Article citation info:
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

Piotr LASKOWSKI
Magdalena ZIMAKOWSKA-LASKOWSKA
Jan MATEJ
Piotr WIŚNIOWSKI

Combustion Engines
Polish Scientific Society of Combustion Engines

The problem of cold start emissions from vehicles

ARTICLE INFO

Received: 30 November 2023
Revised: 29 February 2024
Accepted: 25 March 2024
Available online: 7 June 2024

The progression of passenger vehicles is progressing, and regulations are continually being revised, resulting in a decrease in car exhaust emissions. The European Commission has revised the RDE test procedure to include exhaust emissions during a cold start as part of package 3. The article carried out simulations using COPERT software, which uses tests based on WLTP, assuming ambient temperatures from –10°C to +20°C, at intervals of 5°C. This paper aims to present the results of mathematically modelling the influence of ambient temperature on the cold start emissions of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), nitrogen oxides (NO_x), non–methane volatile organic compounds (NMVOC), hydrocarbons (treated as volatile organic compounds – VOC), total particulate matter (TSP) and particle number (PN) in passenger cars and light duty vehicles. The modelling results show that a change in ambient temperature significantly affects carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), hydrocarbons (treated as volatile organic compounds – VOC), total particulate matter (TSP) and particle number (PN) in cold start emissions.

Key words: *cold start emission, vehicle, COPERT, pollutant, GHG*

1. Introduction

Cold start emissions have received much attention due to their adverse impact on air quality and public health. Cold start emissions are the emissions a vehicle produces when it is started again after being left idle for a while [2]. When an engine is first started up, it typically runs inefficiently, leading to an increase in the emission of pollutants, including carbon monoxide, nitrogen oxides, and volatile organic compounds. This is known as the cold start problem [2]. The phrase "cold start emissions" refers to the pollution released when a vehicle is first started up after being inactive for an extended length of time, generally overnight or after a number of hours of not being used. Emissions from vehicles that have recently started up tend to be higher than those coming from cars that have been running for a while. The main cause of this is the engine and its parts not having reached the ideal working temperature yet. The fuel mixture, combustion efficiency, and emission control systems may not be operating at their best, causing more pollutants to be released into the atmosphere [2, 9]. The release of these substances into the air can lead to a high level of air contamination and can have a damaging impact on both the health of people and the environment [1]. The release of these substances can create smog and tiny particles, which can result in illnesses related to the lungs and heart, in addition to contributing to global warming [1, 15]. It is essential to take action to solve the issue of cold start emissions in order to reduce the amount of emissions from vehicles and enhance air quality.

The European Union Commission Regulation 2017/1154 [20] defines cold start as the initial start of the combustion engine until the engine has been running for a total of 5 minutes. Once the coolant temperature is determined, the cold start period will finish when the coolant reaches 343 K (70°C) for the first time or after the engine has been running for a total of five minutes from the time the engine was first started [9].

Research has indicated that the emissions from vehicles used on roads are a major contributor to air contamination and can have a detrimental effect on air quality and people's wellbeing, especially in metropolitan regions. The European Union is taking steps to lower air pollution and reach a state of climate neutrality, resulting in new, more stringent laws and regulations on vehicle exhaust. In order to comply with these regulations, more advanced exhaust gas aftertreatment systems are required. Research has been conducted in recent years about emissions from cold start operations, illustrating the global significance of this issue [12–14, 16, 22]. Additionally [7, 10, 11, 14], NO_x emissions from vehicles with gasoline engines should be considered in future updates to EU regulations [7].

In 2016 [8, 9], the European Union implemented the first two sets of actual driving emissions (RDE) tests – Regulations 2016/427 and 2016/646 – the world's first type-approved road tests for light duty vehicles. As of September 2017, the tests have binding emission limitations and use portable emission measurement systems (PEMS) to measure contaminants. The European Commission has begun creating two additional RDE programs, which focus on cold start emissions, testing for hybrid vehicles, the measurement of particulate emission numbers (PN) on the road, and the regular adjustment of aftertreatment systems. This is due to a cold start that has a significant impact on emissions, especially in urban areas with frequent short journeys and air quality problems [1, 9].

The latest analysis of [1] shows that the average daily distance travelled by passenger cars is not sufficient for the vehicle's pollution control system to warm up and become fully functional. The resulting high levels of NO_x emissions during cold-starts from both petrol and diesel engines may pose an additional challenge to urban air quality initiatives.

