Article citation info:
Zimakowska-Laskowska M, Kozłowski E, Wiśniowski P, Żbik K, Świderski A, Rostek E et al. The influence of ambient temperature on exhaust emissions during cold start in the homologation test. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-207577

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The influence of ambient temperature on exhaust emissions during cold start in the homologation test

ARTICLE INFO

Received: 19 May 2025
Revised: 6 June 2025
Accepted: 25 June 2025
Available online: 12 July 2025

The cold start phase in an ICE is susceptible to changing environmental conditions, especially ambient temperature. The work aimed to analyse the influence of different thermal conditions on the concentration of pollutants and operating parameters of the drive unit during a cold start. The tests were conducted on a chassis dynamometer at various ambient temperatures. The same homologation cycle was used in both cases, allowing direct comparison of results. The concentrations of HC, CH_4, CO_2, and NO_x were recorded, as well as the basic operating parameters of the engine: coolant temperature, rotational speed, load, and throttle position. Based on empirical data, mathematical models describing the influence of ambient temperature on the dynamics of emissions and stabilisation of engine operation were developed. Relationships were identified that allow for assessing the time to reach steady-state conditions as a function of starting temperature. The results of the analysis provide the basis for developing a start control strategy in climatically variable conditions. They can support the development of adaptive emission control systems compliant with current and future legal standards.

Key words: *cold start, internal combustion engine, ambient temperature, pollutant concentration, quantile regression*

1. Introduction

Cold starting of a combustion engine is one of the most significant challenges concerning pollutant emissions, especially in light of increasingly stringent environmental standards. The significance of this phase has been recently emphasised in studies focused on emission surges during cold start [19]. In this short but intensive phase of the engine's operation, there are rapid emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and methane (CH_4) before the catalytic converter reaches operating temperature. One of the key factors influencing this phenomenon is the ambient temperature and the thermal state of the engine at the time of start-up, reflected, among other things, by the initial coolant temperature.

In emissions research, increasing attention is being paid to analysing the impact of variable thermal conditions on emission dynamics and engine stabilisation. Low starting temperatures result in delayed catalyst warm-up, a richer fuel-air mixture, and higher internal friction, translating into more intense and longer-lasting emissions. Therefore, comparing the cold start process under different initial conditions – especially at different coolant temperatures – allows for a more accurate determination of emission characteristics in real conditions.

The following literature review explores the influence of coolant temperature on emissions, combustion behaviour, and exhaust treatment effectiveness. It highlights findings related to hydrocarbon, carbon monoxide, nitrogen oxide and particulate emissions, as well as the role of fuel type and control strategies.

The influence of coolant temperature on pollutant emissions during cold start has been the subject of numerous studies in both spark-ignition and compression-ignition engines. Similar analyses of low-temperature effects on exhaust composition, including detailed hydrocarbon speciation, were performed by Hunicz and Krzaczek [11] in a gasoline HCCI engine.

Low coolant temperature at start significantly affects combustion processes, fuel-air mixture formation and the efficiency of exhaust gas treatment systems. In their studies on emission dynamics and drive system reliability, Kozłowski et al. [16] emphasised the importance of the technical condition of the system in the context of emissions. Rimkus et al. [29] analysed the influence of hydrogen addition on emissions from combustion engines in dynamic driving conditions, indicating high variability of drive unit operating parameters. Kozłowski et al. [17] also analysed the relationships between vehicle acceleration and energy consumption, which is important in the context of the WLTC start analysis.

He et al. [9] showed that under low coolant temperature conditions, combustion becomes slower and less stable, and HC, CO, and particulate matter (PM) emissions significantly increase. Only with increasing coolant temperature does combustion quality improve and emissions decrease, although NO_x concentration may increase due to higher combustion temperature. Similar relationships were observed by Irimescu et al. [12] in a direct injection engine fueled with gasoline and butanol – the cold coolant promoted the formation of fuel films on the combustion chamber walls, which resulted in slower flame propagation and increased emissions.

Bielaczyc et al. [2] confirmed that the coolant temperature and the low ambient temperature significantly increased the emissions during cold start. In particular, an increase of up to tenfold in HC emissions was observed compared to steady-state conditions.

In the analyses of Mancarella and Marello [24] and Tauzia et al. [33], it was emphasised that higher coolant temperature improves engine thermal efficiency and reduces CO, HC, and PM emissions, but this is associated with the risk of increasing NO_x emissions. Dynamic modelling of thermal parameters (e.g. oil temperature, combustion chamber walls) was also indicated as a key factor in the realistic representation of emissions during the warm-up phase.

The type of fuel is also important. Farooq et al. [6] showed that engines fueled with methanol or its mixtures are characterised by an apparent sensitivity to low coolant temperature, which makes ignition difficult and leads to increased soot and HC emissions, especially at high fuel evaporation enthalpy. In the context of using modern emission analysis and prediction methods, Kłosowski et al. [14] proposed using LSTM networks to monitor industrial processes, which can also be adapted in the context of exhaust emissions. Pawlik et al. [27] indicated the potential of unsupervised algorithms to identify machine operating states, which is a direction for further development of emission models based on empirical data.

Proposed technical solutions include catalytic heaters [4], intake air preheating systems, and injection strategy optimisation [7, 9]. In recent years, predictive models using machine learning algorithms have also gained much popularity, which allow predicting emissions as a function of coolant temperature and starting conditions [21].

The cold start of an internal combustion engine is particularly problematic in low ambient temperature conditions, as it leads to heat losses, ignition delays and increased emissions due to incomplete combustion [1, 35]. This applies especially to hydrocarbons and carbon monoxide, which reach levels even several times higher in this phase than in the steady state.

In the studies by Andrych-Zalewska et al. [1] it was emphasised that not only the ambient temperature, but also the thermal state of the engine itself at the time of start (i.e. coolant and oil temperature) significantly affects the emission characteristics, which is fully confirmed by thermodynamic analyses [5]. A cold engine, even at moderate outside temperatures, can increase HC and PM emissions due to the delayed activation of exhaust gas combustion systems.

