Article citation info:
Wiśniowski P, Zimakowska-Laskowska M, Taubert S, Kozłowski E, Ślęzak M, Żbik K. Comparison of pollutant concentrations and engine operating parameters during cold start with petrol and LPG. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-216339

Piotr WIŚNIOWSKI
Magdalena ZIMAKOWSKA-LASKOWSKA
Sławomir TAUBERT
Edward KOZŁOWSKI
Marcin ŚLĘZAK
Ksawery ŻBIK

Combustion Engines
Polish Scientific Society of Combustion Engines

Comparison of pollutant concentrations and engine operating parameters during cold start with petrol and LPG

ARTICLE INFO

Received: 16 May 2025
Revised: 3 October 2025
Accepted: 2 January 2026
Available online: 5 March 2026

The cold start of an ICE generates conditions conducive to intensive pollutant emission and reduced thermal efficiency. This study compared the concentrations of selected exhaust components and engine operating parameters during the cold start phase of a dual-fuel vehicle powered by petrol and LPG. The tests were conducted on a chassis dynamometer under identical ambient and load conditions, utilizing a repeatable homologation test. The analysis included HC, CH_4, and NO_x concentrations, which were recorded simultaneously with the internal combustion engine's operating parameters: rotational speed, coolant temperature, throttle position, and load. The collected data enabled the development of mathematical models representing the relationships between the dynamics of the start process and pollutant concentrations. The results indicate significant differences in the start characteristics for individual fuels; in particular, LPG exhibits a distinct emission profile during the early phase of engine operation. Conclusions can serve as the basis for designing start control strategies in dual-fuel vehicles, considering environmental requirements and the further development of emission control systems.

Key words: *emission, petrol, cold start, LPG, engine operating parameters*

1. Introduction

The cold start of the combustion engine remains one of the key challenges for engineers seeking to reduce emissions of pollutants. In the initial phase of engine operation, the catalytic converter is not yet sufficiently heated, and the combustion process takes place in conditions that are not optimal, which results in a rapid increase in the emission of harmful exhaust components – including hydrocarbons (HC), methane (CH_4), carbon monoxide (CO) and nitrogen oxides (NO_x) [14, 15, 48].

The literature indicates that alternative fuels, such as LPG, may exhibit a more favorable emission profile during the cold start phase compared to gasoline – especially in terms of lower HC and CO emissions [4, 14, 43]. The combustion efficiency of LPG, along with its physicochemical properties, favors faster catalyst heating and stabilization of the combustion process [21, 33].

At the same time, an increasing number of studies indicate a significant influence of ambient and engine temperatures on emission levels during this phase of the driving cycle [2, 28, 45]. Low temperatures worsen fuel evaporation, delay reaching the ignition temperature, and catalyst activation, resulting in a significantly higher emission level than during steady-state engine operation [6, 51].

In light of the above, the aim of this work is to conduct a quantitative analysis of the effect of fuel type (petrol vs LPG) and engine operating temperature on the emission of selected pollutants during the cold start phase. The tests were conducted on a chassis dynamometer using the repeatable WLTC test in fixed environmental conditions. The dependence of pollutant concentrations on key operating parameters, such as engine load, coolant temperature and crankshaft rotational speed, was also assessed. The conducted analyses enable the identification of differences in exhaust emission characteristics depending on the fuel type, which may have significant implications for the further development of start-up control strategies and emission control systems in dual-fuel vehicles.

2. Literature review

The cold start of an internal combustion engine refers to starting the drive unit, whose temperature–including that of the coolant and exhaust system components – is significantly lower than the operating temperature. This phenomenon occurs most frequently after a prolonged standstill of the vehicle, especially in low ambient temperature conditions, and is associated with several unfavorable effects, including deterioration of the ignition process, incomplete fuel combustion, and delayed activation of exhaust gas aftertreatment systems [28, 51]. During the cold start phase, a sharp increase in HC and CO emissions is observed, resulting from insufficient catalyst heating and instability in the combustion process. According to [28], the definition of cold start should refer not only to the moment of starting the engine, but also to the time needed to achieve full efficiency of the emission reduction system. Specific limit values are provided in the technical and regulatory literature for recognizing that the engine has completed the cold start phase. According to research and engineering practices, the end of the cold start phase is considered to be the moment when the coolant temperature reaches 70–80°C, and the catalyst temperature exceeds the so-called light-off threshold, usually in the range of 250–300°C. In urban driving conditions, these values are reached on average after 180–500 seconds [29, 52]. In the WLTC procedure, the duration of the cold start phase is estimated at about

140–300 s, while in the FTP-75 procedure, it is assumed that the cold start lasts until the catalyst temperature reaches 250°C. However, the length of this phase can be significantly extended at negative ambient temperatures.

Studies show that in this phase of the driving cycle, the vehicle can emit up to 60% of the total HC and CO emissions [3, 48]. This phenomenon concerns not only older vehicles, but also those meeting Euro 6 standards [15]. The increase in emissions during cold start conditions is strongly correlated with engine operating parameters, such as coolant temperature and catalyst activation time [8, 16, 32, 54]. Emissions also depend on the injection and ignition control strategy [11, 19], as well as the fuel atomization properties at low temperatures [30]. Furthermore, particulate matter (PM) emissions from gas direct injection (GDI) engines are significantly higher than those from port fuel injection (PFI) engines [40].

LPG, as an alternative fuel, exhibits a more favorable emission profile during the cold start phase. Comparative studies have shown that LPG-fueled engines emit less HC, CO, and PM compared to gasoline units [21, 26, 36, 44]. These effects are also supported by recent studies involving innovative LPG hardware/software configurations in low-emission vehicle prototypes [35]. The effects result from improved LPG combustion properties and a more homogeneous fuel-air mixture [42]. The reduction of particulate matter emissions in LPG vehicles can reach up to 99% compared to gasoline, especially in urban conditions and at low ambient temperatures [22, 24, 37]. The literature also highlights the lower sensitivity of LPG to temperature changes, which improves its operational predictability [2, 20, 33].

Ambient temperature plays a key role in shaping the level of pollutant emissions. At temperatures below 0°C, HC and CO emissions can increase by as much as tenfold [3, 5, 16, 34]. Low temperatures extend the catalyst warm-up time and reduce the efficiency of exhaust gas treatment systems [48, 53]. This phenomenon also applies to fugitive emissions and organic gases [53]. LPG maintains a more stable emission profile at low temperatures, which is related to its physicochemical properties and injection strategy [31]. Modern combustion management strategies can effectively reduce the negative impact of temperature on emissions, especially through precise control of ignition and mixture composition [30, 45]. Modeling studies and meta-analyses suggest a complex, nonlinear relationship between temperature and emissions [27–29].

Several technical and operational approaches have been described in the literature to reduce cold start emissions. [9, 10]suggested the use of phase change materials (PCM) for heating the evaporator and pressure regulator in LPG systems, which allows for shortening the transition time to gaseous fuel and reducing CO and HC emissions. Kwak [26] and Gong [8] demonstrated that ignition delay and lean mixtures improve combustion stability and reduce catalyst activation time. Gong et al. [8] suggest that changing the injection strategy and fuel ratio in dual-fuel (methanol/LPG) systems can significantly improve cold start emissions. Modern approaches include the use of split-injection strategies and first-cycle ignition control [11, 19]. The use of electric catalyst heaters, as demonstrated by Gao et al. [7], enables faster attainment of the "light-off" temperature, which significantly reduces pollutant emissions. Hao et al. [12] described a start-up strategy for dual-fuel engines (gasoline/hydrogen), indicating the possibility of reducing HC and CO emissions using special ignition maps. In turn, Teymoori et al. [46] proposed trapping HC emissions using selective sorbents. An alternative direction is the development of filter materials and catalytic coatings dedicated to the cold start phase [6, 53] provided evidence that appropriate fiscal policies, such as carbon pricing, can effectively reduce the number of cold starts in urban environments.