At normal temperatures, the amount of emissions released during a cold engine start-up is much greater than when the engine is already warm. In addition, exhaust aftertreatment devices are not effective in reducing emissions due to the catalyst failing to reach a temperature necessary for activation [9].

Diesel engines are commonly employed in the automotive and energy sectors. In order to meet the more demanding automotive exhaust emission regulations, newer and more advanced engine technologies have been created. Adhering to the current standards can be achieved by decreasing the emissions produced during combustion and/or improving the efficiency of exhaust aftertreatment systems [9].

The European Commission (EC) [8, 21] is aiming to lower nitrogen oxide (NO_x) emissions from diesel automobiles through the incorporation of cold start emissions into the Real Driving Emissions (RDE) testing process. The European Commission (EC) implemented particular regulations concerning cold-starts as part of the third Real Driving Emissions (RDE) legislative package due to the fact that selective catalytic reduction (SCR) and lean NO_x scavenger aftertreatment systems can cause heightened NO_x emissions during cold-start.

While conducting literature research, the authors paid attention to the ambient temperature and its impact on cold start emissions. Authors in articles [13, 22, 23] examined the effect that various ambient temperatures (–7°C and 23°C) had on the emission results of vehicles that were equipped with both compression and spark ignition engines. The purpose of the tests was to investigate whether the exhaust emissions during WLTC (Worldwide Harmonized Light Duty Vehicles Test Cycle) tests increase in colder temperatures in comparison to warmer temperatures [3–7, 13] and to check for compliance with Euro 6 emission standards.. Research shows that ambient temperature has a significant impact on cold start emissions.

The literature analysis shows that the problem of cold start emissions is important, and numerous studies confirm this. However, more information on cold start emissions in a wide temperature range is a significant issue. The novelty of this article lies in the detailed analysis of the impact of ambient temperature on cold start emissions for various pollutants emitted by vehicles. The study conducted by the authors using COPERT software to simulate different temperature scenarios and their effect on emissions is a novel approach to understanding the dynamics of cold start emissions. By highlighting the significant reduction in emissions as temperatures increase, the research provides valuable insights into potential strategies to reduce emissions and improve air quality in urban areas. This innovative use of simulation technology and data analysis adds to the knowledge of cold start emissions and provides a basis for further research.

2. Methodology

Vehicles that do not reach their optimal operating temperature tend to produce higher levels of air pollution [2].

For a given pollutant, engine speed, and initial engine temperature, the vehicle's emissions and development over time can be broken down into two stages: the first stage where emissions diminish due to a gradual rise in either the engine or catalyst temperature, and then a stability phase when the engine reaches a regular temperature (Fig. 1). The initial phase is aligned with time t_{cold} [2].

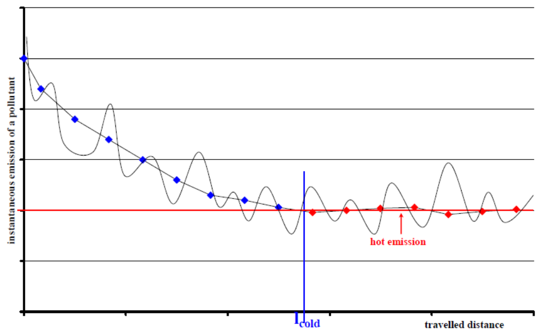

Fig. 1. The change in the amount of exhaust emitted by a vehicle as it travels distances in real-world settings [2]

The amount of pollution produced in excess when travelling a certain distance at a lower temperature than normal operating conditions is referred to as an excess cold emission. The same engine speed and average driving speed can be used to calculate how far a car has gone when driving in cold temperatures (as seen in Fig. 1) [2]. In a driving cycle involving various engines and vehicles in urban areas, the instantaneous emission output becomes much more intricate and irregular. The operating phases and the temperature rise can both affect the fluctuation in motor rotation frequency; this is illustrated in Fig. 1, where the fluctuation is much more rapid when the temperature goes up than it would be in reality. The difference in emissions from a vehicle when the engine is cold compared to when it is running hot is referred to as the total cold emissions of the vehicle and driving cycle. The amount of emission produced is dependent on the temperature surrounding it, which deviates from the standard temperature for operation. The understanding of this idea is dependent on the speed of the cycle of accelerations and decelerations being much quicker than the temperature increase of the vehicle. Once the driving cycle is continued for a sufficient period of time, a constant distance must be maintained so that all excess cold emissions are accounted for as heat emissions on the vehicle's interior. Excess emissions depend on the driving cycle and pollutants [2].

