}. The use of 3 different measurements should ensure the robustness of the results.

The regression model contains twelve explanatory factors. These variables are selected based on 2 criteria, significance in explaining the evolution of CO₂ emissions and data availability. Specifically, the variables *Age*, *Power*, *Weight*, *Volume*, *Speedometer*, *Gearbox*, *Catalyst*, and *Emission Standards 2 to 6*. These variables were used by German Advisory Council of the Environment (SRU 2005), Grelrier (2018), Tsalikidis *et al.* (2020), Zachariadis *et al.* (2001) and Ciuffo *et al.* (2016). They use logarithmic functional forms for most variables, except for dummy variables, is because of the structure of the data. Descriptive statistics for the individual variables are presented in Table 1. We should also mention that the level of emissions also depends on factors for which we do not have available data, namely the use of the start-stop system in the engine (Tsalikidis *et al.* 2020), exhaust gas recirculation system (Mossa *et al.* 2019), adding ethanol to the fuel (Park *et al.* 2010; Ciuffo *et al.* 2016), quality of tyres (Ciuffo *et al.* 2016) and vehicle aerodynamics (Chowdhury *et al.* 2012).

The relationship between the level of emissions and the individual factors can be formally written in the following regression equation:

$$CO_{2i} = \beta_0 + \sum_i (\beta_k \cdot Proxies)_i + \varepsilon_i. \quad (1)$$

We employ a BMA estimator introduced by Magnus *et al.* (2010) to fit a classical linear regression model with uncertainty about the choice of the explanatory variables.

This technique includes 2 types of variables, factories that are theoretically supposed to be in the model and factories for which there is uncertainty about their inclusion. In this article, we consider a constant as the 1st type of factor, while the other variables will be assumed to have some degree of uncertainty. This method estimates models M_j for all combinations of regressors, $j = 1, \dots, 1^{12}$ (that is 4096 models) and then the model with the highest likelihood is selected.

Table 1. Descriptive statistics

| Variable | Observations | Mean | Standard deviation | Min | Max |
|--------------------------|--------------|-------|--------------------|-------|-------|
| CO ₂ -average | 458954 | 14.80 | 0.65 | 0.01 | 62.36 |
| CO ₂ -first | 458954 | 14.80 | 0.65 | 0.004 | 62.36 |
| CO ₂ -min | 458954 | 14.80 | 0.65 | 0.01 | 62.36 |
| Age | 458954 | 13.37 | 5.66 | 1.00 | 52.00 |
| log Power | 458893 | 4.16 | 0.33 | 2.64 | 6.78 |
| log Weight | 458954 | 7.38 | 0.12 | 6.21 | 9.64 |
| log Volume | 458954 | 7.25 | 0.22 | 1.39 | 11.12 |
| log Speedometer | 458954 | 11.64 | 0.69 | 1.39 | 18.87 |
| Gearbox | 455735 | 0.89 | 0.31 | 0 | 1 |
| Catalyst | 458954 | 0.41 | 0.49 | 0 | 1 |
| Emission Standard 2 | 458954 | 0.16 | 0.37 | 0 | 1 |
| Emission Standard 3 | 458954 | 0.23 | 0.42 | 0 | 1 |
| Emission Standard 4 | 458954 | 0.22 | 0.42 | 0 | 1 |
| Emission Standard 5 | 458954 | 0.28 | 0.45 | 0 | 1 |
| Emission Standard 6 | 458954 | 0.09 | 0.28 | 0 | 1 |

Source: own calculations based on data from S-EKA (2026).

BMA provides a coherent method of inference on the regression parameters of interest by taking explicit account of the uncertainty due to both the estimation and the model selection steps. This Bayesian estimator uses conventional noninformative priors on the focus parameters and the error variance, and a multivariate Gaussian prior on the auxiliary parameters. The unconditional BMA estimates are obtained as a weighted-average of the estimates from each of the possible models in the model space with weights proportional to the marginal likelihood of dependent variable in each model (De Luca, Magnus 2011).