Unburned hydrocarbons (HC) and methane (CH_4) are key pollutant components emitted during the cold start phase. Their presence is mainly due to the low temperature of the combustion chamber and insufficient catalyst activity in the initial seconds of engine operation [14, 40]. CH_4, as a persistent greenhouse gas, has high global warming and tropospheric ozone potential, which makes it particularly problematic in the context of modern emission standards [1, 54]. Studies have shown that gasoline direct injection (GDI) engines emit significantly higher concentrations of CH_4 and HC compared to indirect injection engines, especially in low ambient temperature conditions [31, 40, 53]. In the case of LPG fuelling, methane emissions are usually lower, but still significant – especially in converted engines, where the optimization of combustion parameters is not adapted to the fuel characteristics [20, 41]. Various methods for reducing HC and CH_4 emissions have been suggested in the literature, including the use of adsorption coatings in catalysts [54], trapping HC molecules in porous materials [41, 46] and the adaptation of a multiphase injection strategy that improves mixture homogeneity [8].

2. Methodology

2.1. Vehicle specification and test procedure

The tests were performed using a Ford Focus vehicle with a spark-ignition engine, displacing 1798 cm³ in the Flexifuel version. The vehicle was fitted with an LPG injection system designed for vehicles with indirect fuel injection. A chassis dynamometer was used during the tests to simulate the resistance to motion of the vehicle that covered the WLTC cycle route (Fig. 1). The course of the full WLTC cycle and the engine temperature during the test are shown in the figures below (Fig. 2).

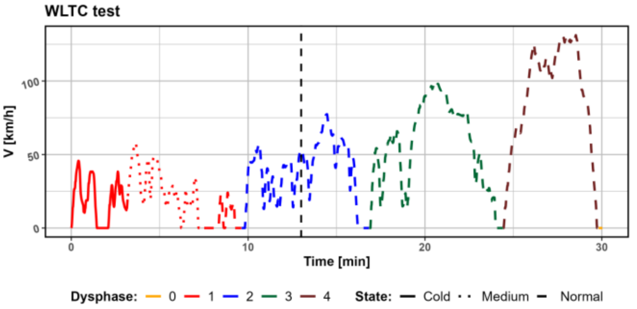

Fig. 1. The complete WLTC cycle on the chassis dynamometer

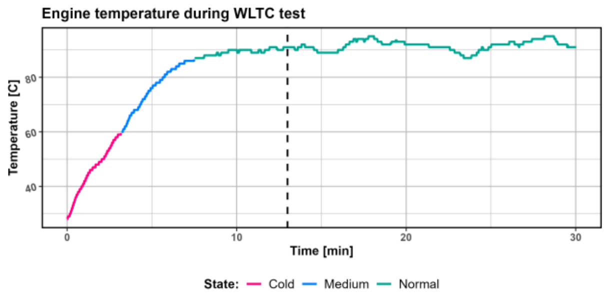

Fig. 2. Engine temperature changes during the WLTC cycle throughout the emissions test

The corresponding distance covered by the vehicle during the WLTC cycle is illustrated in Fig. 3. This plot also shows the division of the test into Cold, Medium, and Normal states, depending on the engine coolant temperature.

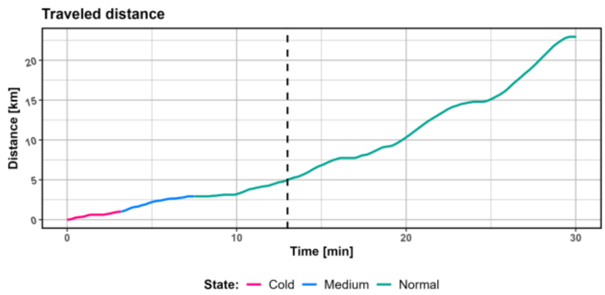

Fig. 3. Distance covered by the vehicle during the WLTC cycle according to the testing procedure on the chassis dynamometer

Engine start at 25°C. The following states were assumed with respect to the engine temperature (T):

– $T < 60°C$ – Cold
– $60°C \leq T < 87°C$ – Medium
– $T \geq 87°C$ – Normal.

In order to compare the results (similar number of concentration readings), the initial 13 min of the test was used for analysis.

2.2. Research tools

The nonparametric Kruskal-Wallis test was used to compare pollution by condition, while the Kolmogorov-Smirnov test was used to compare pollution by fuel type for each condition of the combustion engine. To verify the effect of temperature on the amount of pollution, an analysis of the structural parameters of the nonlinear model describing the effect of engine load, temperature and engine speed on the amount of pollution was performed A similar methodology, combining chassis dynamometer testing with computational modelling, was proposed by Zimakowska-Laskowska et al. [55], confirming the validity of hybrid approaches in vehicle emission research.

2.2.1. Kruskal-Wallis rank sum test

The Kruskal-Wallis test [13, 18] was used to analyze the existence of differences due to the engine operating state depending on the temperature. The Kruskal-Wallis test is used to detect differences between groups when the assumption of normality of distribution in groups is not met. In the considered case, the engine operating state with respect to temperature was selected as the differentiating variable. Let $\{y_i^k\}_{1\leq i\leq n_k}$ denote a sequence representing the concentrations of pollutant readings, where $k \in \{\text{Cold, Medium, Normal}\}$ denotes the belonging to the state according to engine temperature.

To verify the effect of engine condition on pollutant concentrations, $\alpha \in (0,1)$ we create a null hypothesis at the significance level:

H_0: $F_{Cold}(x) = F_{Medium}(x) = F_{Normal}(x)$ for $x > 0$ (distributions of pollutant concentrations are equal and independent of engine operating temperature)

and the alternative hypothesis

H_1: $\exists i, j \in \{\text{Cold,Medium,Normal}\}$ $F_i(x) \neq F_j(x)$(engine operating temperature/condition has a significant influence on distribution of pollutant concentration).

Ranking was performed for the entire sample $\{y_i^k\}_{1\leq i\leq n_k}$, $k \in \{\text{Cold,Medium,Normal}\}$. Let R_{ki} denote the rank in the sample of ithe -th element from kthe -th group.

The test statistic is given by:

$$T = \frac{12}{n(n+1)} \sum_{k\in\{\text{Cold,Medium,Normal}\}} \left(\overline{R}_k - \frac{n+1}{2}\right)^2 n_k \qquad (1)$$

where $n = n_{Cold} + n_{Medium} + n_{Normal}$ and $\overline{R}_k = \frac{1}{n_k}\sum_{i=1}^{n_k} R_{ki}$

The test statistic (1) is a measure of the departure of the sample rank means from the mean value of all ranks, which is $(n + 1)/2$. The statistic T has a distribution $\chi^2$with 2 degrees of freedom.

2.2.2. Kolmogorov-Smirnov test

For each engine operating state, the pollutants generated by the type of fuel supplied were also compared. The Kolmogorov-Smirnov test was used to compare (verify the differences) the distributions of two features Xand Y(pollutant distributions by fuel type). For each feature (group), based on the observation of the realization $\{x_1, x_2, \ldots, x_{n_1}\}$, $\{y_1, y_2, \ldots, y_{n_2}\}$ we create empirical distributions

$$F_X(t) = \frac{\#\{x_i : x_i \leq t, \quad 1 \leq i \leq n_1\}}{n},$$
$$F_Y(t) = \frac{\#\{y_i : y_i \leq t, \quad 1 \leq i \leq n_2\}}{n}$$

where #denotes the power of the set. For the Kolmogorov-Smirnov test at the significance level $\alpha \in (0,1)$ we create the null hypothesis:

H_0:$\forall t \in (-\infty, \infty)$ $F_X(t) = F_Y(t)$ (the distribution functions are identical),

and the alternative hypothesis:

H_1: $\exists t \in (-\infty, \infty)$, that $F_X(t) \neq F_Y(t)$(the distribution functions of the distributions are significantly different).