The authors used COPERT software for this article, as it is accepted for creating emissions inventories in European nations. This program makes use of the "Tier 3" methodology, which computes the complete exhaust emissions by separating between emissions released during the thermal engine operation ("cold start emissions") and those emitted when the engine reaches its regular operating temperature ("hot emissions"). The equation for the 'Tier 3' methodology is provided [15].

$$E_{Total} = E_{Hot} + E_{Cold} \quad (1)$$

where: E_{Total} – total emissions [g] of any pollutant for the spatial and temporal resolution of the application, E_{Hot} – emissions [g] during stabilized (hot) engine operation, E_{Cold} – emissions [g] during transient thermal engine operation (cold-start) [15].

When a vehicle is first turned on, its emissions are higher than when the engine is at its normal operating temperature. This is referred to as cold start emissions and is expressed as grams of pollutants per vehicle start. These emissions can be compared to the hot emissions released when the engine is running normally. The distance travelled before reaching stabilized emissions is known as l_{trip} [15].

To measure cold start emissions in a laboratory, a chassis dynamometer must be used together with a driving cycle that is lengthy enough to reach balance in the engine's operating conditions. This driving cycle should imitate the expected conditions of the vehicle's engine when it is being operated. Evaluating the correlation between the initial pollution and the chosen parameter (like the speed of the vehicle) through the driving cycle should maintain the same driving style during both the cold and hot times. It is commonly assumed that the majority of cold start emissions originate from urban driving, with rural driving as the second largest contributor. This is due to the fact that highway conditions are not usually the starting point for many trips [15].

$$\mathrm{E_{Total}} = \mathrm{E_{Urban}} + \mathrm{E_{Rural}} + \mathrm{E_{Highway}} \tag{2}$$

where E_{Ubran}, E_{Rural}, and $E_{Highway}$ are the total emissions [g] of any pollutant for the respective driving situations.

The ambient temperature can have a major effect on the amount of air pollutants released from both spark ignition and compression ignition engine vehicles. Research has suggested that there could be a link between the temperature of the environment and the amount of emissions given off during a cold-start. At present, the only emissions that are regulated during a vehicle's initial start-up are carbon monoxide, hydrocarbons, nitrogen oxides, and total particulate matter. For this reason, it is essential to review the current EU winter vehicle emissions regulations. Total emissions are calculated by combining the activity data and the emission factors for each vehicle [15]. The amount of emissions released can differ depending on the driving and weather conditions. Emissions produced during a cold start can be estimated by subtracting the amount of emissions that would be released if all vehicles ran with hot engines and active catalysts. This is done using a specific formula [17]:

$$\mathrm{E_{Cold,i,k}} = \beta_{\mathrm{i,k}} \cdot \mathrm{N_k} \cdot \mathrm{M_k} \cdot \mathrm{e_{hot,i,k}} \cdot \left(\frac{\mathrm{e_{cold}}}{\mathrm{e_{hot}}}\bigg|_{\mathrm{i,k}} - 1\right) \tag{3}$$

where $\mathrm{E_{Cold,i,k}}$ – cold start emissions of pollutant i (for the reference year), produced by vehicles of the technology k, $\beta_{\mathrm{i,k}}$ – fraction of the mileage driven with a cold engine (or the catalyst operated below the light-off temperature) for pollutant i and vehicles of the technology k, $\mathrm{N_k}$ – number of vehicles [veh] of the technology k in circulation; $\mathrm{M_k}$ – total mileage per vehicle [km/veh] in vehicles of the technology k, $\mathrm{e_{hot,i,k}}$ – hot emission factor for pollutant i and vehicles of the technology k, $\frac{\mathrm{e_{cold}}}{\mathrm{e_{hot}}}\Big|_{\mathrm{i,k}}$ – cold/hot emission quotient for pollutant i and vehicles of the technology k.