Attention is also drawn to the different engine behaviour depending on the fuel type. For example, fuels with high enthalpy of vaporisation, such as ethanol, methanol, or ammonia, require special ignition and injection management strategies [3, 15], including the use of fuel reformers or mixture preheaters. Koike et al. [15] demonstrated that using on-board ammonia reforming significantly improves the ignition stability during cold start. Recent research increasingly focuses on dynamic thermal management systems, including electrically heated catalysts [4], preheating strategies for intake air or coolant [7], and predictive algorithms for optimizing coldstart emissions using machine learning [21]. These approaches provide practical pathways for reducing pollutant peaks during start-up and improving overall emission control calibration.

An important technical aspect is optimising control strategies – modification of the ignition timing, injection time, and fuel delivery amount [22, 26]. Hybrid systems or auxiliary heat sources are also increasingly used in modern powertrains [15].

This study aims to assess the influence of ambient temperature and initial coolant temperature on pollutant emissions during the cold start of a combustion engine. In the first part, a literature review was conducted on measurement conditions, empirical relationships, and prediction models related to this phenomenon. Then, an experimental analysis of HC, CO, and CO_2 emissions in the WLTC test was conducted for two initial coolant temperature levels: 6°C and 28°C. The study aimed to determine the influence of these thermal differences on emission levels and the rate of their stabilisation during the engine warm-up phase.

In addition to the analysis of instantaneous emission values, a set of quantitative indicators is proposed, such as: total pollution (area under the curve), the relative share of emissions due to cold start, and the sensitivity of emissions to changes in initial temperature. The proposed indicators constitute a new analysis element, enabling a quantitative assessment of the engine's sensitivity to thermal conditions during start-up. In particular, the coefficient $\eta_{T_0^c:T_0^n}$ can be used as a comparative measure of the engine's "ecological sensitivity" and the effectiveness of the applied technical solutions in the context of cold start. This approach allows for a better capture of the relationships between thermal conditions and emission characteristics.

The presented results can be used to develop start strategies in variable climatic conditions and to calibrate emission prediction models in the cold start phase. These conclusions apply to homologation processes and the design of adaptive engine control systems that are compliant with future emission standards.

The main hypothesis of this study is that the initial thermal state of the engine, particularly the coolant temperature, significantly affects both the magnitude and dynamics of pollutant emissions during the cold start phase. The objective is to quantify this impact and propose diagnostic indicators for engine control strategy development.

2. Methodology

The choice of research methodology was based on analyses by previous authors [16, 17, 29], who emphasised the importance of vehicle starting conditions and drive system reliability in the context of pollutant emissions. Particular attention was paid to the influence of driving dynamics and the possibility of reproducing it during laboratory tests. The WLTC cycle was used in the study, following the recommendations for emission measurements in dynamic conditions, which allows for a realistic assessment of the start and initial phase of engine operation.

The tests were performed using a Ford Focus passenger car equipped with a spark-ignition engine with a displacement of 1798 cm^3, in the Flexifuel version. The tests were performed on a chassis dynamometer, which reproduced a vehicle's rolling resistance and aerodynamic drag in real conditions. This combined measurement-modelling approach was successfully used in other studies [36]. The WLTC cycle procedure was carried out for the simulated drive. Figure 2 shows the changes in the coolant temperature during the test, while Fig. 1 shows the vehicle speed profiles in two drives by the WLTC cycle.

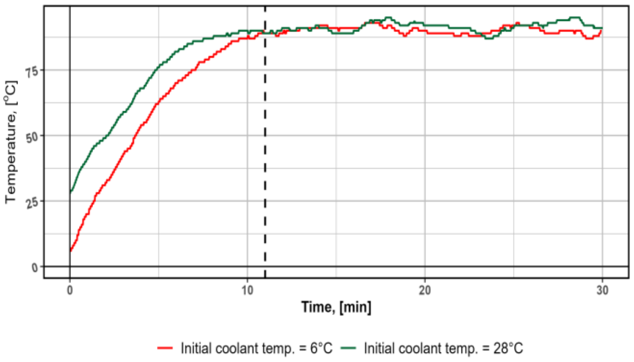

Fig. 1. Coolant temperature changes over time WLTC test

Figure 1 shows the coolant temperature increase during the WLTC test in two starting variants. The higher initial coolant temperature (28°C) resulted in faster achievement of the operating temperature (90°C), which is important for stabilising combustion processes and operating exhaust gas after-treatment systems.

A comparison of emissions was made between CO_2, CO and HC during the start of a passenger car, where in the first case the temperature of the cooling system was 6°C and in the second case 28°C. We consider the sequences $\{(x_i^c, T_i^c, v_i^c)\}_{0\le i\le m}$ and $\{(x_i^n, T_i^n, v_i^n)\}_{0\le i\le m}$, the quantity x_i^a denotes the amount of pollution in [ppm], T_i^a – engine temperature [°C], v_i^a – vehicle speed at the moment of i, $0 \le i \le m$, and $a \in \{c, n\}$, where c- the case where, when the vehicle was started, the temperature of the cooling system was 6°C, i.e. $T_0^c = 6$, n – the case where, when the vehicle was started, the temperature of the cooling system was 28°C, i.e. $T_0^n = 28$.

The contamination was analysed until the moment $\tau = \min\{i: T_i^c = T_i^n, 0 \le i \le m\}$. The moment of reaching identical temperatures $\tau = 656$, i.e. the moment of temperature equalisation (90°C), was obtained after 10 min 56 s. Therefore, the influence of temperature differences on contamination was analysed until the moment τ. When the initial temperature of the cooling system was 28°C, the engine operating temperature reached 90°C after 9 min 31 s.