The test statistic is given by the formula

$$D^{KS} = \sup_{t\geq 0} |F_X(t) - F_Y(t)| \qquad (2)$$

The statistic D has a Kolmogorov distribution. At the significance level α from the Kolmogorov distribution tables, we determine the critical value K_α. If $\sqrt{\frac{n_1+n_2}{n_1 n_2}} D^{KS} > K_\alpha$, where n_1 and n_2 denote the sample numbers, then we reject the null hypothesis H_0 in favor of the alternative hypothesis H_1.

2.2.3. Dependence of pollutant concentration on load, temperature and speed

Let $\{(P_t^k, L_t^k, T_t^k, RPM_t^k)\}_{1\le t\le n_k}$ denote a data frame, where P_t^k denotes the concentration of pollutants within 1 s during measurements (ppm), L_t^k – engine load (% of maximum power output of the engine), T_t^k – current engine temperature C, RPM_t^k – engine speed during fuel supply $k \in \{Gasoline,LPG\}$. During engine operation, the concentration of pollutants $P_t^k > 0$ for each $t, 1 \le t \le n_k$. For the analyzed data set, delays (lags) in AVL readings were taken into account due to the time of exhaust gas flow from the engine exhaust manifold to the measuring device. The average delay time of readings is about 6 s. The relationship

$$\log(P_t^k) = \theta_0^k + \theta_1^k L_t^k + \theta_2^k T_t^k + \theta_3^k RPM_t^k + \varepsilon_t \tag{3}$$

was considered, for $k \in \{Gasoline,LPG\}$, while the influence of external factors is described using a random variable with a normal distribution $N(0, \sigma^2)$.

Let

$$X = \begin{bmatrix} 1 & L_1^k & T_1^k & RPM_1^k \\ 1 & L_2^k & T_2^k & RPM_2^k \\ \vdots & \vdots & \vdots & \vdots \\ 1 & L_{n_k}^k & T_{n_k}^k & RPM_{n_k}^k \end{bmatrix}, \quad Y = \begin{bmatrix} \log(P_1^k) \\ \log(P_2^k) \\ \vdots \\ \log(P_{n_k}^k) \end{bmatrix},$$

$$\varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_{n_k} \end{bmatrix}, \quad \Theta = \begin{bmatrix} \theta_0^k \\ \theta_1^k \\ \theta_2^k \\ \theta_3^k \end{bmatrix}$$

Based on the observations, the relationship (3) can be presented in the form

$$Y = X\Theta^k + \varepsilon \tag{4}$$

Using the least squares method, we estimate the unknown parameters of the model (3). If $(X^T X) \neq 0$ then the best linear estimator of unknown parameters is given as follows

$$\widehat{\Theta}^k = (X^T X)^{-1} X^T Y \tag{5}$$

The variance estimator of residuals is equal

$$\widehat{\sigma}^2 = \frac{1}{n_k - 3 - 1} \sum_{j=1}^{n} \varepsilon_j^2$$

where residual $\varepsilon = Y - X\widehat{\Theta} \in \mathbb{R}^n$. The values of the variance of the structural parameters are determined as $(S_0^k, S_1^k, S_2^k, S_3^k) = \mathrm{diag}(\widehat{\sigma}^2 (X^T X)^{-1})$. Therefore, each of the structural parameters θ_j^k has a normal distribution $N(\widehat{\theta}_j^k, S_j^2)$ for $0 \le j \le 3$.

For equation (3) we examine the significance of the parameter θ_j^k, j = 0,1,2,3 namely the influence of the respective factor on the pollutant concentration. In order to assess the influence of individual predictors [14, 18, 37] at the significance level $0 < \alpha < 1$ for each structural parameter we create a null hypothesis

$$H_0: \theta_j^k = 0$$

and the alternative hypothesis

$$H_0: \theta_j^k \neq 0$$

Test statistic

$$t_j = \frac{\widehat{\theta}_j^k}{\sqrt{S_j^k}} \tag{6}$$

has t – distribution with $n - 3 - 1$ degrees of freedom. The test probability is equal

$$p_j = 2 \cdot P(T > |t_j|) \tag{7}$$

where T is a random variable with a t-Student distribution with $n - 3 - 1$ degrees of freedom. If $p_j < \alpha$, then for the parameter θ_j^k we reject the working hypothesis H_0 in favor of the alternative hypothesis H_1, therefore the appropriate component significantly affects the concentration of pollutants defined by means of (3). If $p_j \ge \alpha$ then at the significance level αthere are no grounds to reject the hypothesis H_0, then the structural parameter is not significantly different from zero and the predictor has a non-significant effect on explaining the variability of the pollutant concentration during the operation of the engine fueled with fuel $k \in \{Gasoline, LPG\}$.

A prediction value of the logarithm of the pollutant concentration is equal

$$\log(\widehat{P}_t^k) = \widehat{\theta}_0^k + \widehat{\theta}_1^k L_t^k + \widehat{\theta}_2^k T_t^k + \widehat{\theta}_3^k RPM_t^k$$

For the analysis of the model fit [14, 18, 24] the coefficient of determination was estimated

$$R^2 = 1 - \frac{\sum_{j=1}^{n} \varepsilon_j^2}{\sum_{j=1}^{n} \left(\log(P_j^k) - \bar{P}^k\right)^2} \tag{8}$$

where $\bar{P}^k = \frac{1}{n} \sum_{j=1}^{n_k} \log(P_j^k)$. The coefficient of determination R^2shows what part of the variability of the dependent variable is explained by the model. The significance test of the multiple correlation coefficient [13, 23] was used to verify the fit of the model to the empirical data. At the significance level $0 < \alpha < 1$ we create a null hypothesis

H_0: $R = 0$ (multiple correlation coefficient is equal to zero or not significantly different from zero)

and the alternative hypothesis

H_0: $R \neq 0$ (the multiple correlation coefficient is significantly different from zero).

For the model (3) for fuel, $k \in \{Gasoline,LPG\}$ the test statistic

$$f = \frac{R^2}{1 - R^2} \frac{n_k - 3 - 1}{3} \tag{9}$$

has a Fischer-Snedecor distribution with $(3,\ n_k - 3 - 1)$ degrees of freedom. The test probability is

$$p_k = P(F > f) \quad (10)$$

where Fis a random variable with a Fischer-Snedecor distribution $(3,\ n_k - 3 - 1)$ degrees of freedom. If $p_k \geq \alpha$ then at the significance level α there is no basis for rejecting the hypothesis H_0, therefore the multiple correlation coefficient is not significantly different from zero and the fitfing of the model describing the concentration of pollutants generated by the fuel-fueled engine $k \in \{\text{Gasoline}, \text{LPG}\}$ to the data is too weak. If the test probability $p_k < \alpha$ then the null hypothesis H_0 should be rejected in favor of H_1, then the fitfing of the model to the data is sufficiently high.