The significance of each variable is determined by the PIPs, which can be calculated using the following equation (Magnus *et al.* 2010). Let us add that variables whose PIP value is greater than 0.8 should be included in the model.

$$\lambda_i = \frac{p(M_i) \cdot p(y | M_i)}{\sum_j p(M_j) \cdot p(y | M_j)}. \quad (2)$$

Following Magnus *et al.* (2010), the BMA method is complemented by the WALs technique. WALs uses the weighted-average least-squares estimator introduced by Magnus *et al.* (2010) to fit a classical linear regression model with uncertainty about the choice of the explanatory variables. This method has the same characteristics as BMA, but has 2 advantages over the above method, its computational burden is trivial and it is based on a transparent definition of prior ignorance (Einmahl *et al.* 2011; Magnus *et al.* 2010). The combination of these 2 methods is chosen to ensure the robustness of the results.

Based on these techniques, the variables most likely to affect CO₂ emissions are selected. These selected variables will then be tested through OLS estimation. Given the structure of the data, it was tested whether the variance of the values is homogeneous (BP/CW).

4. Results

This section has 2 parts. 1st, statistically significant variables are identified through BMA and WALs and 2nd, regression analysis is performed through OLS model with robust Std. Err. (the reason is the presence of heteroscedasticity). The OLS analysis serves as a robustness check.

The Table 2 represents, which variables are most likely to be statistically significant. In the case of BMA, we can consider factors whose PIPs are greater than 0.8, while for WALs, if the *t*-statistic is greater than 1.78. Based on the results, we can assume that the age and weight of the vehicle (*Age* and *Weight*), the maximum power and engine capacity (*Power* and *Volume*), the number of kilometres travelled (*Speedometer*) and compliance with *Emission Standards* 5 and 6 have a statistically significant effect. This finding is consistent with the empirical literature (SRU 2005; Tsalikidis *et al.* 2020; Zachariadis *et al.* 2001; Ciuffo *et al.* 2016).

In the following section, the influence of these factors is identified through an OLS regression model. It should also be mentioned that gearbox type (*Gearbox*), catalytic converter type (*Catalyst*) and older *Emission Standards* (2 to 4) are unlikely to have an effect and are therefore not dealt with further. In the case of transmission type, the ambiguous effect is consistent with the literature, as on the one hand there is the view that automatic transmissions improve vehicle smoothness, which is associated with lower emissions (US EPA 2021; Tsalikidis *et al.* 2020), while, on the other hand, automatic transmissions are associated with a more complex system that can increase emissions (Grelier 2018).

The results of the OLS models (Table 3) confirm previous findings, that CO₂ emissions from petrol engines depend on the age and weight of the vehicle (*Age* and *Weight*), the maximum power and volume of the engine

Table 2. Influence of individual factors on CO₂ emissions (BMA and WALS methods)

