Verification of the dependence of CO, CO_2 and NO_x emission concentrations on vehicle ride dynamics and route profile

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Abstract

The aim of this paper is to verify the dependence of CO, CO_2 and NO_x emission concentrations on vehicle driving dynamics and route profile under real conditions of drive with petrol engine vehicle. The vehicle was tested on roads in hilly countryside in the Czech Republic. The experiments were focused on recording and analysing fuel consumption and subsequently production of emissions (CO, CO_2, NO_x). Results showed dependence between the average CO emissions and the average increase of instantaneous speed, slight tendency towards a lower CO_2 emission. Also, dependence between the average CO_2 emissions and the average gradient was proven, which means there is a tendency towards higher CO_2 emission concentrations in sections with higher average gradient. By contrast, dependence between the average NO_x emissions and the average increase in instantaneous speed or the average gradient were not proved.

Key words: *real driving emissions, concentrations of CO, CO_2 and NO_x*

Introduction

With their mere existence, everyone acts on their surroundings and affects the Earth's climatic system to a various degree. One of the possibilities is slowing down the rate of consumption of fossil energy sources and replacing them with other "non-fossil" or "low-carbon" sources. Transport, particularly individual transport by cars, is one of the main producers of pollution and greenhouse gas emissions in urban areas. Therefore, it is necessary to address, in a comprehensive manner, the technical possibilities of switching over to the use of alternative energy sources as well as social and cultural changes that are associated with the birth of a low-carbon society, which reduces the consumption of fossil fuels, the overall consumption of energy and, based on that, production of CO_2 emissions, too. This trend is also backed by European regulations that put great emphasis mainly on the decarbonisation of transport (Directive 98/69 / EC 1998), which implies increased generation of purely electrical energy and, consequently, hybrid and plug-in hybrid electric vehicles. Promoting EVs only makes sense where the electricity they use is generated from renewable sources. It has been proven that EVs may be less friendly in terms of the production of emissions in certain areas of use than the conventional combustion-engine vehicles[1].

Vehicle exhaust gases typically contain water vapour, nitrogen gas and carbon dioxide. Substances that can also be present include nitrous oxide, nitrogen dioxide, carbon monoxide, dust particles, benzene, formaldehyde, benzopyrene and other polyaromatic hydrocarbons, lead, mercury, arsenic, dioxins and other substances. Exhaust gases contribute a significant fraction to air pollution and contain substances mainly affecting the respiratory organs (e.g. oxides of nitrogen and particulate matter), some of the substances are toxic (such as carbon monoxide, blocking the capacity of haemoglobin to transfer oxygen) and/or carcinogenic (e.g. toluene, styrene, formaldehyde and benzopyrene). Contributing to the formation of smog and near-ground ozone, exhaust gases also pose a significant environmental problem. Their composition depends on the fuel type, type and condition of the combustion system, filters, catalysts, etc.[2]

The need to determine the emissions of the running vehicles in real circumstances led to the development of Real Driving Emissions (RDE) tests, which have been mandatory for new vehicles since 2017 within the Euro 6 standard, as stipulated by Commission Regulation (EU) No 2016/427[3].

Euro 6 defines the RDE test conditions and data analysis methods, including the major factors such as the effect of driving, ambient temperature, altitude and altitude difference. The European Commission (EC) has set (first in 1992) stringent emission limits, and certification tests that must be met by all new vehicles have been introduced[4].

Both current and past emission level measurements within certification procedures are made on a chassis dynamometer in controlled laboratory conditions as prescribed in EU documents[5,6]. The standard driving cycles – the New European Driving Cycle (NEDC) and, currently, the Worldwide harmonized Light vehicle Test Cycles (WLTC), have been criticised as not properly representing driving in real-life situations[7]. The differences between real driving cycles and the NEDC regarding fuel consumption and NO_x production lie within the ranges of 12% to 30% and 32% to 628%, respectively[5]. This led to a test procedure aiming to ascertain the real driving emissions for the EURO 6 standard defining boundary conditions for roads and specific data analysis methods[8].