2.2.4. Analysis of differences in the impact of load, engine operating temperature, rpm, on pollutant concentration for different fuels

Based on the data $\{(P_t^k, L_t^k, T_t^k, rpm_t^k)\}_{1 \leq t \leq n_k}$ for the established pollutant type, we estimate the parameters of the model (3) using the OLS for each of the fuels $k \in \{\text{Gasoline}, \text{LPG}\}$. In order to verify the differences and similarities in the effects of engine load, temperature and rpm on the emission of pollutant concentrations due to the use of different fuel types at the significance level $0 < \alpha < 1$for each of the structural parameters $\theta_j^{\text{Gasoline}}$and $\theta_j^{\text{LPG}}$for $j \in \{1,2,3\}$, we create a null hypothesis

H_0: $\theta_j^{\text{Gasoline}} = \theta_j^{\text{LPG}}$(no significant differences in the effect of the j-th factor when fueled with petrol and LPG)

and the alternative hypothesis

H_1: $\theta_j^{\text{Gasoline}} \neq \theta_j^{\text{LPG}}$(significant difference in the impact of the j-th factor when fueled with petrol and LPG)

Test statistic

$$T_j = \frac{\theta_j^{\text{Gasoline}} - \theta_j^{\text{LPG}}}{\sqrt{\frac{s_j^{\text{Gasoline}}}{n_{\text{Gasoline}} - 4} + \frac{s_j^{\text{LPG}}}{n_{\text{LPG}} - 4}}} \quad (11)$$

has a normal distribution $N(0,1)$. The test probability is equal

$$p_j = 2 \cdot P(U > |T_j|)$$

where U is a random variable with a distribution $N(0,1)$. If $p_j < \alpha$, then we reject the null hypothesis H_0in favor of H_1, then the influence of j-th factor on the pollution significantly depends on the type of fuel.

3. Results

Basic statistics for the logarithm of pollutant concentrations for various conditions with respect to the engine operating temperature range and for various types of fuel used to power the combustion engine are presented below (Table 1 and Table 2).

Tables 1 and 2 present basic statistics for pollutant concentrations (CH_4, HC, NO_x) generated by the petrol- and LPG-fuelled engine in different engine operating states (cold, medium, and operational). Comparison of the results reveals clear differences in emission profiles between the fuels, with LPG exhibiting more stable pollutant concentrations, particularly during the cold start phase.

To compare the effects of engine operating temperature and fuel type on pollutant emissions, the following graphs present logarithmic concentrations of gases: methane (CH_4), hydrocarbons (HC), and nitrogen oxides (NO_x), varying with engine operating temperature and fuel type (gasoline and LPG). The results indicate significant differences in the emission profiles of these gases under different temperature conditions, with particular emphasis on the

Table 1. Basic statistics of pollution generated by combustion engine powered by gasoline

State	Pollution	minutes	$q_{0.25}$	Mean	Median	$q_{0.75}$	max	Std.dev	Skewnes	Kurtosis
Cold	log(CH_4)	2.13	2.84	3.57	3.32	4.43	6.01	0.94	0.42	–0.83
Cold	log(HC)	4.57	5.18	6.10	5.66	7.25	8.59	1.20	0.75	–0.84
Cold	log(NO_x)	1.19	2.48	4.15	3.94	5.49	7.49	1.72	0.33	–1.10
Medium	log(CH_4)	–0.20	1.52	2.01	2.23	2.58	4.42	0.85	–0.54	0.34
Medium	log(HC)	3.24	3.77	4.13	4.08	4.43	5.47	0.51	0.41	–0.35
Medium	log(NO_x)	0.35	2.11	3.18	2.75	4.28	7.49	1.46	0.60	–0.33
Normal	log(CH_4)	–1.10	0.86	1.60	1.86	2.49	4.16	1.26	-0.53	–0.55
Normal	log(HC)	2.79	3.18	3.69	3.57	4.13	5.61	0.59	0.70	–0.19
Normal	log(NO_x)	–0.10	1.13	2.56	2.44	3.77	7.02	1.75	0.42	–0.65

Table 2. Basic statistics of pollution generated by combustion engine powered by LPG

State	Pollution	minutes	$q_{0.25}$	Mean	Median	$q_{0.75}$	max	Std.dev	Skewnes	Kurtosis
Cold	log(CH_4)	2.66	3.74	4.15	3.96	4.64	5.83	0.70	0.19	–0.21
Cold	log(HC)	5.11	6.02	6.71	6.54	7.62	8.77	1.01	0.19	–1.08
Cold	log(NO_x)	0.59	2.65	4.16	4.18	5.33	7.53	1.68	0.20	–0.93
Medium	log(CH_4)	0.06	2.01	2.60	2.76	3.17	4.66	0.83	–0.34	0.31
Medium	log(HC)	3.24	4.11	4.61	4.56	5.08	6.97	0.72	0.39	–0.14
Medium	log(NO_x)	0.33	2.30	3.38	2.96	4.36	7.27	1.58	0.52	–0.40
Normal	log(CH_4)	–0.75	1.73	2.20	2.39	2.90	4.52	1.06	-0.84	0.54
Normal	log(HC)	2.75	3.50	4.23	4.11	4.96	6.18	0.90	0.23	–0.95
Normal	log(NO_x)	0.08	1.74	3.30	2.97	4.93	7.65	2.02	0.32	–0.90

differences between fuels during the cold start phase. Figures 4–6 illustrate how the concentrations of individual pollutants vary with temperature and fuel type, confirming earlier observations reported in the literature.

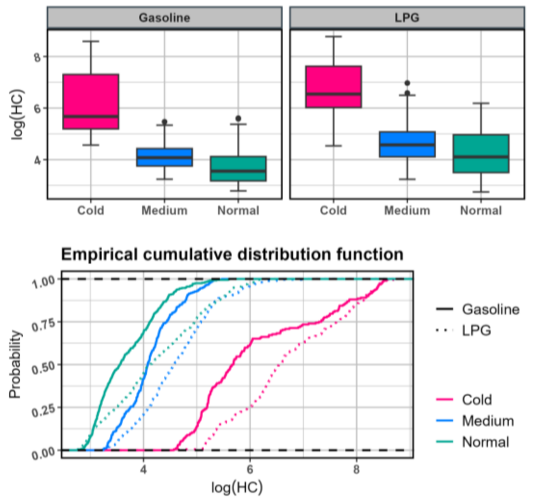

Fig. 4. Comparison of HC concentrations in logarithmic scale depending on engine operating temperature and fuel type

Figure 4 shows a comparison of hydrocarbon (HC) concentrations on a logarithmic scale, plotted against engine operating temperature and fuel type. There is a clear difference in the emission profiles between petrol and LPG, especially during the cold start phase. The dots in the boxplots represent statistical outliers, defined as values lying more than 1.5 times the interquartile range from the nearest quartile.

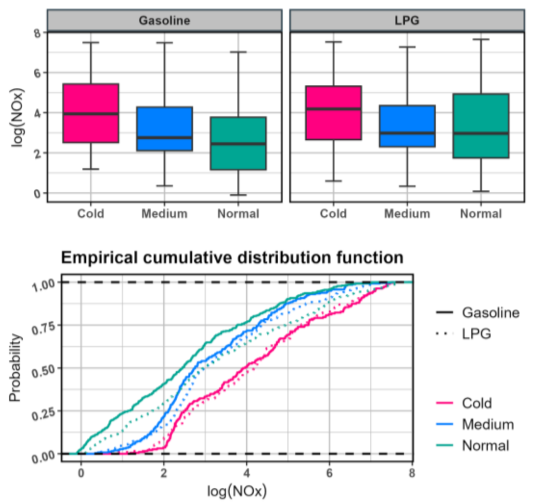

Fig. 5. Comparison of NO_x concentrations in logarithmic scale depending on engine operating temperature and fuel type

Figure 5 shows a comparison of nitrogen oxides concentrations on a logarithmic scale for different engine operating temperatures and fuels. We observe that the differences in NO_x emissions are more pronounced at lower temperatures, where LPG shows a more stable emission profile than gasoline.