| BMA | CO _{2-<i>average</i>} | | | CO _{2-<i>first</i>} | | | CO _{2-<i>min</i>} | | |
|----------------------------|--------------------------------|-----------|----------------------|------------------------------|-----------|----------------------|----------------------------|-----------|----------------------|
| | Coef. | Std. Err. | PIP | Coef. | Std. Err. | PIP | Coef. | Std. Err. | PIP |
| <i>Intercept</i> | 17.143 | 0.083 | 1.00 | 17.139 | 0.084 | 1.00 | 17.144 | 0.083 | 1.00 |
| <i>Age</i> | -0.017 | 0.000 | 1.00 | -0.017 | 0.001 | 1.00 | -0.017 | 0.000 | 1.00 |
| <i>log Power</i> | 0.113 | 0.006 | 1.00 | 0.112 | 0.006 | 1.00 | 0.113 | 0.006 | 1.00 |
| <i>log Weight</i> | -0.149 | 0.014 | 1.00 | -0.145 | 0.014 | 1.00 | -0.152 | 0.014 | 1.00 |
| <i>log Volume</i> | -0.108 | 0.009 | 1.00 | -0.111 | 0.009 | 1.00 | -0.105 | 0.009 | 1.00 |
| <i>log Speedometer</i> | -0.059 | 0.002 | 1.00 | -0.059 | 0.002 | 1.00 | -0.059 | 0.002 | 1.00 |
| <i>Gearbox</i> | -0.001 | 0.004 | 0.15 | -0.002 | 0.004 | 0.20 | -0.001 | 0.003 | 0.12 |
| <i>Catalyst</i> | 0.000 | 0.002 | 0.01 | 0.000 | 0.003 | 0.01 | 0.000 | 0.002 | 0.01 |
| <i>Emission Standard 2</i> | 0.000 | 0.001 | 0.01 | 0.000 | 0.001 | 0.01 | 0.000 | 0.001 | 0.01 |
| <i>Emission Standard 3</i> | 0.004 | 0.005 | 0.42 | 0.004 | 0.005 | 0.36 | 0.005 | 0.005 | 0.47 |
| <i>Emission Standard 4</i> | 0.000 | 0.004 | 0.07 | 0.000 | 0.005 | 0.07 | 0.000 | 0.004 | 0.07 |
| <i>Emission Standard 5</i> | -0.025 | 0.007 | 0.96 | -0.024 | 0.008 | 0.95 | -0.025 | 0.007 | 0.97 |
| <i>Emission Standard 6</i> | -0.119 | 0.009 | 1.00 | -0.118 | 0.010 | 1.00 | -0.119 | 0.009 | 1.00 |
| WALS | CO _{2-<i>average</i>} | | | CO _{2-<i>first</i>} | | | CO _{2-<i>min</i>} | | |
| | Coef. | Std. Err. | <i>t</i> -statistics | Coef. | Std. Err. | <i>t</i> -statistics | Coef. | Std. Err. | <i>t</i> -statistics |
| <i>Intercept</i> | 17.037 | 0.084 | 201.84 | 17.037 | 0.084 | 202.68 | 17.035 | 0.085 | 201.35 |
| <i>Age</i> | -0.016 | 0.001 | -20.81 | -0.016 | 0.001 | -20.61 | -0.016 | 0.001 | -20.96 |
| <i>log Power</i> | 0.108 | 0.006 | 17.91 | 0.107 | 0.006 | 17.75 | 0.109 | 0.006 | 18.01 |
| <i>log Weight</i> | -0.134 | 0.013 | -9.98 | -0.131 | 0.013 | -9.83 | -0.137 | 0.014 | -10.13 |
| <i>log Volume</i> | -0.107 | 0.009 | -12.11 | -0.111 | 0.009 | -12.49 | -0.105 | 0.009 | -11.8 |
| <i>log Speedometer</i> | -0.058 | 0.002 | -32.59 | -0.058 | 0.002 | -32.45 | -0.058 | 0.002 | -32.67 |
| <i>Gearbox</i> | -0.009 | 0.003 | -2.94 | -0.010 | 0.003 | -3.05 | -0.009 | 0.003 | -2.86 |
| <i>Catalyst</i> | -0.038 | 0.013 | -2.87 | -0.042 | 0.013 | -3.14 | -0.035 | 0.013 | -2.66 |
| <i>Emission Standard 2</i> | 0.015 | 0.008 | 1.84 | 0.015 | 0.008 | 1.82 | 0.015 | 0.008 | 1.87 |
| <i>Emission Standard 3</i> | 0.026 | 0.010 | 2.63 | 0.026 | 0.010 | 2.64 | 0.026 | 0.010 | 2.63 |
| <i>Emission Standard 4</i> | -0.012 | 0.018 | -0.7 | -0.015 | 0.018 | -0.86 | -0.010 | 0.018 | -0.58 |
| <i>Emission Standard 5</i> | -0.031 | 0.019 | -1.58 | -0.033 | 0.019 | -1.69 | -0.029 | 0.019 | -1.5 |
| <i>Emission Standard 6</i> | -0.116 | 0.022 | -5.37 | -0.118 | 0.022 | -5.43 | -0.115 | 0.022 | -5.32 |

Source: own calculations based on data from S-EKA (2026).