For example, Faria et al.[9] presented a data analysis method for the use of the cold start and driving on a road. Some of the results presented show that the consumption is 110% higher in the cold start mode than in the hot start mode and emissions can be as much as 910% higher. As to the altitude and road gradient. Gallus et al.[10] analysed their effects on the CO_2 and NO_x emissions. By testing two LDVs the authors concluded that the emissions increase in all driving categories, reaching a maximum increase within the ranges of 66% to 81% for CO_2 and from 94% to 115% for NO_x. Rapone and Andre[11] studied the effect of the traffic conditions by measuring the acceleration and NO_x emissions. Accelerations and NO_x emissions are most pronounced in the heavy urban setting, where the emissions NO_x are three times as high as in the country setting where cars run at a steady speed. Gallus et al.[12] examined the effect of the driving style on the emissions. Three drivers who practised 3 different driving styles in 2 vehicles participated in the experiment. During normal to sharp driving, CO_2 emissions increase by 20% to 40%, NO_x emissions, by 50% to 255% depending on both the driver and the vehicle.

The transport sector contributes nearly one-quarter to the total European greenhouse gas (GHG) emissions, road transport being the predominant contributor[13]. Road transport is also the main source of air pollutants, oxides of nitrogen (NO_X) in particular[14]. So, traffic planning is an important step because drivers will presumably select a route that will minimise the travel time and/or the travel costs (including the toll where present)[15]. However, minimisation of the driver's own travel costs can bring an increase in the costs of the entire system[16]. Studies demonstrate that drivers' environmentally friendly behaviour can adversely affect the emissions of the whole system, and selection of a route to reduce the production of CO_2 can increase the quantities of other pollutants. Such results suggest that an approach taking into account multiple factors should be applied[17].

The aim of this paper is to verify the dependence of CO, CO_2 and NO_x emission concentrations on vehicle driving dynamics and route profile under real conditions of drive with petrol-engine vehicle. Test route was selected based on the results of questionnaire survey, which the respondents use most often to commute to work.

Methods

A Škoda Citigo with a three-cylinder petrol engine by Škoda Auto (Figure 1) was used for this experiment.

Figure 1: Škoda CitiGo

The technical parameters of the vehicle are summarised in Table 1. Operational data from the engine control unit were recorded via an OBD interface (engine speed, vehicle speed) and, in addition, the VAG – COM diagnostics system was used. The measurement of the current position (GPS coordinates) and instantaneous speed was conducted by means of Garmin GPS 18x USB with a frequency of 1 Hz.

Table 1: Technical parameters of Škoda CitiGo

	Škoda CitiGo
	ENGINE
Engine type	3-cylinder, spark ignition, atmospheric
Max. power	55 kW at 5 000 rpm
Max. torque	95 Nm at 3 000 - 4 300 rpm
Fuel system	Multi - point gasoline injection
	CAR BODY
Service weight	929 kg
Manufacture year	2016
	DRIVE PERFORMANCE
Max. speed	160 km h^{-1}
Acceleration 0 - 100 km h^{-1}	13,2 s
Fuel consumption	4,7 l 100 km^{-1}
Tank range	750 km

To measure Škoda CitiGo emissions, use was made of a PEMS VMK mobile on-board emission analyser, which employs the non-dispersion infrared (NDIR) method for detecting CO and CO_2 emissions and an electrochemical cell for detecting O_2 and NO_X emissions. The data were recorded with a frequency of 1 Hz onto a memory card. The technical data are summarised in Table 2.

Table 2: Technical parameters of mobile emission analyser[18]

Measured values	**Measurement range**	**Resolution**	**Accuracy**
CO	0…10 % Vol.	0,001 % Vol.	0…0,67%:0,02% absolute, 0,67%...10%:3% of measured value
CO_2	0…16% Vol.	0,01 % Vol.	0…10%:0,3% absolute, 10…16%:3% m.v.
HC	0…20 000 ppm	1 ppm	10 ppm or 5% m.v.
NO_X	0…5 000 ppm	1 ppm	0…1 000 ppm: 25 ppm, 1 000…4 000 ppm: 4% m.v.
O_2	0…22% Vol.	0,1% Vol.	0…3%:0,1%, 3…21%:3%

The experimental drives were made during working days in the period of morning and afternoon rush hours from 19 to 21 September 2017. The route was covered five times. The driver maintained a careful driving style affected by the traffic situation. The outdoor temperature was around 12°C, with no wind, the skies were partly cloudy and the roads were dry. The indoor temperature in the vehicle was set at 20°C, and no electric device was used. Table 3 gives a brief description of the route in terms of the time and length.