The use of statistical and predictive methods is based on the approach proposed in [14] and [27], where the usefulness of machine learning algorithms in analysing technical and emission data has been demonstrated. This approach enables future extension of classical analysis methods with predictive components based on neural networks and temporal models as recommended in introductory machine learning frameworks [13]. Such extensions can be supported by cognitive tools and simulation-based frameworks developed for sustainable engine control [25].

Figure 2 shows the vehicle speed dynamics in two runs by the WLTC cycle, conducted at different initial coolant temperatures (6°C and 28°C). The similarity of the curves indicates high repeatability of the driving conditions, enabling a reliable comparison of the effect of the initial temperature on the dynamics of changes in the concentrations of pollutants in the exhaust gases.

Let $\{v_i\}_{0\le i\le\tau}$ be a sequence of speed differences at the appropriate moments of the journey between the two tests until τ (the moment when the engine temperatures equalise), i.e. $v_i = v_i^n - v_i^c$, $0 \le i \le \tau$. The average of speed differences in the tests $\bar{v} = \frac{1}{\tau}\sum_{i=1}^{\tau} v_i$ is – 0.08 km/h. In contrast, the standard deviation of speed differences $S_v = \sqrt{\frac{1}{\tau}\sum_{i=1}^{\tau}(v_i - \bar{v})^2}$ is 1.66 km/h, the average of absolute values of speed differences $\tilde{v} = \frac{1}{\tau}\sum_{i=1}^{\tau}|v_i|$ is equal 1.06 km/h. The statistical convergence of the recorded speeds, confirmed by the low deviation and the average difference, is consistent with the course shown in Fig. 2 and provides a basis for a reliable comparison of emissions under conditions of different initial temperatures.

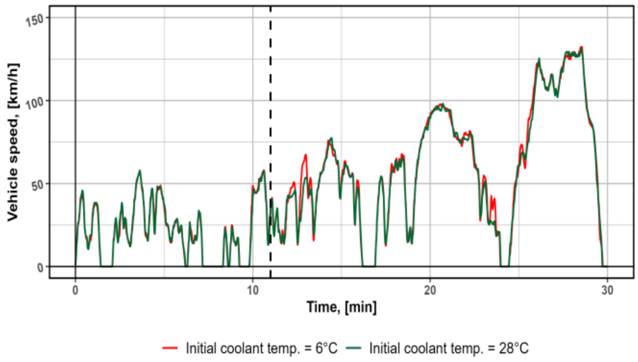

Fig. 2. WLTC cycle course for two tests with different temperatures initial liquid cooling

The graphs below show the differences in pollution (red curve for starting from a temperature of 6°C and green curve for starting from a temperature of 28°C) and vehicle speed (black curve, scale on the right side of the graph).

Starting at a lower initial temperature led to increased CO_2 concentrations in the exhaust gases in the first minutes of the test (see Fig. 3), which reflects the intensification of the combustion process with an enriched mixture. As the coolant warms up, a gradual convergence of the concentration curves for both cases is observed.

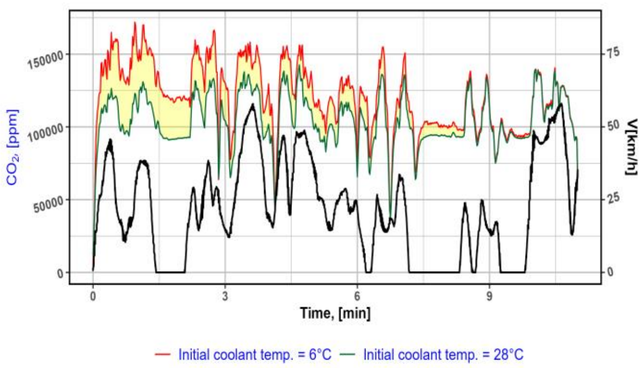

Fig. 3. CO_2 concentration and vehicle speed as a function of time (WLTC)

The concentration of carbon monoxide (CO) remains significantly higher during cold start (Fig. 4), which confirms the lower efficiency of exhaust gas combustion in this operation phase. The differences decrease with the increase in coolant temperature, but complete stabilisation occurs only after reaching operating conditions.

From Fig. 5, we can see that the concentration of unburned hydrocarbons (HC) after a cold start is several times higher than in the case of a start with a higher coolant temperature due to fuel condensation on the cold surfaces of the combustion chamber and delayed activation of emission reduction systems.

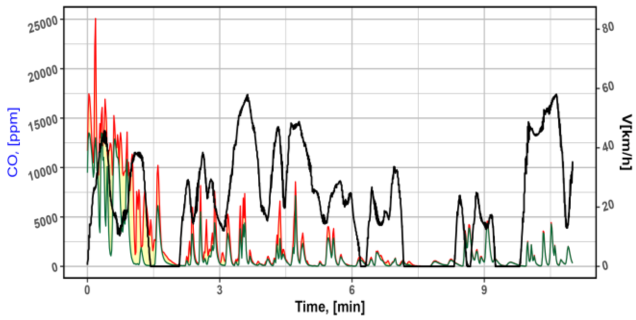

Fig. 4. CO concentration and vehicle speed as a function of time (WLTC)

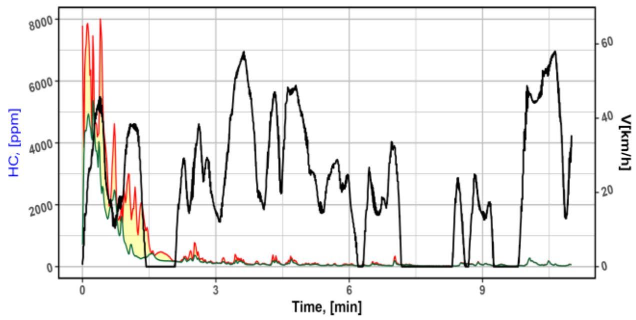

Fig. 5. HC concentration and vehicle speed as a function of time (WLTC)