(*Power* and *Volume*), the number of kilometres travelled (*Speedometer*) and compliance with *Emission Standards* 5 and 6.

Taking a closer look, we can see that the predicted effect is for vehicles with higher maximum engine power and *Emission Standards* 5 and 6. Thus, higher CO₂ emissions were measured for petrol cars with higher maximum power (SRU 2005; Grelier 2018) and at the same time it can be argued that vehicles with the latest emission standards achieve significantly lower emissions (Paltsev *et al.* 2015).

On the other hand, for the other variables we can observe the opposite, unexpected, effect. Specifically, lower emissions have been measured for petrol cars that are older, have a higher maximum permissible weight, a larger engine capacity and a higher mileage. Which is contrary to the literature, whether in the case of engine volume (Mickūnaitis *et al.* 2007; Patil *et al.* 2017; Tsalikidis *et al.* 2020) or the age of the vehicle (Andrlík 2013; Zachariadis *et al.* 2001). The indirect relationship between engine capacity and CO₂ consumption can be explained by the fact that the NEDC method of measuring emissions under lab-

oratory conditions showed lower values of emissions produced by road vehicles. As demonstrated by the literature review (Fontaras *et al.* 2017; Pavlovic *et al.* 2016), the change of the emission measurement method from NEDC to WLTP has included the element of normal operation in the measurement of emission parameters of road vehicles. This has significantly increased the reported values of emission parameters including CO₂. The declared direct dependence between the reduction of engine volume and the reduction of CO₂ emissions was therefore valid for the NEDC method, whereas the linkage may not occur in the case of WLTP (Mock *et al.* 2014).

A comparison of the impact of each factor is shown in the following graph. The X-axis shows the effect of each statistically significant variable, with the values indicating the standardized coefficient of determination. The Y-axis includes the individual variables. The effect is expressed in terms of average CO₂ emissions. The most significant impact is the age of the vehicle, where an increase in vehicle age by one year leads to a 0.15 reduction in CO₂ emissions, while for the other factors an increase of 100% leads

Table 3. Influence of selected factors on CO₂ emissions (regression results)

| Factor | CO _{2-<i>average</i>} | CO _{2-<i>first</i>} | CO _{2-<i>min</i>} |
|----------------------------|--------------------------------|------------------------------|----------------------------|
| <i>Intercept</i> | 17.09*** (195.57) | 17.09*** (193.42) | 17.09*** (196.24) |
| <i>Age</i> | -0.02*** (-43.74) | -0.02*** (-43.52) | -0.02*** (-43.84) |
| <i>log Power</i> | 0.11*** (17.47) | 0.11*** (17.09) | 0.11*** (17.6) |
| <i>log Weight</i> | -0.14*** (-10.33) | -0.17*** (-9.9) | -0.14*** (-10.56) |
| <i>log Volume</i> | -0.11*** (-11.92) | -0.11*** (-11.91) | -0.1*** (-11.74) |
| <i>log Speedometer</i> | -0.06*** (-31.05) | -0.06*** (-30.81) | -0.06*** (-31.15) |
| <i>Emission Standard 5</i> | -0.02*** (-8.26) | -0.03*** (-8.06) | -0.03*** (-8.39) |
| <i>Emission Standard 6</i> | -0.12*** (-24.06) | -0.12*** (-23.77) | -0.12*** (-24.21) |
| Observations | 458893 | 458893 | 458893 |
| Adjusted R ² | 0.029 | 0.029 | 0.029 |
| BP/CW | 0.00 (87889.02) | 0.00 (87872.16) | 0.00 (87862.24) |

Notes:

- *, ** and *** denote significance at 10%, 5% and 1% level, respectively;
- t-statistics are reported in parentheses;
- all regression models include robust Std. Err.;
- source: own calculations based on data from S-EKA (2026).

to a 0.06 increase (maximum vehicle power) or decrease (maximum permissible vehicle weight, engine capacity, mileage) in emissions. In the case of emission standards, it is assumed that cars meeting *Emission Standard 6* have lower emissions than other cars. The same is true for *Emission Standard 5*, but with the expected result that the difference with other emission standards is not so great.