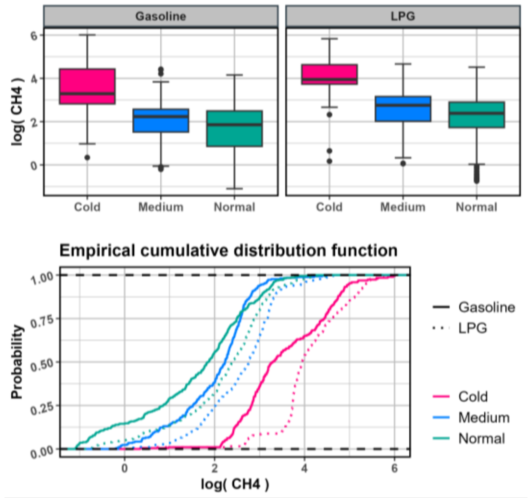

Fig. 6. Comparison of CH_4 concentrations in logarithmic scale depending on engine operating temperature and fuel type

Figure 6 shows methane (CH_4) concentrations on a logarithmic scale, varying with temperature and fuel type. Methane emissions are clearly lower for LPG, especially at higher engine operating temperatures, confirming the more favorable emission profile of this fuel.

Tables 1 and 2, and Fig. 4–6, demonstrate that the Kruskal-Wallis test was employed to investigate the presence of differences in the distribution of pollutant concentrations on a logarithmic scale across engine operating states. The table below presents the values of the test statistics T and the corresponding test probabilities Table 3 shows that for each fuel and for each type of pollutant, the test probability is below the level $\alpha = 0.05$. Therefore, for both Gasoline fuel and LPG, the engine operating temperature significantly affects the value of pollutant concentrations NO_x, CH_4, HC.

Table 3. The result of the Kruskal-Wallis test regarding the differences in the distribution of pollutant concentrations due to the operating temperature range of the combustion engine

Fuel	Pollution	T	p.value
Gasoline	NO_x	78.96	7.144×10^{-18}
Gasoline	HC	511.41	8.901×10^{-112}
Gasoline	CH_4	297.36	2.685×10^{-65}
LPG	NO_x	19.10	7.104×10^{-5}
LPG	HC	604.57	5.239×10^{-132}
LPG	CH_4	484.45	6.3659×10^{-106}

The Kolmogorov-Smirnov test was used to compare the distributions of pollutant concentration differences on a logarithmic scale by fuel type. Empirical distribution functions are presented in Fig. 4–6. Table 4 presents the values of the test statistics D and the test probability values. For the 'Cold' state and NO_x pollution, for the 'Medium' state and NO_x pollution, the test probability is above 0.05, so for these cases , there is no basis for rejecting the working hypothesis; the pollutant concentration distributions are equal or differ insignificantly. For the remaining states and pollutants, the test probability is below the value 0.05, so the pollutant distributions differ significantly.

Table 4. The result of the Kolmogorov-Smirnov test regarding the differences in the distribution of pollutant concentrations due to fuel type

State	Pollution	D	p.value
Cold	NO_x	0.062	0.8475
Cold	HC	0.391	3.781×10^{-13}
Cold	CH_4	0.469	9.533×10^{-19}
Medium	NO_x	0.112	0.07777
Medium	HC	0.344	1.045×10^{-13}
Medium	CH_4	0.382	7.355×10^{-17}
Normal	NO_x	0.153	4.381×10^{-4}
Normal	HC	0.304	8.476×10^{-15}
Normal	CH_4	0.240	2.259×10^{-9}

According to formula (3), the effects of engine load, engine operating temperature, and rpm on the concentration of pollutants were identified. The values of structural parameters, standard deviation of these parameters, test statistic values (6) and test probability (7) for both Gasoline and LPG fueled engines are presented in Tables 5–9.

Table 5. Structural parameter values, standard deviations, test statistic values and test probabilities for contamination HC

	Value	Std.Error	t	p.value
$\theta_0^{Gasoline}$	7.54	0.12	61.46	7.76×10^{-305}
$\theta_1^{Gasoline}$	0.01	0.001	9.66	5.82×10^{-21}
$\theta_2^{Gasoline}$	–0.05	0.001	–49.77	6.7×10^{-247}
$\theta_3^{Gasoline}$	0.0002	0.0001	6.49	1.51×10^{-10}
θ_0^{LPG}	7.99	0.17	46.69	1.99×10^{-230}
θ_1^{LPG}	0.01	0.002	5.87	6.36×10^{-9}
θ_2^{LPG}	–0.05	0.002	–35.26	6.25×10^{-165}
θ_3^{LPG}	0.0004	0.0001	5.95	4.09×10^{-9}

From Table 5 we can see that for both Gasoline and LPG at the significance level 0.05 for each of the structural parameters should be rejected in favor of the alternative hypothesis, each of the factors (engine load, engine temperature, rpm) significantly affects the value of concentration HC. The values of structural parameters $\theta_2^{Gasoline}$ and θ_2^{LPG} are negative, which assumes that with the increase of engine temperature, the concentration decreases HC. It should be noted that the extremely small p-values reported in Table 5 do not carry a physical meaning in themselves but only confirm that the corresponding parameters are highly statistically significant.

Table 6. Structural parameter values, standard deviations, test statistic values and test probabilities for contamination CH_4

	Value	Std.Error	t	p.value
$\theta_0^{Gasoline}$	4.13	0.22	19.18	1.02×10^{-67}
$\theta_1^{Gasoline}$	0.01	0.002	3.81	0.0002
$\theta_2^{Gasoline}$	–0.04	0.002	–21.61	6.77×10^{-82}
$\theta_3^{Gasoline}$	0.001	0.00008	7.16	1.85×10^{-12}
θ_0^{LPG}	4.99	0.19	25.95	4.12×10^{-108}
θ_1^{LPG}	0.002	0.002	1.16	0.25
θ_2^{LPG}	–0.04	0.002	–23.38	1.61×10^{-92}
θ_3^{LPG}	0.0005	0.00007	6.71	3.66×10^{-11}

From Table 6 we can see that for LPG at the significance level 0.05 there is no basis for rejecting the null hypothesis for the parameter θ_1^{LPG} (engine load), while for the remaining parameters, both for Gasoline and LPG, the working hypothesis should be rejected in favor of the alternative hypothesis, therefore each of the factors (engine load, engine temperature, rpm) significantly affects the concentration value CH_4. The values of the structural parameters $\theta_2^{Gasoline}$ and θ_2^{LPG} are negative, which means that with the increase in engine temperature, the concentration decreases CH_4.

Table 7. Structural parameter values, standard deviations, test statistic values and test probabilities for contamination NO_x

	Value	Std.Error	t	p.value
$\theta_0^{Gasoline}$	2.028	0.308	6.589	8.007×10^{-11}
$\theta_1^{Gasoline}$	0.03169	0.003	9.606	9.505×10^{-21}
$\theta_2^{Gasoline}$	–0.029	0.0033	–10.769	2.4104×10^{-25}
$\theta_3^{Gasoline}$	0.00156	0.0001	13.169	5.533×10^{-36}
θ_0^{LPG}	0.596	0.324	1.839	0.0663
θ_1^{LPG}	0.037	0.003	10.725	3.652×10^{-25}
θ_2^{LPG}	–0.014	0.003	–4.973	8.0813×10^{-7}
θ_3^{LPG}	0.0018	0.0001	15.334	1.0557×10^{-46}

Table 7 shows that for LPG, at the 0.05 significance level, there is no basis to reject the working hypothesis for the parameter θ_0^{LPG}, while for the remaining parameters, both gasoline and LPG, the working hypothesis should be rejected in favor of the alternative hypothesis, therefore each of the factors (engine load, engine temperature, rpm) significantly affects the NO_x concentration.