Quantitative analysis of pollution growth

The value

$$W_{T_0^a} = \int_0^\tau x_t^a \, dt \tag{1}$$

is called the total pollution caused by starting the car for initial temperatures T_0^a, $a \in \{c, n\}$. The quantity $W_{T_0^a}$ means the area under the curve x_t^a for $0 \le t \le \tau$. In the case of measurements taken, for example, every second, the total pollution up to the moment $\tau$is approximated by $W_{T_0^a} \approx \sum_{i=0}^{\tau} x_i^a$. The quantity

$$\kappa_{T_0^c:T_0^n} = \frac{W_{T_0^c} - W_{T_0^n}}{W_{T_0^c}} \tag{2}$$

denotes the share of the increase in pollutants caused by starting the engine from the initial temperature T_0^c compared to the state of temperature T_0^n($T_0^c < T_0^n$) and operating the engine until the engine operating temperature is reached, i.e. $T_\tau^c = T_\tau^n$.

In order to compare the differences caused by different initial temperatures, the coefficient

$$\eta_{T_0^c:T_0^n} = \frac{\int_0^\tau |x_t^c - x_t^n| dt}{\int_0^\tau |T_t^n - T_t^c| dt} \approx \frac{\sum_{i=1}^{\tau} |x_i^c - x_i^n|}{\sum_{i=1}^{\tau} |T_i^n - T_i^c|} \tag{3}$$

was defined, which means the rate of change of pollutant concentration about changes in the initial engine operating temperature (emission sensitivity to changes in initial temperature). The parameters presented in equations (1)–(3) are an extension of the classical emission assessment methods with an approach that considers instantaneous concentrations. The indicator $\kappa_{T_0^c:T_0^n}$ expresses the relative increase in the cumulative pollutant concentration in cold start conditions, compared to a start with a higher initial temperature. In turn, the value $\eta_{T_0^c:T_0^n}$ describes the rate of change of cumulative concentration about the change in initial temperature, constituting a measure of the sensitivity of the drive system to cooling down. On the one hand, these indicators allow for a quantitative assessment of the impact of start conditions on emissions from the perspective of the concentration curve, and on the other hand – especially in the case of CO and HC – they indicate the variability of combustion efficiency and operation of exhaust gas treatment systems in the warm-up phase. A high value η for a given component may indicate limited engine capability for stable fuel energy conversion in low-temperature conditions. The proposed indicators can be used in thermal diagnostics and when comparing emission reduction strategies in different start scenarios.

Analysis of the impact of temperature differences

To analyse the effect of temperature differences on pollutants generated by the combustion engine, we define the sequence $\{(p_t, T_t)\}_{0 \le t \le \tau}$, where $T_t = T_t^n - T_t^c$ denotes the temperature difference and the pollutant difference $p_t = x_t^c - x_t^n$ for the moments $0 \le t \le \tau$, by the definition $T_\tau = 0$ and the largest temperature difference $T_{max} = \max\{T_j^n - T_j^c : 0 \le j \le \tau\}$. The interval $[0, T_{max}]$ has been divided into k −separate intervals, so that $[0, T_{max}] \subset [0, d) \cup [d, 2d) \cup \ldots \cup [(k-1)d, kd)$ and $T_{max} \in [(k-1)d, kd)$. As a representative of the temperature interval $[(j-1)d, jd)$ for $j = 1, 2, \ldots, k$ the value $t_j = (j - 0.5)d$ was taken.

For each set $P_j = \{p_i : T_i \in [(j-1)d, jd), 0 \le i \le \tau\}, j = 1, 2, \ldots, k$ the quantiles of order $\alpha/2$ and $1 - \alpha/2$ were determined and denoted as $q_j^{\alpha/2}$and $q_j^{1-\alpha/2}$respectively. The sequences $\left\{\left(t_j, q_j^{\alpha/2}\right)\right\}_{1 \le j \le k}$and $\left\{\left(t_j, q_j^{1-\alpha/2}\right)\right\}_{1 \le j \le k}$consist of a representative of the temperature difference interval $\left\{\left(t_j, q_j^{\alpha/2}\right)\right\}_{1 \le j \le k}$and the limits of the pollutant quantiles for these intervals. In order to predict the pollutants concerning the temperature difference for each of the sequences $\left\{\left(t_j, q_j^{\alpha/2}\right)\right\}_{1 \le j \le k}$ and $\left\{\left(t_j, q_j^{1-\alpha/2}\right)\right\}_{1 \le j \le k}$ the dependence

$$\log\left(q_j^s\right) = \theta_0^s + \theta_1^s t_j + \theta_2^s \sqrt{t_j} + \theta_3^s \frac{1}{t_j} + \varepsilon_j \tag{4}$$

was considered, where ε_j denotes a random variable with a normal distribution $N(0, \sigma_s^2)$, $s \in \{\alpha/2, 1 - \alpha/2\}$. The Least Squares Method was used to estimate the structural parameters of the model (4). Additionally the coefficient of determination

$$R^2 = 1 - \frac{\sum_{j=1}^{k} \varepsilon_j^2}{\sum_{j=1}^{k}\left(\log\left(q_j^s\right) - \hat{g}^s\right)^2} \quad (5)$$

was determined, where $\hat{g}^s = \frac{1}{k}\sum_{j=1}^{k} \log\left(q_j^s\right)$. The determination coefficient shows what part of the quantile variability of the order $s \in \{\alpha/2, 1-\alpha/2\}$ due to the temperature difference is explained by the model, Based on the following formula

$$q^s(t) = \exp\left(\hat{\theta}_0^s + \hat{\theta}_1^s t + \hat{\theta}_2^s \sqrt{t} + \hat{\theta}_3^s \frac{1}{t}\right) \quad (6)$$

the values of the quantile of order $s \in \{\alpha/2, 1-\alpha/2\}$ for temperature differences $t \in (0, T_0]$ were estimated.