If we link the OLS model results to the graphical output (Figure), we then conclude that the maximum engine power and the latest emission standards can be used as a design element for the taxation of petrol road vehicles, as a positive relationship between the growth of this factor and the magnitude of CO₂ emissions of petrol vehicles has been demonstrated. Other examined factors recorded in the context of the implementation of regular vehicle technical inspections cannot be used as a relevant factor for taxation, as there is no positive relationship between the measured factor (age and weight of the vehicle, engine capacity, mileage) and CO₂ emissions or a statistically significant effect could not be demonstrated (type of gearbox and type of catalytic converter).

The taxation of passenger road vehicles in EU Member States is based on 2 basic views, the acquisition and ownership/operation of a passenger road vehicle. Specifically, we focus on tax design features that our results suggest have the potential to reduce negative externalities in the form of emissions from road motor transport.

For the taxation of the purchase of a passenger road motor vehicle, according to European Automobile Manufacturers' Association (ACEA 2021), the most important design elements for taxation are CO₂ emissions (14 countries), maximum engine power (5 countries) and the EURO emission standard (4 countries). The basic formula for taxation is the higher the CO₂ emissions or maximum engine power and the older the EURO emission standard, the higher the taxation is applied. Other elements affecting

the charging obligation are the age of the vehicle, differentiation by vehicle fuel and NO_x emissions. Some countries even have a combination of CO₂ emission factor and maximum engine power (France and Italy) or CO₂ emissions and EURO emission standards (Belgium). The specific case is Slovenia, which applies all 3 of these parameters to determine the final tax liability. The 2nd view is the taxation of the ownership and operation of passenger road vehicles. The most important design features of this type of tax are again CO₂ emissions (15 countries), maximum engine power (5 countries) and the EURO emission standard (4 countries). Other elements affecting the tax liability are the age of the vehicle, fuel, engine capacity, weight and number of axles. Again, there are several countries that use a combination of the 2 elements highlighted, namely Bulgaria, Italy and Hungary, or a combination of CO₂ and emission standards (Belgium) or in combination with engine power (Austria).

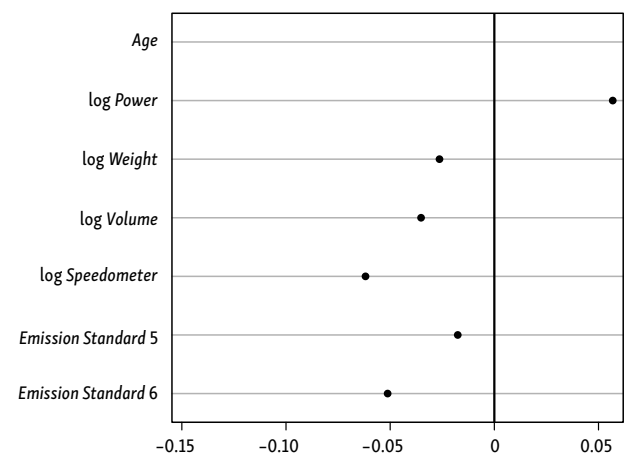


Figure. Standardised effect of individual factors on average CO₂ emissions; source: own calculations based on data from S-EKA (2026)

From the above overview of the situation in the EU and the results obtained, the authors conclude that in order to achieve reductions in CO₂ emissions from passenger road transport, it is necessary for most EU countries to focus on greater consideration of maximum engine power and emission standards when setting tax obligations. Especially in the case of Slovakia, where these design elements are minimally taken into account.

