Research Article

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Consumption of gasoline in vehicles equipped with an LPG retrofit system in real driving conditions

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Abstract: Vehicles equipped with an LPG retrofit system are always started on gasoline. Therefore, part of the vehicle's annual mileage will be run on gasoline. This article describes the results of tests conducted on a vehicle equipped with a propane-butane gas retrofit system (LPG system) regarding gasoline consumption in the LPG mode depending on the temperature at which the engine is started. The research was carried out on a passenger car from the C segment with an engine with indirect gasoline injection system. Based on these studies, the analysis of various vehicle use scenarios and the related gasoline consumption in relation to LPG consumption was made.

Keywords: pollutant emissions, LPG retrofit system, exhaust emissions, fuel consumption, emission inventory

1 Introduction

Vehicles equipped with LPG systems are always started on gasoline. Two installation operation modes can be distinguished in those vehicles: gasoline mode and LPG mode. In the case of the active operating mode with LPG fueling, the operating time in which the engine is supplied with gas immediately after starting depends on a number of parameters:

- the temperature of the engine coolant at the time of engine's start-up,
- the speed of heating up the engine and LPG reducer,
- or the settings of the LPG controller regarding the parameters of switching from gasoline to LPG.

Depending on the aforementioned parameters and the length of a single trip and its profile, the consumption of

gasoline by these vehicles will change. The operating time during which the engine is fueled by gasoline will depend primarily on the temperature of the engine coolant that heats the LPG reducer. The lower the ambient temperature and the lower the engine coolant temperature are, the longer the engine will run on gasoline. Therefore, the share of gasoline in the total fuel consumption (gasoline and LPG in total) will increase inversely proportional to the length of a single trip. Hence the conclusion that the part of the vehicle's annual mileage will be run on gasoline.

This is important, for example, when estimating emissions from road transport, especially when we do not have data on fuel consumption by individual vehicle categories. Such data is required, for example, by the Tier 1 method [1]. According to this method, the pollutant emission “i” is the product of the fuel consumption of the vehicle category “j” using the fuel “m” and the pollutant emission factor “i” of the vehicle category “j” using the fuel “m” expressed in grams per kilogram of fuel used. Such statistics are not published, therefore the fuel consumption of different modes of transport needs to be estimated. Different methods are used for this purpose depending on the available data. One of them may be the so-called “Bottom up” method [2]. In this method, the sum of estimated values is compared with the data on the total consumption of a given type of fuel by means of road transport in the country. In the event of differences, the data adopted for the calculations are corrected. The first to be corrected are those data for which the uncertainty is the highest, i.e. vehicle mileage (number of vehicle kilometers traveled). The procedure should be repeated until the sum of estimated consumption values is fully consistent with the data on total consumption.

Therefore if we do not take into account the mileages made with gasoline fueling in the estimation of emissions for vehicles equipped with an LPG system, then we incorrectly estimate the emissions from these vehicles. Due to the fact that Poland is one of the countries with one of the largest number of LPG-powered vehicles (Figure 1) and they account for approx. 20% of all vehicles equipped with spark ignition engines and approx. 13% of all registered vehicles in Poland (Figure 2), therefore this error may have a sig-

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nificant impact on the estimation of emissions from these vehicles.

Figure 1: Countries with the largest number of LPG-powered vehicles in 2018 (mln. units.) [3].

Figure 2: The share of vehicles powered by different fuels in the total number of vehicles in Poland in 2017 [4].

2 Methodology

The tests were carried out on a passenger car belonging to the C segment, equipped with a spark ignition engine with indirect gasoline injection system and a capacity of 1.6 dm³. The vehicle was approved to meet the Euro 4 emission requirements. The tested vehicle was equipped with LPG system with sequential injection of LPG in the gas phase into the intake manifold. The exhaust tailpipe emissions were tested on a chassis dynamometer located in a low temperature chamber. The chassis dynamometer was ad-