3. Results

Using formulas (1)–(3), the indicators of the impact of the initial temperature on the pollutants generated by the operation of the combustion engine were estimated.

Table 1: Total pollution for normal start, total pollution from cold start, relative pollution due to starting the engine from low temperature, and the coefficient of change of contaminant concentration relative to changes in initial temperatures

	$W_{T_0^n}$	$W_{T_0^c}$	$\kappa_{T_0^c:T_0^n}$	$\eta_{T_0^c:T_0^n}$
CO_2	68506849	78926888	0.132	1328
CO	929425	1537429	0.3955	77
HC	221151	378723	0.4161	20

Using the quantitative indicators in Table 1, a clear relationship was observed between the initial engine temperature and the cumulative concentration of pollutants in the exhaust gases. The highest relative increase in the total concentration was noted for unburned hydrocarbons (HC), the share of which in emissions attributed to the cold start phase exceeded 40%. It is worth noting that, according to the time graphs (Fig. 5), this increase is concentrated mainly in the initial phase of the test, especially during accelerations, when the combustion chamber remains cooled. The concentration sensitivity indicator to initial temperature differences (η) reached the highest value for CO_2, which indicates a significant dependence of combustion intensity on thermal conditions of start-up, even though the total increase in the concentration of this component was relatively low. High values of the indicators for CO and HC indicate a high susceptibility of these compounds to the effect of delayed activation of after-treatment systems and combustion quality in the initial phase of the cycle.

The temperature difference interval $[0,24]$ was divided into intervals of length $d = 1$. For each type of pollutant, CO_2, CO, and HC, for the appropriate intervals and level, $\alpha = 0.1$ quantiles of order $\alpha/2 = 0.05$ and were estimated, $1 - \alpha/2 = 0.95$ and sequences $\left\{\left(t_j, q_j^{0.05}\right)\right\}_{1 \le j \le k}$ and were determined, $\left\{\left(t_j, q_j^{0.95}\right)\right\}_{1 \le j \le k}$. Using the least squares method, structural parameters (4) were determined and using formula (6), quantiles for pollutants were predicted concerning the temperature difference at the start. In Fig. 6–8 in the Cartesian coordinate system, the realisation of the sequence $\{(p_t, T_t)\}_{0 \le t \le \tau}$, where the temperature difference $T_t = T_t^n - T_t^c$ on the abscissa axis, and the pollutant difference on $p_t = x_t^c - x_t^n$ the ordinate axis for the moments, were marked with black points $0 \le t \le \tau$. Values prediction of quantiles are salmon coloured.

The models describing the behaviour of quantiles for CO_2, CO, and HC concentrations showed high values of the coefficient of determination ($R^2 > 0.86$), confirming the agreement between the difference in initial temperatures and the distribution of the analysed components' concentrations. The differences in the values of structural parameters between quantiles 0.05 and 0.95 reflect the increasing risk of extreme concentrations in conditions of strong cooling of the powertrain. In particular, a larger range of these parameters results in wider confidence intervals for the predicted concentrations, which means that a larger difference in initial temperatures leads to increased prediction uncertainty. The smallest differences in structural parameters and the smallest fitting error were observed for CO_2 (quantile 0.95), which indicates the stable nature of this component's emissions. In turn, for CO, the highest values of standard deviations of predictions and relatively lower R^2 were observed (especially for the 0.05 quantile), which confirms its greater susceptibility to the variability of start conditions and lower accuracy of representation in the model.

Table 2: The values of estimators of structural parameters, the values of coefficient determination and the values of standard deviations for quantitative models

Pollution	s	θ_0^s	θ_1^s	θ_2^s	θ_3^s	R_s^2	σ_s
CO_2	0.05	5.73	–0.17	1.73	–0.62	0.90	0.39
CO_2	0.95	3.82	–0.28	2.57	0.76	0.99	0.11
CO	0.05	64.12	3.79	–29.49	–67.34	0.87	0.96
CO	0.95	6.44	0.44	–1.39	–0.79	0.94	0.430
HC	0.05	26.76	2.56	–16.47	–10.38	0.95	0.65
HC	0.95	5.87	0.79	–3.08	–1.17	0.975	0.42

For each of the pollutants, the values of structural parameters for the model (4), the values of the standard deviation of the residuals, and the values of the coefficient of determination (5) are given in Table 2. The lowest value of the coefficient of determination, equal to 0.8674, was obtained for the CO pollutant when fitting the dependence of the quantile of the order of 0.05 on the temperature differences, while for the remaining pollutants, the value of the coefficient of determination exceeds 0.90.

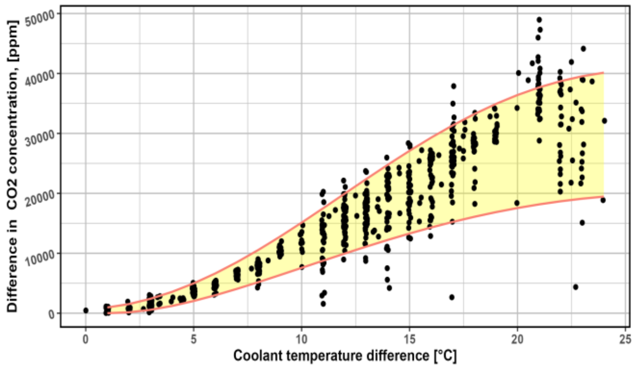

Fig. 6. Fitting models of 0.05 and 0.95 quantiles of CO_2 concentration with respect to the initial temperature difference

The increase in the initial temperature difference results in a moderate increase in CO_2 concentrations within both analysed quantiles. The model shows a perfect fit, especially for the 0.95 quantile ($R^2 = 0.9915$), which indicates the stability of this component's characteristic concerning the start-up's thermal conditions.