5. Conclusions

The aim of the article was to identify the factors that influence the development of CO₂ emissions of gasoline passenger cars in Slovakia. Specifically, the article focuses on the factors that can be obtained when measuring emissions as part of the vehicle control at the technical inspection station. The underlying source was data for the year 2019 provided by S-EKA (2026), the company that provides vehicle control at the technical inspection station. From this dataset, all passenger petrol cars of the M1 category were used, that is almost 460000 passenger cars were analysed. 12 factors were used for each car, from which 7 variables were identified through 2 methods (BMA and WALS) as likely to have a statistically significant effect on the magnitude of CO₂ emissions. Subsequently, the effect of each factor was determined by OLS with robust Std. Err. This identification was used to determine the factors derived from the measurements at the technical inspection stations that should be used as a design element for the taxation of petrol road vehicles in order to reduce CO₂ emissions and thus comply as much as possible with the set reductions in transport emissions in a Europe-wide framework.

Our results show that the maximum engine power and the latest emission standards can be used as a design element for the taxation of gasoline road vehicles, as a positive relationship between the growth of this factor and the magnitude of CO₂ emissions of gasoline vehicles has been demonstrated. These elements, in various combinations with the magnitude of CO₂ emissions, are already incorporated in several EU Member States, notably in the taxation of the acquisition of a passenger road motor vehicle (Belgium, France, Italy and Slovenia) or in the taxation of the ownership and operation of a passenger road motor vehicle (Belgium, Bulgaria, Italy, Hungary and Austria). Other factors examined (age and weight of the vehicle, engine capacity, mileage, type of gearbox and type of catalytic converter), recorded as part of the implementation of regular technical inspections, cannot, according to the results obtained, be used as a relevant factor for the taxation of motor vehicles, although they are used by a number of EU Member States (for example, higher vehicle age leads to higher tax liability in the Czechia or Slovakia). From this perspective, it is in these 2 countries that a change in the design of the road tax base should be made, with an emphasis on the link to the CO₂ reduction element.

At the same time, it should be added that it was not possible to work with all relevant variables because some of the relevant factors are not measured during the ve-

hicle tests at the technical inspection station. Specifically, changes in fuel composition, combustion technology, engine start-stop system, exhaust gas recirculation system, tyre rolling resistance and vehicle aerodynamics. With regard to the changes in fuel composition, the use of fuels with a higher proportion of biobased components (for example, ethanol E10) reduces fuel consumption (Al-Hasan 2003) and produces fewer CO₂ emissions (Park *et al.* 2010; Ciuffo *et al.* 2016). At the same time, the extension of gasoline direct injection technology is improving engine performance and reducing fuel consumption (Posada, Façanha 2015). The engine with start-stop system leads to a reduction in fuel consumption in urban traffic of between 11 and 15% (Merkisz *et al.* 2011). The use of exhaust gas recirculation not only reduces NO_x emissions (Zheng *et al.* 2004), but can also lead to lower CO₂ emissions (Mossa *et al.* 2019). Low rolling resistance tyres have also been shown to reduce petrol consumption and thus CO₂ emissions (SRU 2005; Ciuffo *et al.* 2016). Finally, lower CO₂ emissions can be observed in vehicles that have better aerodynamic design elements (Chowdhury *et al.* 2012; Crolla 2009). Therefore, for further research, he proposes to link measurements at the technical inspection stations with other databases in order to take these factors into account when constructing road taxes. For this purpose of setting tax obligations, it would be appropriate to specify more precisely the range of the above-mentioned parameters at the technical control stations, so that the independent database reflecting the current state of the vehicle created in this way enables the most accurate punishment of the negative externalities of the given vehicle.

Author contributions

Břetislav Andrlík was responsible for conception of the study, writing the 1st draft of the article and supervision.

Michal Mádr was responsible for collecting the data, analysing it, interpreting it and revision of the article.

All authors have read and agreed to the submitted version of the article.

Disclosure statement

The authors declare that they have not any competing financial, professional, or personal interests from other parties.

Declaration on the use of Artificial Intelligence (AI)

During the preparation of this manuscript, the authors used *Grammarly AI* to assist with grammar checking.

While the authors acknowledge the usage of AI, they maintain that *Břetislav Andrlík* and *Michal Mádr* are the sole authors of this article and take full responsibility for the content therein, as outlined in COPE recommendations and journal policies.

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