Table 8 presents the values of the standard deviations of the residuals in the model (3), the values of the coefficient of determination R^2, the values of the test statistic (9) and the test probability (10) regarding the significance of the multiple correlation coefficient for each pollutant and each fuel type.

Table 8. Values of the standard deviation σ, coefficient of determination R^2, test statistic F and test probability values

Fuel	Pollution	σ	R^2	F	p.val
Gasoline	NO_x	1.39	0.38	162.83	2.45×10^{-82}
Gasoline	HC	0.56	0.78	966.86	3.56×10^{-265}
Gasoline	CH_4	0.98	0.44	207.42	1.89×10^{-99}
LPG	NO_x	1.47	0.37	152.98	2.57×10^{-78}
LPG	HC	0.78	0.65	488.41	4.19×10^{-180}
LPG	CH_4	0.87	0.46	223.40	3.43×10^{-105}

Table 9 presents the results regarding the significance of differences in structural parameters for model (3) for each of the different fuels.

For pollution, HC there is no basis to reject the null hypothesis for the coefficients with the variables engine load, engine temperature and rpm (differences between parameters in equation (3) for Gasoline and LPG are not significant), whereas for the intercept the null hypothesis is rejected in favor of the alternative hypothesis (significant difference in the effect of fuel type on the concentration value HC).

Table 9. Statistics values of structural parameters and test probability values

Pollution	j	T_j	p_j
NO_x	0	50.89	0.00
NO_x	1	–1.94	0.026
NO_x	2	–5.69	0.00
NO_x	3	–0.62	0.27
HC	0	–23.82	0.00
HC	1	0.96	0.17
HC	2	–0.30	0.38
HC	3	–0.22	0.41
CH_4	0	–37.99	0.00
CH_4	1	2.72	0.003
CH_4	2	–0.64	0.26
CH_4	3	0.21	0.42

For pollution CH_4 there is no basis to reject the null hypothesis for the coefficients with the variables engine temperature and rpm, whereas for the intercept and engine load, the null hypothesis is rejected in favor of the alternative hypothesis (significant difference in the effect of fuel type and engine load for various fuels on the concentration value CH_4).

For NO_x pollution, there is no basis to reject the null hypothesis for the coefficient at rpm (rpm has a similar effect on the NO_x concentration values for different fuels), whereas for the intercept, engine load and engine temperature, the null hypothesis is rejected in favour of the alternative hypothesis (significant difference in the effect of fuel type and engine load and temperature when fuelled with different fuels on the NO_x concentration value).

4. Conclusions and discussion of results

The laboratory measurements carried out and the statistical analysis of the obtained results allowed the formulation of the following conclusions:

1. The increase in engine load has a significant impact on the increase in the level of hydrocarbon, methane and nitrogen oxide emissions, both when fuelled with gasoline and LPG (the exception is the lack of a significant increase in methane emissions for gas fuelling). Although the increase in engine load and crankshaft speed in LPG engines has a smaller impact on emissions compared to gasoline engines, this is due to the unique combustion characteristics of LPG. Thanks to a more homogeneous fuel-air mixture and higher combustion efficiency, the LPG engine is able to maintain a more stable combustion process, even at higher loads and rotational speeds, which limits the increase in emissions.
2. The increase in engine coolant temperature, representing the increase in catalytic converter temperature, has a significant impact on reducing hydrocarbon, methane and nitrogen oxides emissions when fueled with gasoline and LPG. Although both LPG and gasoline have a significant impact on pollutant emissions during the cold start phase, the differences in their emission profiles result from different combustion dynamics. LPG, due to its superior physicochemical properties, promotes faster catalyst heating, which in turn leads to a more rapid reduction in HC and CO emissions compared to gasoline. At the same time, its lower sensitivity to ambient temperature changes makes LPG emissions more stable in winter conditions, which is confirmed by the results of literature studies [21, 44].
3. The increase in the engine crankshaft speed is associated with a significant increase in the emission of hydrocarbons, methane and nitrogen oxides. There were no significant differences between the fuels considered.
4. In the WLTC cycle, the highest emission level occurs at the beginning of the test, when the catalytic converter has not yet reached its starting temperature.
5. Frequent cold starts and short distances covered by the vehicle contribute to increased emissions of harmful exhaust gas components.

The laboratory tests and analysis of the results indicate a relationship between selected engine operating parameters (load, temperature and rotational speed) and the emission of hydrocarbons, methane and nitrogen oxides for gasoline and LPG fuelling. The issue of the relationship between engine load and emission of harmful substances was raised, among others, in the article by Hashem et al. The authors performed an experimental and numerical analysis using simulation software and showed that with increasing load (and constant engine speed) the emission of selected exhaust components increases, including nitrogen oxides. According to the authors, the increase is greater during operation on LPG, which may be due to the faster combustion process when fueled with gas. The data presented in our article also show that increasing load leads to an increase in NO_x for both test fuels. The same authors also examined the issue of the effect of increasing the rotational speed of the engine shaft at constant load. They measured the concentration of nitrogen oxides, among others, which increased with the increase in the shaft rotational speed. They emphasized that this is related to the increase in temperature in the combustion chamber, and this effect was noticeable for gasoline and, to a greater extent, for LPG. These observations are consistent with those presented in the paper.

The results of this study indicate the need for further development of catalyst temperature management strategies, particularly under low ambient temperature conditions, which can significantly enhance the efficiency of pollutant emission reduction in dual-fuel engines. Another area that requires in-depth research is the optimization of ignition and injection strategies in LPG engines, especially in the context of different temperature conditions.

The research presented in the study revealed a significant impact of engine coolant temperature on the emission of hydrocarbons, nitrogen oxides, and methane from the engine. The coolant temperature represents the engine operating conditions, but also the catalytic converter heating process. This effect may be further enhanced by interactions between injected fuel and residual exhaust gases, as demonstrated in HCCI engine studies [17]. This is confirmed by the research conducted by Worsztynowicz and Uhryński [50], who measured, among other things, the temperatures of the coolant and the reactor during their study. The topic of increased emission of harmful substances in exhaust gases right after a cold start is discussed from different perspectives. Woo Jeong et al. [49] investigated the relationship between the content of ammonia and nitrogen oxides in exhaust gases, varying the temperature. One of their observations was a significantly increased NO_x emission after a cold start, which gradually decreased as the catalytic converter temperature increased. The simulations conducted by Reiter et al. [39] are another confirmation of the problem of methane and nitrogen oxides emissions by LDVs during a cold start. Te authors, among others, drew attention to the variability of emissions depending on the season, additionally emphasizing the effect of temperature on emissions. In winter, the catalytic converter needs even more time to reach the light-off temperature. Usman et al. [47], During their studies on emissions depending on the fuel used, they presented, among others, a graph showing the emissions of hydrocarbons and nitrogen oxides as a function of the crankshaft's rotational speed. With the increase in rotational speed, the emission of nitrogen oxides increased, and that of hydrocarbons decreased. The reduction of hydrocarbon emissions did not occur in our studies.