In the case of CO, there is a clear dependence of the upper quantile value on the temperature difference, which indicates an increased probability of high concentrations occurring when the system is strongly cooled. However, the data scatter is larger than in the case of CO_2, which translates into a lower quality of the model fit for the quantile of the order of 0.05.

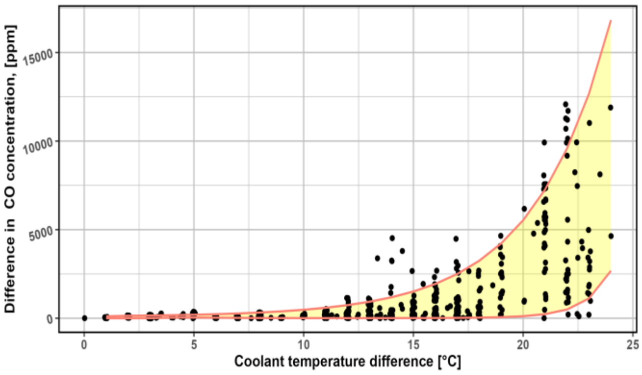

Fig. 7. Fitting models of 0.05 and 0.95 quantiles of CO concentration with respect to the initial temperature difference

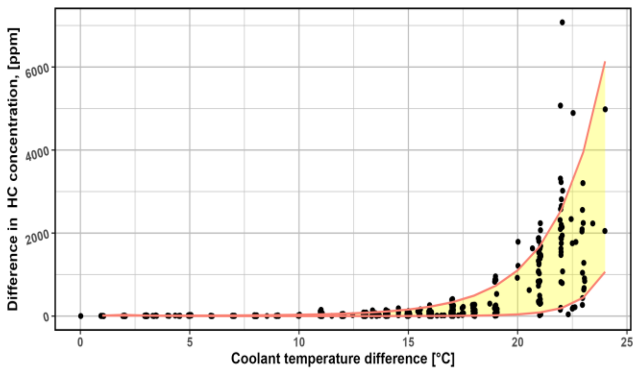

Fig. 8. Fitting models of 0.05 and 0.95 quantiles of HC concentration with respect to the initial temperature difference

HC concentration shows an apparent sensitivity to temperature differences in the cold start phase. At a lower initial engine temperature, significantly higher values of unburned hydrocarbon concentration are observed, which results from worse ignition conditions, fuel condensation on the cold walls of the combustion chamber, and delayed activation of exhaust gas after-treatment systems. With decreasing starting temperature difference, HC concentration values stabilise quickly – the curves of the courses get closer to each other, confirming this component's strong dependence on the thermal conditions of start-up. A high level of fit of regression models for both quantiles ($R^2 = 0.9485$ and $R^2 = 0.9695$ for 0.05 and 0.95) indicates high predictability of this dependence, despite significant dynamics of concentration changes.

4. Discussion of the results

The results of the conducted studies confirm that lowering the initial coolant temperature significantly affects the combustion process and the concentration of pollutant components in the cold start phase. The increases in HC, CO, and CO_2 concentrations observed in the WLTC tests at a lower starting temperature (6°C vs. 28°C) are consistent with the phenomenon of reduced combustion quality and delayed achievement of catalyst activation conditions described in the literature [2, 9, 12]. The formation of a liquid fuel film on the cold surfaces of the combustion chamber, as well as enrichment of the mixture to improve ignition, results in increased emissions of hydrocarbons and carbon monoxide in the initial minutes of engine operation [6, 12].

The time dependencies in Fig. 3–5 show apparent differences in CO_2, CO, and HC concentrations between tests with different initial temperatures. Especially for HC, a several-fold increase in concentration was observed in the first minutes of the test at low temperature conditions, consistent with the results of Andrych-Zalewska et al. [1] and Yusuf and Inambao [35]. At the same time, the CO concentration remained at a higher level throughout the test under cold start conditions, indicating insufficient catalyst activity in the transient phase [34].

The quantitative indicators presented in Table 1 are also of diagnostic value, including the relative share of emissions related to cold start and the sensitivity of emissions to changes in initial temperature. The most significant relative increase in concentration was for HC (over 40%), while for CO it reached almost 40% and for CO_2 slightly above 13%. The high sensitivity index for CO_2 indicates that, despite the relatively stable nature of this component, the combustion process at low temperature may be less efficient, which translates into its increased emission, which is also confirmed by Hossain et al. [10].

The $\eta_{T_0^c:T_0^n}$ [ppm/°C or g/km/°C] indicator describes the sensitivity of pollutant concentrations or emissions generated during engine operation to changes in thermal start-up conditions. It determines the average increase in these values for each 1°C drop in initial temperature. The lower the indicator's value, the smaller the increase in pollutants associated with a decrease in initial temperature, which means greater emission resistance of the system to cold start conditions. Depending on the available measurement data, this indicator can analyse concentrations (e.g. ppm) and emissions (e.g. g/km). In the future, it may be a universal comparative tool for assessing the emission sensitivity of different drive units, control strategies, or exhaust gas treatment technologies to variations in initial temperature.

Quantile regression allowed for better capturing the variability of extreme pollutant concentrations concerning the initial temperature difference in line with advanced statistical learning approaches [8]. The models (Fig. 6–8) showed a perfect fit for CO_2 ($R^2 \approx 0.99$) and HC ($R^2 \approx 0.97$), slightly lower for CO, which is probably due to the greater scatter and temporary increase in emissions in response to the engine operation dynamics. The range of prediction values in the upper quantiles (0.95) was significant, which increased nonlinearly with the initial temperature difference.

This phenomenon indicates an increased risk of extreme concentration levels in severe cooling conditions [21].