justed so as to reproduce the total road load measured for the tested vehicle. Measurements were made on the WLTC driving cycle (World harmonized Light-duty Test Cycle). Before the measurement, the vehicle was conditioned for at least 12 hours in one of three temperatures: +23°C, 0°C and -10°C. During the LPG emission tests, the vehicle engine was started on gasoline. After reaching the minimum parameters set in the LPG controller, the LPG controller switched the fuel supply to LPG fuel. During driving the WLTC cycle, instantaneous values of carbon dioxide (CO₂), carbon monoxide (CO) and total hydrocarbons (THC) in the diluted exhaust gas were recorded. A proportional samples of the diluted exhaust gas was collected in special bags, two bags for each of four phases of the WLTC cycle. The measuring equipment met the requirements set out in the Regulations 83 [5]. Accuracy of the main measuring equipment are given in Table 1. The voltage on the electrovalve installed upstream of the LPG inlet to the LPG pressure regulator was also recorded. The time after which the engine started to be supplied with LPG was considered the time elapsed from starting the engine until the voltage appeared on the contacts of this electrovalve, adding the time of switching the LPG system from gasoline to LPG. This time was set in the LPG controller and amounted to 3.1 seconds (the sum of the switching time and the pressure regulator filling time).

Table 1: Accuracy of the measuring equipment

Measured parameter	Measuring equipment	Accuracy
Flow	Exhaust dilution system	±0.5%
Speed	Chassis dynamometer	±0.025%
Distance	Chassis dynamometer	±0.1%
Concentration	Analysers	±2%

On the basis of the engine operation time determined in this way while running on gasoline and the instantaneous values of the concentrations of the measured pollutants, the emission and fuel consumption with gasoline and LPG were calculated. For the calculation of total hydrocarbons (THC) emissions, the following fuel composition and density δ_{THC} were adopted (in accordance with section 6.6.2 of Annex 4a to UN Regulation 83, 07 series of amendments [5]):

- for gasoline (E5): $C_1H_{1.89}O_{0.016}$ and $\delta_{THC} = 0.631$ g/dm³;
- for LPG: $C_1H_{2.522}$ and $\delta_{THC} = 0.649$ g/dm³.

Fuel consumption was calculated according to the carbon balance method, specified in the UN Regulation No.

101, revision 3 (1), (2) [6].

$$FC_{LPG} = 0.1212 \quad (1)$$

$$\times (0.825 \times THC + 0.429 \times CO + 0.273 \times CO_2) / \rho_{LPG},$$

$$FC_{BS} = 0.118 \quad (2)$$

$$\times (0.848 \times THC + 0.429 \times CO + 0.273 \times CO_2) / \rho_{BS},$$

where:

FC – volumetric fuel consumption, [dm³/100 km]

THC , CO , CO_2 – emission of pollutants from the exhaust system – sum of hydrocarbons, carbon monoxide and carbon dioxide respectively [g/km],

ρ_{LPG} – density of LPG [kg/dm³],

ρ_{BS} – density of gasoline [kg/dm³].

Volumetric fuel consumption was calculated taking into account the measured fuel densities in temperature 15°C:

- for gasoline (E5): 0.737 kg/dm³,
- for LPG: 0.521 kg/dm³.

Pollutants emissions were calculated according to the method set out in the Annex XXI to the Regulation of Commission (UE) 2017/1151 [7].

The tests were carried out using the following fuels:

- liquefied petrol gas LPG, some properties of which are presented in the Table 2,
- commercial fuel E5 – unleaded gasoline with 5% ethanol addition.

Table 2: Selected basic properties of LPG fuel.

Parameter	Result
Density in temp. 15°C	520.6 kg/m ³
Relative vapour pressure in temp. 40°C	1207 kPa
Temperature at which the relative vapor pressure is not less than 150 kPa	–17°C

The fuels used in tests meets the requirements for fuels sold in winter time. Those requirements are specified in the Polish law – the Regulation of the Minister of Energy of April 14, 2016 on the quality requirements for liquefied gas (LPG), which is based on EN 589 [8] and the Regulation of the Minister of Economy of October 9, 2015 on the quality requirements for liquid fuels – based on EN 228 [9].

3 Test results

Several measurements of pollutant emissions and fuel consumption were performed in the WLTC test for each engine starting temperature (–10°C, 0°C, +23°C). Figure 3 shows the course of instantaneous values of carbon dioxide concentration and Figure 4 shows the signal controlling gasoline-LPG switching as a function of time for one of the measurements made at –10°C, while Figure 5 shows the cumulative value of mass of the emitted carbon dioxide. The value of the control signal equal to 0 means that the engine was fueled with gasoline, and control signal equal to 1 means that the engine was fueled with LPG. The blue

Figure 3: The course of carbon dioxide concentration as a function of the WLTC cycle time for the temperature of –10°C.

Figure 4: The control signal for switching the power supply to LPG as a function of the WLTC cycle time for the temperature of –10°C.