The β parameter is affected by the temperature of the environment, the way the vehicle is used, and the average distance travelled before emission levels stabilize (l_{trip}). The methodology followed the guidelines set out by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and EMEP/EEA air pollutant emission inventory guidebook 2019 [17] which serve as basic guidelines for inventories of greenhouse gases and air pollutants [15] indicate that l_{trip} is usually increased [15]. In accordance with the above guidelines, l_{trip} was adopted for passenger cars – 12 km and for light duty vehicles – 12 km.

The introduction of stricter emissions standards for catalyst petrol vehicles has shortened the amount of time needed for the catalyst to reach light-off temperature. As a result, the mileage driven under cold start conditions is lower. The β-parameter is also affected by the degree of emission control legislation for petrol catalyst vehicles [17].

The quantity of emissions released in cold or hot conditions is known as the e^{COLD}/e^{HOT} ratio and is impacted by the surrounding temperature and the type of pollutant being examined. While the model used in the original version of this methodology is still applied to the calculation of emissions during cold-starts, more current ratios were included in the last revision of this chapter for cars with catalytic converters [17].

Cold start emissions are usually only connected to urban driving, but a percentage can be ascribed to rural driving when the mileage driven with an engine that is not at the optimal temperature (β-parameter) is greater than the mileage driven in urban areas (S_{URBAN}). This means that equation (4) needs to be modified, which produces the following result [17]:

If $\beta_{i,k} > S_{URBAN}$

$$\mathrm{E_{COLD\ URBAN;i,k}} = \mathrm{S_{URBAN;\,k}} \cdot \mathrm{N_k} \cdot \mathrm{M_k} \cdot \mathrm{e_{HOT\ URBAN;\,i,k}} \cdot \left(\frac{\mathrm{e_{cold}}}{\mathrm{e_{hot}}}\bigg|_{\mathrm{i,k}} - 1\right) \tag{4}$$

It is thought that the mileage driven in urban areas is equivalent to warming up the engine, while any additional emissions are a result of driving in rural areas. Equation (4) is an extreme example for a national inventory, and only happens when a tiny amount is given as l_{trip}. It is also noteworthy that the urban hot emission factor is used for both variations of eq. (4). The overall emissions of N_2O and CH_4 should not be distinguished based on where they were released. The determination of these emissions is based on four types of driving conditions: 'cold urban', 'hot urban', 'rural', and 'highway'. This algorithm outlines the process for determining the emission of pollutants, particularly methane (CH_4). It is especially important to estimate CH_4 emissions because NMVOCs are calculated by taking the difference between VOCs and CH_4. To begin, it is necessary to determine if the portion of the mileage driven under non-stabilized engine temperature (represented by the β parameter) is greater than the portion of the mileage attributed to urban conditions (S_{URBAN}). For each vehicle type (j) and pollutant (i, either CH_4, N_2O), this calculation is expressed in the following way [17]:

if $\beta_{i,k} > S_{URBAN;k}$

$$\mathrm{E_{COLD\ URBAN;i,k}} = \beta_{\mathrm{i,k}} \cdot \mathrm{N_k} \cdot \mathrm{M_k} \cdot \mathrm{e_{HOT\ URBAN;i,k}} \tag{5}$$

where: $S_{URBAN;k}$ – mileage share attributed to urban conditions for vehicle technology k, $S_{RURAL;k}$ – mileage share attributed to rural conditions for vehicle technology k, $S_{HIGHWAY;k}$ – mileage share attributed to highway conditions for vehicle technology k, $e_{COLD\ URBAN;i,k}$ – urban cold start emission factor for pollutant i, by vehicle technology k, $e_{HOT\ URBAN;i,k}$ – urban hot emission factor for pollutant i, by vehicle technology k, $e_{HOT\ RURAL;i,k}$ – rural hot emission factor for pollutant *i*, by vehicle technology k, $e_{HOT\ HIGHWAY;i,k}$ – highway hot emission factor for pollutant *i*, by vehicle technology k.

It is important to note that all of the emissions values found in the COPERT model have been obtained through laboratory testing that follows the WLTP driving cycle [15]. In this paper, the authors investigated the impact of changes in ambient temperature on the cold start emissions carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), hydrocarbons (treated as volatile organic compounds – VOC), total particulate matter (TSP) and particle number (PN) in passenger cars and light duty vehicles.

The authors analyzed the average monthly temperatures in Poland in the years 2015–2021. The maximum and minimum average temperatures were adopted for the analysis and are presented in Table 1.