Figures 1 and 2, illustrating the WLTC cycle and the change in coolant temperature, confirm that differences in starting conditions did not significantly affect the vehicle speed profile, while the time needed for the cooling system to reach the operating temperature was significantly extended in the case of a lower starting temperature (10:56 min vs. 9:31 min). The extension of the warm-up time is associated with a delayed achievement of the catalyst's light-off temperature, which, according to literature data [23, 28], may result in an even several-fold increase in the total HC and CO emissions in this phase. Similar conclusions were drawn by Slavin et al. [30], who showed that electrically heated catalysts can effectively reduce cold start emissions in LPG-fueled vehicles, highlighting the importance of thermal emission management.

From the perspective of designing emission reduction strategies, the presented results emphasise the validity of using technical solutions such as heated catalysts [4], advanced injection strategies [32], or thermal management systems with heat recovery from exhaust gases [28]. Quantile regression models can also help predict extreme emissions, which is reflected in the growing interest in using machine learning techniques for this purpose [21].

5. Conclusions

The analyses showed that the coolant's initial temperature significantly affects the dynamics of changes in the concentrations of pollutants emitted by the spark-ignition engine during cold start. Lowering the starting temperature to 6°C resulted in a significant increase in CO, HC, and CO_2 concentrations in the first minutes of the WLTC cycle, which can be associated with delayed activation of exhaust gas treatment systems, lower charge temperature, and enrichment of the fuel-air mixture.

CO and HC showed the greatest sensitivity to start conditions among the compounds tested. In the case of HC, the share of concentration assigned to the cold start phase exceeded 40%, which confirms its high susceptibility to the effect of cooling the combustion chamber. Similar HC emission patterns during cold start were reported in previous studies [18, 20]. Conversely, CO showed the greatest scatter of values in the empirical data, which is confirmed by high standard deviations and discrepancies between quantiles, especially at significant differences in initial temperatures.

In order to quantitatively assess the effect of thermal conditions on emissions, a set of indicators was used, such as the total cumulative concentration, the share of emissions attributed to cold start $\kappa_{T_0^c:T_0^n}$ and the sensitivity indicator $\eta_{T_0^c:T_0^n}$. These indicators allowed to capture the relationship's nonlinear nature and distinguish the response of individual exhaust components to engine cooling. The highest thermal sensitivity was demonstrated for CO_2, although its total increase was moderate, which may indicate variable combustion efficiency depending on the initial temperature.

Quantile models allowed the analysis of both average and extreme drive system behaviour. High coefficients of determination ($R^2 > 0.90$) obtained for CO_2, CO, and HC confirm the validity of the approach. The models showed that the upper quantile values (0.95) of HC and CO concentrations increase nonlinearly with the starting temperature difference, indicating an increased risk of extreme emissions in winter conditions.

In addition, it was found that the time to reach the operating coolant temperature at a lower initial temperature is longer by more than 1 minute (10:56 min vs. 9:31 min), directly affecting the length of the period of increased emissions. The extended warm-up phase is associated with limited efficiency of the afterburning systems, which can significantly increase the total environmental load of the vehicle in urban and suburban cycles.

The obtained results have practical applications both in designing start strategies in variable climatic conditions and in the calibration of emission prediction tools used in homologation procedures and systems for assessing the impact of transport on air quality. This approach can also support broader life-cycle and environmental impact assessments [31]. The proposed analytical approach can also be a starting point for further research on optimising injection, ignition, and thermal management systems in modern drive systems.

Furthermore, these indicators may support the development of advanced cold start control strategies, enable dynamic thermal management and improving catalyst activation during homologation cycles and real-world driving.

Bibliography

[1] Andrych-Zalewska M, Chlopek Z, Merkisz J, Pielecha J. Impact of the internal combustion engine thermal state during start-up on the exhaust emissions in the homologation test. Energies. 2023;16(4):1937. https://doi.org/10.3390/en16041937

[2] Bielaczyc P, Szczotka A, Woodburn J. The effect of a low ambient temperature on the cold-start emissions and fuel consumption of passenger cars. P I Mech Eng D-J Aut. 2011;225(9):1253-1264. https://doi.org/10.1177/0954407011406613

[3] Cao Y, Chen D. A cold-start method and analysis for internal combustion engines particularly using a renewable fuel. Int J Energ Res. 2011;35(4):358-364. https://doi.org/10.1002/er.1683

[4] Duan L, Tan P, Liu J, Liu Y, Chen Y, Lou D et al. Emission characteristics of a diesel engine with an electrically heated catalyst under cold start conditions. J Clean Prod. 2022;380: 134965. https://doi.org/10.1016/j.jclepro.2022.134965

[5] E J, Liu G, Zhang Z, Han D, Chen J, Wei K et al. Effect analysis on cold starting performance enhancement of a diesel engine fueled with biodiesel fuel based on an improved thermodynamic model. Appl Energ. 2019;243:321-335. https://doi.org/10.1016/j.apenergy.2019.03.204

[6] Farooq MS, Baig A, Wei Y, Liu H, Ali U. A concise review of developments to overcome the cold start problems by analyzing combustion and emissions of methanol-based-fueled spark ignition engines. Int J Hydrogen Energy. 2025;99:852-871. https://doi.org/10.1016/j.ijhydene.2024.12.263

[7] Galindo J, Dolz V, Monsalve-Serrano J, Bernal Maldonado MA, Odillard L. EGR cylinder deactivation strategy to accelerate the warm-up and restart processes in a diesel engine operating at cold conditions. Int J Engine Res. 2022;23(4): 614-623. https://doi.org/10.1177/14680874211039587

[8] 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

[9] He X, Zhou Y, Liu Z, Yang Q, Sjöberg M, Vuilleumier D et al. Impact of coolant temperature on the combustion characteristics and emissions of a stratified-charge direct-injection spark-ignition engine fueled with E30. Fuel. 2022;309: 121913. https://doi.org/10.1016/j.fuel.2021.121913

[10] Hossain A, Smith D, Davies P. Effects of engine cooling water temperature on performance and emission characteristics of a compression ignition engine operated with biofuel blend. J Sustain Dev Energy Water Environ Syst. 2017;5(1): 46-57. https://doi.org/10.13044/j.sdewes.d5.0132