Figure 5: Cumulative value of CO₂ emission in WLTC cycle for temperature 10°C.

color shows the values corresponding to the engine fueling phase with gasoline, and the red color – to the engine fueling phase with LPG.

Table 3 shows the average values of the time of switching from gasoline to LPG, the share of gasoline consumption in the total fuel consumption and the distance traveled with gasoline fueling for various initial engine temperatures. Mass consumption of gasoline and LPG was calculated on the basis of the sum of the instantaneous mass emissions of carbon dioxide, carbon monoxide and the sum of hydrocarbons expressed in g/s.

Table 3: Average values of the time of switching the fueling from gasoline to LPG, the share of gasoline consumption in the total fuel consumption and the distance traveled when running on gasoline in the WLTC cycle for various initial engine temperatures.

Parameter	Engine initial temperature		
	–10°C	0°C	+23°C
Time [s]	215±3%	170±3%	74±3%
Share [%]	7.63±0.03	5.71±0.05	2.3±0.3
Distance [m]	1100±40	790±20	396±10

The greatest influence on the accuracy of the determination the share of gasoline consumption in the total fuel consumption and the distance traveled when running on gasoline has the uncertainty of determining the working time on gasoline. The following factors has influence on the value of this uncertainty:

- uncertainty of time measurement,
- ambient temperature at engine start-up,
- the way in which the driver recreates the driving cycle, which may affect the time when all the conditions for switching from gasoline to LPG occur,
- speed of engine and LPG pressure regulator warm-up.

The uncertainty component related to the measurement of time is in this case negligible. It is difficult to estimate the other components separately. They were determined together on the basis of the standard deviation of the measurement result. For this purpose several exhaust emission tests were performed at each engine initial temperature. Based on the measured scatter of the measurement results the uncertainty of the time of switching the fueling from gasoline to LPG, the share of gasoline consumption in the total fuel consumption and the distance traveled when running on gasoline was calculated. They are given in Table 3 of the article.

4 Analysis of test results

The share of gasoline consumption in the total fuel consumption of vehicles equipped with an LPG system will depend not only on the ambient temperature at which the engine is started, but also on the length of a single trip. According to [1], it is assumed that for European countries the typical value of a single trip is 12.4 km, and this value ranges between 8 and 15 km. The distance traveled in the WLTC cycle, in which the measurements were made, is approx. 23 km, which is almost twice as long as the average length of a single trip in Europe. The WLTC cycle consists of 4 phases: Low, Medium, High and Extra-High. The first two phases reflect urban traffic, the High phase is driving on country roads and the Extra-High phase is driving on expressways and motorways. The distance covered in individual phases is: 3, 5, 7, 8 km respectively (values rounded to whole numbers).

Two scenarios are analyzed in this article. Both assume that the vehicle makes two trips (it is used for commuting to and from work), the engine is started at 7:30 a.m. and 4:00 p.m. These scenarios differ in the distance traveled: in the first one the length of a single trip is 8 km and the speed profile corresponds to the Low and Medium phases of the WLTC (scenario 1) and in the second one, the length of a single trip is 15 km and the speed profile corresponds to the Low, Medium and High phases of the WLTC (scenario 2).

In both cases, switching to LPG fueling takes place in the first phase of the WLTC cycle, and the distance traveled on the LPG fuel is reduced. Table 4 shows the share of gasoline mass consumption in the total fuel consumption, taking these mileages into account.

Table 4: Average values of the share of gasoline mass consumption [%] in total fuel consumption for various engine initial temperatures and different vehicle use scenarios

Scenario	Engine initial temperature		
	–10°C	0°C	+23°C
Scenario 1	20.9	16.2	7.7
Scenario 2	12.2	9.3	3.8

Figure 6 shows the change in the share of mass consumption of gasoline in the total fuel consumption for different engine initial temperatures and different vehicle use scenarios.

In order to estimate the annual mileage of a vehicle with an LPG system in which the vehicle is fueled with gasoline, the average monthly ambient temperature at the en-

Figure 6: Average values of the share of gasoline mass consumption [%] in total fuel consumption for various engine initial temperatures and different vehicle use scenarios.

Table 5: Average monthly ambient temperature at 7:30 a.m. and 4 p.m. and engine running time on gasoline.