Table 1. Average monthly temperatures in Poland in 2015–2021

	2015	2016	2017	2018	2019	2020	2021
Average minimum temperature							
Jan.	–1.3	–5.9	–7.6	–2	–8.5	–2.3	–7.9
Feb.	–2.4	1.4	–2.2	–6.4	–6.4	–4.5	–5.2
Mar.	1.3	1.9	3.6	–2	–4.7	–4.5	–4.3
Apr.	5.1	6.7	4.6	9.5	–1.5	0.9	–3.8
May	9.9	10.8	11.1	13.4	1.9	1.6	1.3
Jun.	14	15.4	15.6	14.6	6.4	7.8	10.6
Jul.	16.9	16	12.7	16.2	8.3	9	10.4
Aug.	18.2	14.5	16.9	17.3	8.7	11.3	7.7
Sep.	12.3	12.9	10.8	12.3	5.2	7.8	7
Oct.	2.8	4.8	6.8	8	1.7	2.1	2.1
Nov.	3.7	1.3	1.2	2.4	–3	1	–1.3
Dec.	1.8	–2.5	–1.2	–1.8	–5	–3.2	–6
Average maximum temperature							
Jan.	2.9	–0.3	0.1	3.3	1	4.6	0.7
Feb.	2.1	4.9	1.9	–1.7	4	5.8	0.2
Mar.	6	5.2	7.6	1.9	6.3	5.8	4.8
Apr.	9.4	9.9	8.6	14.3	10.9	10.7	7
May	13.9	16	15	18.3	14.9	12.4	12.9
Jun.	18	19.5	19.3	19.7	22.8	19.3	20.7
Jul.	21.3	20.3	19.9	21.4	20.9	19.3	22.3
Aug.	23.2	19	20.3	22	20.9	21.1	18.1
Sep.	15.8	17.7	14.6	16.7	14.6	16.1	15.8
Oct.	9.2	9.1	11.5	11.5	11.2	11.7	10.6
Nov.	7.1	4.9	6.2	6.1	6	7.9	6.9
Dec.	6.7	3.9	3.6	3.9	3.6	3.3	1.2

Based on the temperature values in Table 1, the authors decided that simulations are performed assuming ambient temperatures from –10°C to +20°C with 5°C intervals.

Simulations were carried out by using the COPERT software, assuming that vehicles from each type of passenger cars travelled 10,000 km in each vehicle's category: passenger cars (PC) and light duty vehicles (LDV).

The authors checked how the external temperature affects cold start emissions from PC and LDV, but there was no division into Euro standards and fuel type. The result of the simulations is the sum of emissions caused by passenger cars of all classes (Mini, Small, Medium, Large) and for all types of fuels (petrol, diesel, LPG and CNG) and Euro categories (Pre-Euro-Euro 6) and by light duty vehicles also of all classes (N1-I, N1-II and N1-III) and for all types of fuels (petrol, diesel) and Euro categories (Conventional-Euro 6).

According to the above information, simulations were carried out for one vehicle that travelled 10,000 km.

In addition, a study was carried out to show the change in total emissions depending on the ambient temperature in urban areas where cold start emissions have the greatest impact.

3. Results

Figures 2–9 show the influence of ambient temperature on cold start emissions in all driving conditions (urban, rural, highway). Dependence is present for passenger cars and light duty vehicles. In Tables 2–9, pollutant emissions in urban areas in the cold and hot phases are shown.

The methane emission dependence for the cold start phase presented in Fig. 2 clearly shows that the emission decreases with increasing temperature. The difference between –10°C and +20°C is 74% for passenger cars and 64% for light duty vehicles. For methane, cold start emissions from passenger cars are approximately 30% higher than for light duty vehicles.

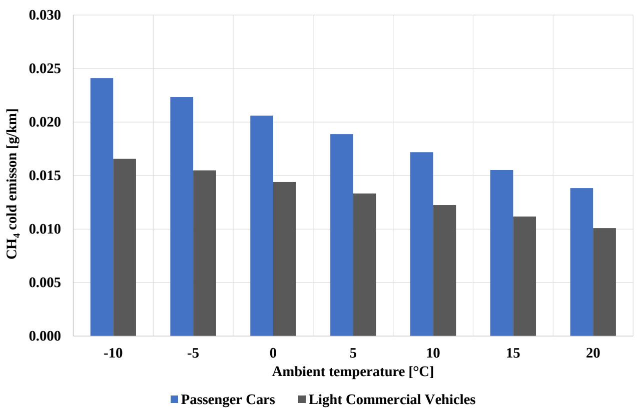

Fig. 2. The dependence of methane (CH_4) emissions from cold start on the ambient temperature

Table 2 shows the impact of temperature on emissions in the cold and hot phases in urban areas. It is clearly visible that in the city emissions in the cold start phase are much higher than in the hot phase. At temperatures –10°C and –5°C, the emission from the hot phase is equal to or close to 0. The differences in CH_4 emissions for other temperatures between the phases are up to 41 times.