Table 3: Characteristics of the route measured

Total route length (km)	80,77
Total travel time (s)	7 239 ± 278
Avg. speed (km h^{-1})	44± 3
Elevation difference (m)	442
HORIZONTAL SECTIONS	
Section length (km)	6,58
UPHILL SECTIONS	
Section length (km)	37,62
Ascent (m)	1,953
Avg. gradient (%)	5,19
DOWNHILL SECTIONS	
Section length (km)	36,57
Descent (m)	1,943
Avg. gradient (%)	5,31

The measurement was conducted in an area with moderately high elevation range, in the hilly terrain near the municipality of Ústí nad Labem (Figure 2). An extensive questionnaire survey was also conducted in the area. A test route, which the respondents use most often to commute to work, was selected based on the results.

Figure 2: Map of the area - Ústí nad Labem

The elevation profile of the test route is shown in Figure 3.

Figure 3: Elevation profile of the area under test

Result and discussion

The measured data contained 11,791 second-by-second records of current vehicle driving parameters. The focus was put on driving dynamics, gradient and CO, CO_2 and NO_x emissions. The analysis aimed to verify the dependence of CO, CO_2 and NO_x concentrations on the driving dynamics and route profile. Similar approaches are used for the development of a new method that is related to the dynamics of the certification driving cycles and dynamics of the test vehicles on the road, with the objective to evaluate the fuel consumption and real driving emission tests in a manner comparable to the certification driving cycles, as recommended by Varella et al.[25]. The data set and variables were prepared in the following manner. Records made when the vehicle stood still, i.e. zero-speed records, were excluded from the data. Furthermore, some problematic records made when the vehicle was moving at slow speeds up to 1 km/h, but it was not meaningful to take such records into account considering the accuracy of measurement of GPS coordinates and other parameters, were also excluded from the data.

8,630 records remained in the data set after the abovementioned records had been excluded. These records were divided into continuous sections with typical duration of 100 records. In several cases, the number of records was different when the sections were interrupted due to the data exclusion. Overall, the route was divided into 91 sections. Average CO, CO_2 and NOx emissions as well as average percentage gradient were calculated and the driving dynamics was characterised for each of these sections.

The average CO and CO_2 emission concentrations for a given section were calculated as the average of all records. Individual records showed, for each second, CO and CO_2 emissions in percent, with the resultant value characterising the CO and CO_2 emissions for a given section also being shown in percent. The range of average values of CO and CO_2 emissions within the 91 sections is displayed in Table 4.

Table 4: The average CO, CO_2 emissions

The average CO emissions (%)	The average CO_2 emissions (%)
Median = 0,0214	**Median** = 12,8153
25%-75% = (0,0136,0,0389)	**25%-75%** = (10,7522,13,8285)
Non - Outlier Range = (0,0007,0,073)	**Non - Outlier Range** = (6,222,14,5111)

The median value of the average CO emissions within the 91 sections of the route was 0.021%. The middle 50% of the values of CO emissions ranged between 0.014% and 0.039%. The non-outliers ranged from 0.0007% to 0.073%. The average emissions of several sections were evaluated as outliers or extreme values, from 0.073% to 0.5%.

The median value of average CO_2 emissions within the 91 sections of the route was 12.8%. The middle 50% of CO_2 emission concentrations values ranged between 10.8% and 13.8%. The non-outliers ranged from 6.2% to 14.5%. The average emissions of several sections were evaluated as outliers or extreme values, these included emissions lower than 6.2%, two values amounted nearly to zero. The same extreme levels were attained[19], where the emissions were governed by the road profile as well as by the driving style[20].

The average NO_x emissions for a given section were calculated as the average of all the records. Individual records showed, second by second, NO_x emissions in ppm, with the resultant value characterising the NO_x emissions for a given section also being shown in ppm. The distribution of the values of average NO_x emissions within the 91 sections was displayed by table 5.

Table 5: The average NO_x emissions

The average NO_x emissions (ppm)
Median = 30,92
25%-75% = (24,55,38,24)
Non - Outlier Range = (10,7568,54,13)

The median value of the average NO_x emissions within the 91 sections of the route was 30.92 ppm. The middle 50% of the values of NO_x emissions ranged between 24.6 ppm and 38.2 ppm. The non-outliers ranged from 10.8 ppm to 54.1 ppm. The average emissions of several sections were evaluated as outliers or extreme values, greater than 54.13 ppm. Overall, the results indicate that the NO_x emissions are low compared to the EU requirements for road traffic[21].