Nomenclature

CI	compression ignition
CNG	compressed natural gas
DI	direct injection
LPG	liquefied petroleum gas
SI	spark ignition

Bibliography

[1] Adam TW, Astorga C, Clairotte M, Duane M, Elsasser M, Krasenbrink A et al. Chemical analysis and ozone formation potential of exhaust from dual-fuel (liquefied petroleum gas/gasoline) light duty vehicles. Atmos Environ. 2011;45: 2842-2848. https://doi.org/10.1016/j.atmosenv.2011.03.002

[2] Appel D, Hagen FP, Wagner U, Koch T, Bockhorn H, Trimis D. Influence of low ambient temperatures on the exhaust gas and deposit composition of gasoline engines. ASME 2020 Internal Combustion Engine Division Fall Technical Conference, Virtual, Online: American Society of Mechanical Engineers. 2020:V001T04A003. https://doi.org/10.1115/ICEF2020-2932

[3] Bielaczyc P, Szczotka A, Woodburn J. The effect of a low ambient temperature on the cold-start emissions and fuel consumption of passenger cars. Proc Inst Mech Eng Part D-J Automob Eng. 2011;225:1253-1264. https://doi.org/10.1177/0954407011406613

[4] Çinar C, Şahin F, Can Ö, Uyumaz A. A comparison of performance and exhaust emissions with different valve lift profiles between gasoline and LPG fuels in a SI engine. Appl Therm Eng. 2016;107:1261-1268. https://doi.org/10.1016/j.applthermaleng.2016.07.031

[5] Faria MV, Varella RA, Duarte GO, Farias TL, Baptista PC. Engine cold start analysis using naturalistic driving data: City level impacts on local pollutants emissions and energy consumption. Sci Total Environ. 2018;630:544-559. https://doi.org/10.1016/j.scitotenv.2018.02.232

[6] Frondel M, Marggraf C, Sommer S, Vance C. Reducing vehicle cold start emissions through carbon pricing: evidence from Germany. Environ Res Lett. 2021;16:034041. https://doi.org/10.1088/1748-9326/abde06

[7] Gao J, Tian G, Sorniotti A, Karci AE, Di Palo R. Review of thermal management of catalytic converters to decrease engine emissions during cold start and warm up. Appl Therm Eng. 2019;147:177-187. https://doi.org/10.1016/j.applthermaleng.2018.10.037

[8] Gong C, Yan S, Su Y, Wang Z. Effects of fuel injection timing on combustion and emissions of a spark-ignition methanol and methanol/liquefied petroleum gas (LPG) engine during cold start. Energy Fuels. 2009;23:3536-3542. https://doi.org/10.1021/ef900190q

[9] Gumus M. Reducing cold-start emission from internal combustion engines by means of thermal energy storage system. Appl Therm Eng. 2009;29:652-660. https://doi.org/10.1016/j.applthermaleng.2008.03.044

[10] Gumus M, Ugurlu A. Application of phase change materials to pre-heating of evaporator and pressure regulator of a gaseous sequential injection system. Appl Energ. 2011;88: 4803-4810. https://doi.org/10.1016/j.apenergy.2011.06.053

[11] Gutierrez LG, Wooldridge MS, Petersen BR, Wooldridge ST. In-cylinder imaging and emissions measurements of cold-start split injection strategies. J Eng Gas Turbines Power. 2025;147:081014. https://doi.org/10.1115/1.4067602

[12] Hao L, Xu X, Guo X, Ji C, Wang X, Tan J et al. Investigation of cold-start emission control strategy for a bi-fuel hydrogen/gasoline engine. Int J Hydrogen Energ. 2016;41: 18273-18281. https://doi.org/10.1016/j.ijhydene.2016.08.038

[13] Hastie T, Tibshirani R, Friedman J. The elements of statistical learning. Springer New York 2009. https://doi.org/10.1007/978-0-387-84858-7

[14] Henein NA, Tagomori MK. Cold-start hydrocarbon emissions in port-injected gasoline engines. Prog Energy Combust Sci. 1999;25:563-593. https://doi.org/10.1016/S0360-1285(99)00003-9

[15] Hu J, Frey HC, Boroujeni BY. Contribution of cold starts to real-world trip emissions for light-duty gasoline vehicles. Atmosphere. 2022;14:35. https://doi.org/10.3390/atmos14010035

[16] Hu J, Li D, Hall M, Matthews R, Moilanen P, Wooldridge S et al. A parametric study to improve first firing cycle emissions of a gasoline direct injection engine during cold start. Int J Eng Res. 2023;24:3428-3444. https://doi.org/10.1177/14680874231153302

[17] Hunicz J. An experimental study into the chemical effects of direct gasoline injection into retained residuals in a homogeneous charge compression ignition engine. Int J Eng Res. 2016;17:1031-1044. https://doi.org/10.1177/1468087416636492

[18] James G, Witten D, Hastie T, Tibshirani R. An introduction to statistical learning: with applications in R. Springer 2021. https://doi.org/10.1007/978-1-0716-1418-1

[19] Jatana GS, Dal Forno Chuahy F, Szybist J. Effect of split-injection strategies on engine performance and emissions under cold-start operation. SAE Technical Paper 2023-01-0236. 2023. https://doi.org/10.4271/2023-01-0236

[20] Joshua Ikiaye D, Moore Ojapah M. Performance, emission and cost analysis of LPG and gasoline in a single cylinder engine. IJERSTE 2023;12:212-219. https://doi.org/10.55948/IJERSTE.2023.0424

[21] Kim J, Choi K, Myung C-L, Park S. Experimental evaluation of engine control strategy on the time resolved THC and nano-particle emission characteristics of liquid phase LPG direct injection (LPG-DI) engine during the cold start. Fuel Process Technol. 2013;106:166-173. https://doi.org/10.1016/j.fuproc.2012.07.020

[22] Kim K, Kim J, Oh S, Kim C, Lee Y. Lower particulate matter emissions with a stoichiometric LPG direct injection engine. Fuel. 2017;187:197-210. https://doi.org/10.1016/j.fuel.2016.09.058

[23] Kłosowski G, Rymarczyk T, Niderla K, Kulisz M, Skowron Ł, Soleimani M. Using an LSTM network to monitor industrial reactors using electrical capacitance and impedance tomography – a hybrid approach. Eksploat Niezawodn. 2023; 25(1):11. https://doi.org/10.17531/ein.2023.1.11

[24] Kontses A, Triantafyllopoulos G, Ntziachristos L, Samaras Z. Particle number (PN) emissions from gasoline, diesel, LPG, CNG and hybrid-electric light-duty vehicles under real-world driving conditions. Atmos Env. 2020;222:117126. https://doi.org/10.1016/j.atmosenv.2019.117126

[25] Kozłowski E, Borucka A, Oleszczuk P, Leszczyński N. Evaluation of readiness of the technical system using the semi-Markov model with selected sojourn time distributions. Eksploat Niezawodn. 2024;26. https://doi.org/10.17531/ein/191545

[26] Kwak H, Myung C-L, Park S. Experimental investigation on the time resolved THC emission characteristics of liquid phase LPG injection (LPLi) engine during cold start. Fuel. 2007;86:1475-1482. https://doi.org/10.1016/j.fuel.2006.11.023

[27] Laskowski P, Zasina D, Zimakowska-Laskowska M, Orliński P. Modelling hydrocarbons cold-start emission from passenger cars. Adv Sci Technol Res J. 2021;15:117-125. https://doi.org/10.12913/22998624/138764

[28] Laskowski P, Zimakowska-Laskowska M, Matej J, Wiśniowski P. The problem of cold start emissions from vehicles. Combustion Engines. 2024;199(4):43-51. https://doi.org/10.19206/CE-186471

[29] Laskowski P, Zimakowska-Laskowska M, Zasina D. Modelling of the air pollutants' cold-start emissions depending on average vehicles' speed. Combustion Engines. 2022;188:96-103. https://doi.org/10.19206/CE-142171

[30] Lee K, Pintor DL, Assanis D, Cho S, Hwang J. Fuel temperature and injection pressure influence on the cold start GDI sprays. Appl Energy Combust Sci. 2023;16:100206. https://doi.org/10.1016/j.jaecs.2023.100206

[31] Liu F, Shafique M, Luo X. Literature review on life cycle assessment of transportation alternative fuels. Environ Technol Innov. 2023;32:103343. https://doi.org/10.1016/j.eti.2023.103343

[32] Liu H, Liu Q, Wang C. A novel valve strategy for particulate matter reduction in a gasoline direct injection engine operated at cold conditions. Int J Engine Res. 2025;26:325-338. https://doi.org/10.1177/14680874241276263

[33] Liu Z, Li L, Deng B. Cold start characteristics at low temperatures based on the first firing cycle in an LPG engine. Energy Convers Manag. 2007;48:395-404. https://doi.org/10.1016/j.enconman.2006.07.011.