The carbon dioxide emission dependence for the cold start phase presented in Fig. 3 clearly shows that the emission decreases with increasing temperature.

The difference between –10°C and +20°C is 226% for passenger cars and 238% for light duty vehicles. For carbon dioxide, cold start emissions from passenger cars are approximately 40% smaller than for light duty vehicles.

Table 2. Change of methane (CH_4) emissions in the cold start and hot phases depending on the ambient temperature

Temperature [°C]	PC CH_4 emission [g/km]		LDV CH_4 emission [g/km]	
	cold	hot	cold	hot
–10	0.024	0.000	0.017	0.000
–5	0.022	0.001	0.015	0.000
0	0.021	0.001	0.014	0.000
5	0.019	0.002	0.013	0.001
10	0.017	0.002	0.012	0.001
15	0.016	0.003	0.011	0.001
20	0.014	0.004	0.010	0.002
15	0.012	0.004	0.009	0.002
20	0.019	0.002	0.013	0.001

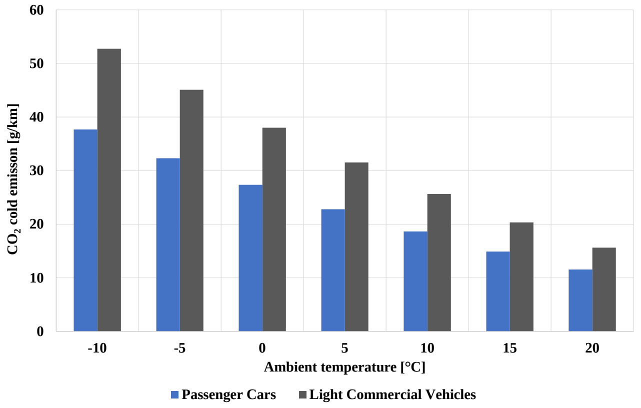

Fig. 3. The dependence of carbon dioxide (CO_2) emissions from cold start on the ambient temperature

Table 3 shows the impact of temperature on emissions in the cold and hot phases in urban areas. It is unmistakable that emanations within the cold start are much higher within the city than within the hot phase. At –10°C and 0°C, the emanation from the hot stage breaks even with or near light duty vehicles. The differences in carbon dioxide outflows for other temperatures between the stages are substantial.

Table 3. Change of carbon dioxide (CO_2) emissions in the cold start and hot phases depending on the ambient temperature

Temperature [°C]	PC CO_2 emission [g/km]		LDV CO_2 emission [g/km]	
	cold	hot	cold	hot
–10	37.380	0.000	49.625	0.000
–5	32.315	0.001	45.081	0.000
0	27.349	0.001	38.012	0.000
5	22.790	0.002	31.532	0.001
10	18.638	0.002	25.641	0.001
15	14.892	0.003	20.337	0.001
20	11.552	0.004	15.621	0.002
15	8.619	0.004	11.494	0.002
20	22.752	0.002	31.489	0.001

The nitrous oxide emission dependence for the cold start phase presented in Fig. 5 clearly shows that the emission decreases with increasing temperature.

The difference between –10°C and +20°C is 64% for passenger cars and light duty vehicles.

Table 4 shows the impact of temperature on emissions in urban areas' cold and hot phases. The emissions in the city are much higher in the cold start phase than in the hot phase. At –10°C and –5°C, hot phase emissions are at or near zero. The difference in nitrogen oxide emissions at other temperatures between phases can be up to 4 times, especially for passenger cars and 121 times for light duty vehicles at –5°C.