The average gradient for a given section was calculated as the ratio of the elevation gain and the distance covered in metres. The result was given in per cent. The descent was not included.

A change in instantaneous speed was calculated for each consecutive pair of records with respect to a given section. All the positive values within a given section, i.e. where acceleration occurred, were used for calculating the average relative to the total number of records of the given record. Specifically, if a section included 100 records, 98 changes in instantaneous speed were calculated, and a certain number of them was positive. The positive changes were added up and divided by 99. The resultant variable characterises the driving dynamics. The higher this number was, greater and more frequent acceleration occurred in the section concerned. The variable is reported in kilometres per hour.

The distribution of the values of the average *ascent and acceleration* within the 91 sections is listed in Table 6.

Table 6: The average ascent and acceleration

The average ascent (%)	**The average acceleration (km/h)**
Median = 0,9227	**Median** = 0,6768
25%-75% = (0,5671,1,8919)	**25%-75%** = (0,3778,0,9374)
Non - Outlier Range = (0,3,727)	**Non - Outlier Range** = (0,1374,1,6455)

The median value of the average gradient within the 91 sections of the route was 0.92%. The middle 50% of the values of the average gradient ranged between 0.56% and 1.89%. The non-outliers ranged between 0% (i.e. sections with no gradient) and 3.7%. The average gradients of several sections were evaluated as outliers, greater than 3.7%. The maximum gradient in one of the sections was 9.1%.

The median value of the average acceleration within the 91 sections of the route was 0.68 km/hs. The middle 50% of the values of the average acceleration ranged between 0.38 km/hs and 0.94 km/hs. The range from the minimum to the maximum was between 0.14 km/hs and 1.65 km/hs.

When evaluating the variability of the values of the individual variables (CO, CO_2 and NO_x emissions, gradient and driving dynamics), it is possible to state that the data prepared encompassed diverse sections with sufficiently variable values of driving dynamics and gradient, whose effect on the emissions was further investigated using statistical methods. As Varella et al.[22] pointed out, reproducibility of the tests can pose a problem. In fact, the dynamic and environmental factors (such as the ambient conditions, route, etc.) are unique for the specific geographic location, which can be representative of one site.

To prevent the results from being distorted owing to extreme and outlying values, the data were converted to ranks (rank 1 was assigned to the lowest values and rank 91 to the highest) and tested using an independence test based on Spearman's rank correlation coefficient. Statistical hypotheses formulated for individual variables were tested at a significance level of 0.05. The TIBCO STATISTICA 13 program was employed for calculating the statistical testing, and Microsoft Excel was used for data preparation. Table 7 summarizes the resulting operating parameter values of tested vehicle.

Table 7: Consumption and production of emissions

Vehicle	Fuel consumption (l 100 km^{-1})	CO_2 (g km^{-1})	CO (mg km^{-1})	NO_X (mg km^{-1})
Škoda CitiGo	4,61±0,22 l	108±6	816±84	24,11±0,31

Production of CO emissions

H: There is rank dependence between the average CO emission concentrations and the average increase in instantaneous speed.

The p-value of the independence test based on Spearman's correlation coefficient amounted to 0.004, i.e. lower than the selected significance level of 0.05. The hypothesis was not rejected. At the significance level of 0.05, dependence between the average CO emissions and the average increase in instantaneous speed was proven. Considering a positive value of the correlation coefficient of 0.3, it is possible to interpret that there is a slight tendency towards a higher CO emission concentration in sections with a higher value of the average increase in instantaneous speed. The effect of the driver on the CO production can be disregarded: in fact, the emission concentrations normally lie well below the standard limits[23].

H: There is rank dependence between the average CO emission concentrations and the average gradient.

The p-value of the independence test based on Spearman's correlation coefficient amounted to 0.001, i.e. lower than the selected significance level of 0.05. The hypothesis was not rejected. At the significance level of 0.05, dependence between the average CO emissions and the average gradient was proven. Considering a positive value of the correlation coefficient of 0.35, it is possible to interpret that there is a slight tendency towards higher CO emission concentrations in sections with a higher value of the average gradient.

Production of CO_2 emissions

H: There is rank dependence between the average CO_2 emission concentrations and the average increase in instantaneous speed.