[34] Ludykar D, Westerholm R, Almén J. Cold start emissions at +22, −7 and −20°C ambient temperatures from a three-way catalyst (TWC) car: regulated and unregulated exhaust components. Sci Total Environ. 1999;235:65-69. https://doi.org/10.1016/S0048-9697(99)00190-4

[35] Małek A, Caban J, Sarkan B. Research on low-emission vehicle powered by LPG using innovative hardware and software. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2020;89:19-36. https://doi.org/10.14669/AM.VOL89.ART2

[36] Myung C-L, Kim J, Choi K, Hwang IG, Park S. Comparative study of engine control strategies for particulate emissions from direct injection light-duty vehicle fueled with gasoline and liquid phase liquefied petroleum gas (LPG). Fuel. 2012;94:348-355. https://doi.org/10.1016/j.fuel.2011.10.041

[37] Napolitano P, Alfè M, Guido C, Gargiulo V, Fraioli V, Beatrice C. Particle emissions from a HD SI gas engine fueled with LPG and CNG. Fuel. 2020;269:117439. https://doi.org/10.1016/j.fuel.2020.117439

[38] Pawlik P, Kania K, Przysucha B. Fault diagnosis of machines operating in variable conditions using artificial neural network not requiring training data from a faulty machine. Eksploat Niezawodn. 2023;25. https://doi.org/10.17531/ein/168109

[39] Reiter MS, Kockelman KM. The problem of cold starts: A closer look at mobile source emissions levels. Transp Res Part D Transp Environ. 2016;43:123-132. https://doi.org/10.1016/j.trd.2015.12.012

[40] Saliba G, Saleh R, Zhao Y, Presto AA, Lambe AT, Frodin B et al. Comparison of gasoline direct-injection (GDI) and port fuel injection (PFI) vehicle emissions: emission certification standards, cold-start, secondary organic aerosol formation potential, and potential climate impacts. Environ Sci Technol. 2017;51:6542-6552. https://doi.org/10.1021/acs.est.6b06509

[41] Šarkan B, Jaśkiewicz M, Kubiak P, Tarnapowicz D, Loman M. Exhaust emissions measurement of a vehicle with retrofitted LPG system. Energies. 2022;15:1184. https://doi.org/10.3390/en15031184

[42] Sharma NK. Comparison of spark ignition engine performance and emission analysis using gasoline, LPG and mixture fuels. IJMTST. 2020;6:33-36. https://doi.org/10.46501/IJMTST060608

[43] Talib Hashem G, Al-Dawody MF, Sarris IE. The characteristics of gasoline engines with the use of LPG: an experimental and numerical study. Int J Thermofluids. 2023a;18: 100316. https://doi.org/10.1016/j.ijft.2023.100316

[44] Talib Hashem G, Al-Dawody MF. Use of LPG in SI engine – a review study. Al-Qadisiyah J Eng. 2021;14(1):52-59, https://doi.org/10.30772/qjes.v14i1.751

[45] Tan D, Wang Y, Tan J, Li J, Wang C, Ge Y. Influence of ambient temperature on the CO_2 emitted of light-duty vehicle. J Environ Sci. 2024;140:59-68. https://doi.org/10.1016/j.jes.2023.04.018.

[46] Teymoori MM, Chitsaz I, Kashani NA, Davazdah Emami M. Cold-start emission reduction of the gasoline-powered vehicle utilizing a novel method. Int J Engine Res. 2023;24: 1840-1859. https://doi.org/10.1177/14680874221100816

[47] Usman M, Farooq M, Naqvi M, Saleem MW, Hussain J, Naqvi SR et al. Use of gasoline, LPG and LPG-HHO blend in SI engine: a comparative performance for emission control and sustainable environment. Processes. 2020;8:74. https://doi.org/10.3390/pr8010074

[48] Weilenmann M, Favez J-Y, Alvarez R. Cold-start emissions of modern passenger cars at different low ambient temperatures and their evolution over vehicle legislation categories. Atmos Environ. 2009;43:2419-2429. https://doi.org/10.1016/j.atmosenv.2009.02.005

[49] Woo Jeong J, Baek S, Park S, Lee S, Lim Y, Lee K. Trends in NO_x and NH_3 emissions caused by three-way catalysts. Fuel. 2024;366:131282. https://doi.org/10.1016/j.fuel.2024.131282

[50] Worsztynowicz B, Uhryński A. The analysis of heating process of catalytic converter using thermo-vision. Combustion Engines. 2015;162:41-51.

https://doi.org/10.19206/CE-116864
[51] Yusuf AA, Inambao FL. Effect of cold start emissions from gasoline-fueled engines of light-duty vehicles at low and high ambient temperatures: recent trends. Case Stud Therm Eng. 2019;14:100417. https://doi.org/10.1016/j.csite.2019.100417
[52] Zhang B, Li X, Wan Q, Liu B, Jia G, Yin Z. Hydrocarbon emission control of an adsorptive catalytic gasoline particulate filter during cold-start period of the gasoline engine. Energy. 2023;262:125445. https://doi.org/10.1016/j.energy.2022.125445
[53] Zhang Z, Man H, Zhao J, Jiang Y, Zeng M, Cai Z et al. Primary organic gas emissions in vehicle cold start events: Rates, compositions and temperature effects. J Hazard Mater. 2022;435:128979. https://doi.org/10.1016/j.jhazmat.2022.128979
[54] Zhang Z, Zhong W, Tan D, Cui S, Pan M, Zhao Z et al. Hydrocarbon adsorption mechanism of modern automobile engines and methods of reducing hydrocarbon emissions during cold start process: a review. J Environ Manage. 2024; 353:120188. https://doi.org/10.1016/j.jenvman.2024.120188
[55] Zimakowska-Laskowska M, Kozłowski E, Laskowski P, Wiśniowski P, Świderski A, Orynycz O. Vehicle exhaust emissions in the light of modern research tools: synergy of chassis dynamometers and computational models. Combustion Engines. 2025;200:145-154. https://doi.org/10.19206/CE-201224

Piotr Wiśniowski, DEng. – Motor Transport Institute, Poland.
e-mail: *piotr.wisniowski@its.waw.pl*

Edward Kozłowski, DSc, Prof. LUT – Faculty of Management, Lublin University of Technology, Poland.
e-mail: *e.kozlovski@pollub.pl*

Magdalena Zimakowska-Laskowska, DEng. – Environment Protection Centre, Motor Transport Institute, Poland.
e-mail: *magdalena.zimakowska-laskowska@its.waw.pl*

Prof. Marcin Ślęzak, DSc., DEng. – Motor Transport Institute, Poland.
e-mail: *marcin.slezak@its.waw.pl*

Sławomir Taubert, DEng. – Environment Protection Centre, Motor Transport Institute, Poland.
e-mail: *slawomir.taubert@its.waw.pl*

Ksawery Żbik, MEng. – Environment Protection Centre, Motor Transport Institute, Poland.
e-mail: *ksawery.zbik@its.waw.pl*