[11] Hunicz J, Krzaczek P. Detailed speciation of emissions from low-temperature combustion in a gasoline HCCI engine. Pol J Environ Stud. 2016;25(1):137-145. https://doi.org/10.15244/pjoes/60082

[12] Irimescu A, Merola SS, Tornatore C, Valentino G. Effect of coolant temperature on air–fuel mixture formation and combustion in an optical direct injection spark ignition engine fueled with gasoline and butanol. J Energy Inst. 2017;90(3): 452-465. https://doi.org/10.1016/j.joei.2016.03.004

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

[14] 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

[15] Koike M, Suzuoki T, Takeuchi T, Homma T, Hariu S, Takeuchi Y. Cold-start performance of an ammonia-fueled spark ignition engine with an on-board fuel reformer. Int J Hydrogen Energ. 2021;46(50):25689-25698. https://doi.org/10.1016/j.ijhydene.2021.05.052

[16] 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(4):191545. https://doi.org/10.17531/ein/191545

[17] Kozłowski E, Wiśniowski P, Gis M, Zimakowska-Laskowska M, Borucka A. Vehicle acceleration and speed as factors determining energy consumption in electric vehicles. Energies. 2024;17(16):4051. https://doi.org/10.3390/en17164051

[18] Laskowski P, Zasina D, Zimakowska-Laskowska M, Orliński P. Modelling hydrocarbons cold-start emission from passenger cars. Adv Sci Technol Res J. 2021;15(3): 117-125. https://doi.org/10.12913/22998624/138764

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

[20] Laskowski P, Zimakowska-Laskowska M, Zasina D. Modelling of the air pollutants' cold-start emissions depending on average vehicles' speed. Combustion Engines. 2022;188(1): 96-103. https://doi.org/10.19206/CE-142171

[21] Liu K, Zhou J, Pei Z, Fu W, Yang H, Jiang Z et al. Research on transient emissions prediction for natural gas engine using the tuna swarm optimization-extreme gradient boosting algorithm under worldwide harmonized transient cycle. Atmos Pollut Res. 2025;16(4):102425. https://doi.org/10.1016/j.apr.2025.102425

[22] Liu R, Wei M, Yang H. Cold start control strategy for a two-stroke spark ignition diesel-fuelled engine with air-assisted direct injection. Appl Therm Eng. 2016;108:414-426. https://doi.org/10.1016/j.applthermaleng.2016.07.148

[23] Lodi F, Zare A, Arora P, Stevanovic S, Jafari M, Ristovski Z et al. Engine performance and emissions analysis in a cold, intermediate and hot start diesel engine. Appl Sci. 2020; 10(11):3839. https://doi.org/10.3390/app10113839

[24] Mancarella A, Marello O. Effect of coolant temperature on performance and emissions of a compression ignition engine running on conventional diesel and hydrotreated vegetable oil (HVO). Energies. 2022;16(1):144. https://doi.org/10.3390/en16010144

[25] Orynycz O, Tucki K, Prystasz M. Implementation of lean management as a tool for decrease of energy consumption and CO_2 emissions in the fast food restaurant. Energies. 2020;13(5):1184. https://doi.org/10.3390/en13051184

[26] Pastor JV, García-Oliver JM, Pastor JM, Ramírez-Hernández JG. Ignition and combustion development for high speed direct injection diesel engines under low temperature cold start conditions. Fuel. 2011;90(4):1556-1566. https://doi.org/10.1016/j.fuel.2011.01.008

[27] 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(3):168109. https://doi.org/10.17531/ein/168109

[28] Rakov V, Pikalev O, Bogomolov A, Dymov N. Modeling of engine warm-up with the use of an exhaust gas recuperator at low ambient temperatures. Transp Res Proc. 2021;57:547-552. https://doi.org/10.1016/j.trpro.2021.09.083

[29] Rimkus A, Kozłowski E, Vipartas T, Pukalskas S, Wiśniowski P, Matijošius J. Emission characteristics of hydrogen-enriched gasoline under dynamic driving conditions. Energies. 2025;18(5):1190. https://doi.org/10.3390/en18051190

[30] Slavin V, Shuba Y, Caban J, Matijosius J, Rimkus A, Korpach A et al. The performance of a car with various engine power systems – part I. LOGI – Scientific Journal on Transport and Logistics. 2022;13(1):130-140. https://doi.org/10.2478/logi-2022-0012

[31] Sobaszek Ł, Piasecka I, Flizikowski J, Tomporowski A, Sokolovskij E, Bałdowska-Witos P. Environmentally oriented analysis of benefits and expenditures in the life cycle of a wind power plant. Materials. 2023;16(2):538. https://doi.org/10.3390/ma16020538

[32] Song J, Lee Z, Song J, Park S. Effects of injection strategy and coolant temperature on hydrocarbon and particulate emissions from a gasoline direct injection engine with high pressure injection up to 50 MPa. Energy. 2018;164:512-522. https://doi.org/10.1016/j.energy.2018.09.011

[33] Tauzia X, Karaky H, Maiboom A. Evaluation of a semi-physical model to predict NOx and soot emissions of a CI automotive engine under warm-up like conditions. Appl Therm Eng. 2018;137:521-531. https://doi.org/10.1016/j.applthermaleng.2018.04.005

[34] Tsiuman M, Sadovnyk I. Research on the efficiency of catalytic conversion of exhaust gases from a car engine during warm-up mode. Avtošljachovyk Ukraïny. 2024;2(279): 70-73. https://doi.org/10.33868/0365-8392-2024-2-279-70-73

[35] 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 Studies in Thermal Engineering. 2019;14:100417. https://doi.org/10.1016/j.csite.2019.100417

[36] 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(1):145-154. https://doi.org/10.19206/CE-201224

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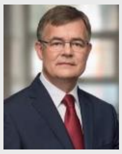

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