Month	7:30 a.m.		4 p.m.	
	T [°C]	t_{gasoline} [s]	T [°C]	t_{gasoline} [s]
January	-2.6	183	-0.7	174
February	1.3	166	5.8	147
March	4.2	154	9.7	130
April	14.0	112	18.5	93
May	11.3	123	17.4	97
June	20.7	83	27.5	54
July	17.8	96	23.6	71
August	17.6	97	26.2	60
September	11.6	122	18.3	94
October	7.8	138	14.8	108
November	4.5	152	7.3	140
December	-2.6	183	-0.5	174

Figure 7: Engine operation time in the phase of its fueling with gasoline as a function of the engine's initial temperature.

Table 6: Daily and monthly mileage [km] obtained when fueling a vehicle equipped with an LPG system with gasoline.

Month	D_{daily} [m]	D_{monthly} [km]
January	1732	34.6
February	1391	27.8
March	1302	26.0
April	1206	24.1
May	1222	24.4
June	808	16.2
July	988	19.8
August	940	18.8
September	1211	24.2
October	1226	24.5
November	1286	25.7
December	1732	34.6

Figure 8: Gasoline mileage share in the total mileage of a vehicle equipped with an LPG system.

engine start-up was determined (Table 5). These temperatures were determined on the basis of data provided by Stacja Meteorologiczna Warszawa [10]. These are data from the weather station located on the border of Warsaw and Reguły.

Figure 7 presents a curve showing the change in engine operation time in the phase of its fueling with gasoline as a function of the engine's initial temperature. Based on the equation of this curve, the average working time with gasoline fueling was calculated for each month (Table 5). The distance traveled on gasoline was taken to be equal to the distance that would have been traveled on the WLTC cycle in time t_{gasoline} .

When estimating the monthly mileage, it was assumed that the vehicle is used only for commuting to the work, and the number of working days in each month is 20. Table 6 shows the daily and monthly mileage for gasoline fueling. Figure 8 shows the shares of the mileage when engine is fu-

eled with gasoline in the total mileage of a vehicle equipped with an LPG system. To calculate this mileage, a monthly total mileage was assumed – 314 km for scenario 1 and 600 km for scenario 2.

5 Conclusions

The engines of vehicles equipped with LPG installations are always started with gasoline [11]. The operating time in the gasoline fueling phase depends on the engine's initial temperature and the time needed for the LPG reducer to reach the gasoline-LPG switching temperature. For the tested vehicle, this time ranged from 74 s for a temperature of +23°C to 215 s for a temperature of –10°C, which corresponds to the distance traveled in the WLTC cycle from 400 to 1100 m. The average share of the mass consumption of gasoline in the total fuel consumption measured in the WLTC cycle is in the range of 2.3% ÷ 7.6%. Taking into account the average lengths of a single trip, which range from 8 to 15 km, these shares increase and fall within the ranges of 7.7% ÷ 20.9% and 3.8% ÷ 12.2% respectively.

The share of mileage with gasoline in the total mileage of a vehicle equipped with LPG system strongly depends on the length of a single trip. In two vehicle use scenarios considered in this article, these shares are in the range from 5.1% to 11% for scenario 1 and from 2.7% to 5.8% for scenario 2. Estimated values should be treated as maximum values, because these scenarios assume the use of the vehicle only for commuting to the work and do not take into account journeys longer than 15 km. Annual mileage is 3800 km for scenario 1 and 7200 km for scenario 2. It is estimated that the annual average mileage of a vehicle equipped with an LPG system in Poland is approximately 11000 km [12]. Higher mileage can be achieved with more rides per day or greater distance traveled on a single ride. Increasing both of these parameters leads to a decrease in both the share of gasoline consumption in the total fuel consumption as well as the share of gasoline mileage in the total mileage of the vehicle.

The influence of the driving profile or the efficiency of LPG reducer on the share of mileage with gasoline fueling in the total mileage of a vehicle equipped with an LPG retrofit system was not investigated in this article. Both of these factors affect the speed of the reducer heating and – indirectly – the time of work on gasoline. Research on the impact of these factors will be the subject of further work.

In order to increase the accuracy of the estimation of the above-mentioned shares, it is necessary to know at least the average values of the number of journeys during the day,

the length of a single ride, and the times between engine starts. However, such data is not available.

It is important to note that the article only considers the case when the vehicle is equipped with a spark ignition engine with indirect gasoline injection. For vehicle with direct gasoline injection, a different test methodology should be adopted, because in case of these vehicles, after switching to LPG fueling, gasoline injectors still works [13, 14]. This is due to the need to ensure cooling of the gasoline injectors. Such methodology will be developed and described in subsequent articles by the authors team.

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