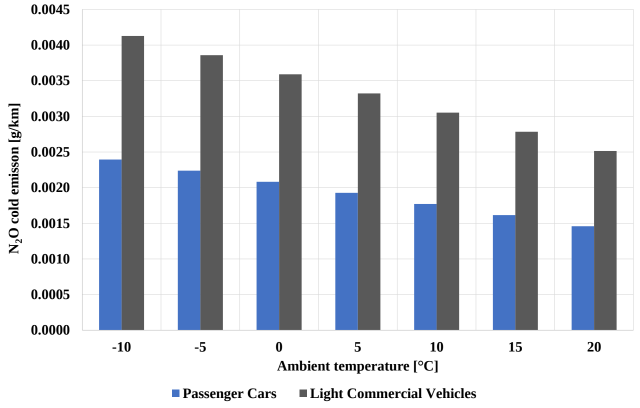

Fig. 4. The dependence of nitrous oxide (N_2O) emissions from cold start on the ambient temperature

Table 4. Change of nitrous oxide (N_2O) emissions in the cold start and hot phases depending on the ambient temperature

Temperature [°C]	PC N_2O emission [g/km]		LDV N_2O emission [g/km]	
	cold	hot	cold	hot
–10	0.002	0.000	0.004	0.000
–5	0.002	0.001	0.004	0.000
0	0.002	0.001	0.004	0.000
5	0.002	0.002	0.003	0.001
10	0.002	0.002	0.003	0.001
15	0.002	0.003	0.003	0.001
20	0.001	0.004	0.003	0.002
15	0.001	0.004	0.002	0.002
20	0.002	0.002	0.003	0.001

The non-methane volatile organic compounds emission dependence for the cold start phase presented in Fig. 5 clearly shows that the emission decreases with increasing temperature.

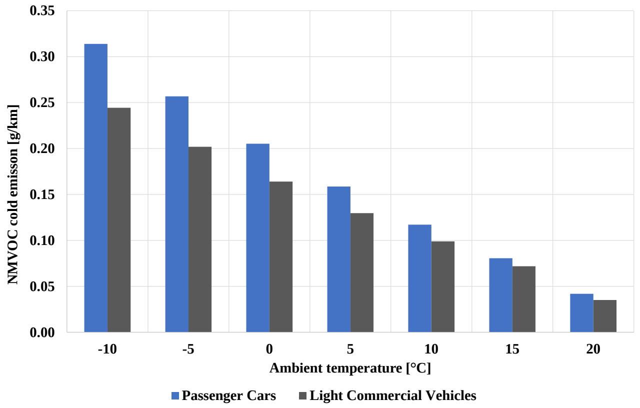

Fig. 5. The dependence of non-methane volatile organic compounds (NMVOC) emissions from cold start on the ambient temperature

The difference between –10°C and +20°C is 650% for passenger cars and 596% for light duty vehicles.

Table 5 shows the impact of temperature on emissions in the cold and hot phases in urban areas. Emissions in the city are significantly higher during the cold start than during the hot phase. The emission from the hot phase is equal to or nearly equal to zero for temperatures between –10°C and 0°C. At –5°C, there are variations in non-methane volatile organic compound emissions for passenger cars up to 17 times and light duty vehicles up to 486 times between the phases.

Table 5. Change of non-methane volatile organic compounds (NMVOC) emissions in the cold start and hot phases depending on the ambient temperature

Temperature [°C]	PC NMVOC emission [g/km]		LDV NMVOC emission [g/km]	
	cold	hot	cold	hot
–10	0.312	0.000	0.233	0.000
–5	0.257	0.001	0.202	0.000
0	0.205	0.001	0.164	0.000
5	0.159	0.002	0.130	0.001
10	0.117	0.002	0.099	0.001
15	0.081	0.003	0.072	0.001
20	0.042	0.004	0.035	0.002
15	0.014	0.004	0.011	0.002
20	0.158	0.002	0.129	0.001

The nitrogen oxides emission dependence for the cold start phase presented in Fig. 6 clearly shows that the emission decreases with increasing temperature.

The difference between –10°C and +20°C is 195% for passenger cars and 319% for light duty vehicles.