The p-value of the independence test based on Spearman's correlation coefficient amounted to 0.024, i.e. lower than the selected significance level of 0.05. The hypothesis was not rejected. At the significance level of 0.05, dependence between the average CO_2 emission concentrations and the average increase in instantaneous speed was proven. Considering a negative value of the correlation coefficient of -0.24, it is possible to interpret that there is a slight tendency towards a lower CO_2 emission concentration in sections with a higher value of the average increase in instantaneous speed, which depends on the driving style, where excessive speed and aggressive acceleration play a major role[24].

H: There is rank dependence between the average CO_2 emission concentrations and the average gradient

The p-value of the independence test based on Spearman's correlation coefficient amounted to 0.000, i.e. lower than the selected significance level of 0.05. The hypothesis was not rejected. At the significance level of 0.05, dependence between the average CO_2 emission concentrations and the average gradient was proven. Considering a positive value of the correlation coefficient of 0.51, it is possible to interpret that there is a slight tendency towards a higher CO_2 emission concentration in sections with a higher value of the average gradient.

Production of NOx emissions

H: There is rank dependence between the average NO_x emission concentrations and the average increase in instantaneous speed.

The p-value of the independence test based on Spearman's correlation coefficient amounted to 0.793, i.e. higher than the selected significance level of 0.05. The hypothesis was rejected. At the significance level of 0.05, dependence between the average NO_x emissions and the average increase in instantaneous speed was not proven.

H: There is rank dependence between the average NO_x emission concentrations and the average gradient.

The p-value of the independence test based on Spearman's correlation coefficient amounted to 0.507, i.e. higher than the selected significance level of 0.05. The hypothesis was rejected. At the significance level of 0.05, dependence between the average NO_x emissions and the average gradient was not proven.

The NO_x concentrations observed during the testing of passenger cars with a petrol-fuelled engine in dependence on the route were negligible. Next research will target passenger vehicles with CI engines, where a very wide range of NO_x emissions was observed also for Euro 6 vehicles[25]. Emissions can also be reduced by using new-generation biofuels[26].

Conclusion

The experiments demonstrated that with respect to the production of harmful emissions, there was dependence between the average CO emission concentrations and the average increase in instantaneous speed. The results can also be interpreted that there was a slight tendency towards higher CO emission concentrations in sections with a higher value of the average increase in instantaneous speed, and a slight tendency towards a higher CO emission concentration in sections with a higher value of the average gradient. There was a slight tendency towards lower CO_2 emission concentrations in sections with a higher value of the average increase in instantaneous speed, too. Also, dependence between the average CO_2 emission concentration and the average gradient was proven, which means there is a tendency towards a higher CO_2 emission concentration in sections with a higher value of the average gradient. By contrast, dependence between the average NO_x emissions and the average increase in instantaneous speed or dependence between the average NO_x emissions and the average gradient were not proved. Based on these results, the drivers could decide how they will affect the production of emissions based on their choice of route taking into consideration the course of gradient and driving style.

Acknowledgement

The paper was supported by ULS Prague, Faculty of engineering - IGA 2017: 31150/1312/3122 - Monitoring the quality of life of rural microregions with regard to energy consumption

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Ověření závislosti koncentrace CO, CO_2 a NO_x na dynamice jízdy vozidla a profilu trasy

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Abstrakt

Cílem tohoto článku je ověření závislosti koncentrace CO, CO_2 a NO_x na dynamice jízdy vozidla a profilu trasy v reálném provozu vozidla Škoda Citigo s benzínovým motorem. Vozidlo bylo testováno na silnicích v kopcovité krajině v České republice. Prováděné experimenty byly zaměřeny na záznam a analýzu spotřeby energie (paliva) a následné produkce emisí (CO, CO_2, NO_X). Výsledky prokázaly závislost mezi průměrnými emisemi CO a průměrným zvýšením okamžité rychlosti, mírnou tendencí k nižším emisím CO_2. Rovněž byla prokázána závislost mezi průměrnými emisemi CO_2 a průměrným převýšením, což znamená, že v úsecích s vyšší hodnotou průměrného převýšení existuje tendence k vyšší koncentraci emisí CO_2. Naproti tomu nebyla prokázána závislost mezi průměrnými emisemi NO_x a průměrným zvýšením okamžité rychlosti nebo průměrným převýšením.

Klíčová slova: *skutečné emise v reálném provozu, koncentrace CO, CO_2 a NO_x*