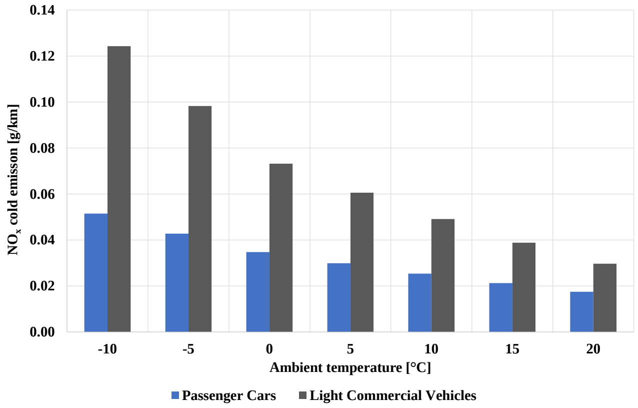

Fig. 6. The dependence of nitrogen oxides (NO_x) emissions from cold start on the ambient temperature

Table 6. Change of nitrogen oxides (NO_x) emissions in the cold start and hot phases depending on the ambient temperature

Temperature [°C]	PC NO_x emission [g/km]		LDV NO_x emission [g/km]	
	cold	hot	cold	hot
–10	0.051	0.000	0.120	0.000
–5	0.043	0.001	0.098	0.000
0	0.035	0.001	0.073	0.000
5	0.030	0.002	0.061	0.001
10	0.025	0.002	0.049	0.001
15	0.021	0.003	0.039	0.001
20	0.017	0.004	0.030	0.002
15	0.015	0.004	0.024	0.002
20	0.030	0.002	0.062	0.001

Table 6 shows the impact of temperature on emissions in the cold and hot phases in urban areas. The contrast between emissions during cold and warm phases in urban areas is evident. In temperatures of –10°C and –5°C, emissions during warm starts hover around zero or are negligible. The disparity in nitrogen oxide emissions between the two phases varies significantly across different temperatures, reaching up to 42 times for passenger cars and 480 times for light duty vehicles at –5°C.

The particulate matter emission dependence for the cold start phase presented in Fig. 7 clearly shows that the emission decreases with increasing temperature.

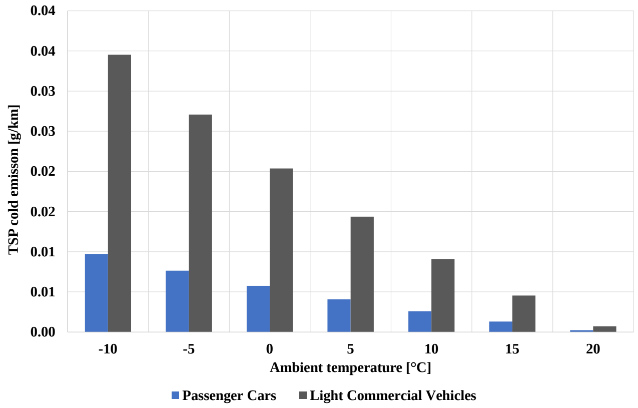

Fig. 7. The dependence of total particulate matter (TSP) emissions from cold start on the ambient temperature

Table 7 shows the impact of temperature on emissions in the cold and hot phases in urban areas. It is clearly visible that in the city emissions in the cold start phase are much higher than in the hot phase. At temperatures –10°C and –5°C, the emission from the hot phase is equal to or close to 0. The differences in particulate matter emissions for other temperatures between the phases are up to 42 times for passengers' cars and more than 480 times for light duty vehicles at –5°C.

Table 7. Change of total particulate matter (TSP) emissions in the cold start and hot phases depending on the ambient temperature

Temperature [°C]	PC TSP emission [g/km]		LDV TSP emission [g/km]	
	cold	hot	cold	hot
–10	0.010	0.000	0.032	0.000
–5	0.008	0.001	0.027	0.000
0	0.006	0.001	0.020	0.000
5	0.004	0.002	0.014	0.001
10	0.003	0.002	0.009	0.001
15	0.001	0.003	0.005	0.001
20	0.000	0.004	0.001	0.002
15	0.000	0.004	0.000	0.002
20	0.004	0.002	0.015	0.001

The particle number emission dependence for the cold start phase presented in Fig. 8 clearly shows that the emission decreases with increasing temperature.

The difference between –10°C and +20°C is 64% for passenger cars and light duty vehicles.

Table 8 shows the impact of temperature on emissions in the cold and hot phases in urban areas. The disparity is evident in urban environments, where emissions during cold start significantly surpass those during warm phases. At a temperature of –10°C, emissions during warm phases are either zero or negligible. The contrast in particle number emissions between the two phases varies across different temperatures, with differences of up to 42 times for passenger cars and 480 times for light duty vehicles at –5°C.

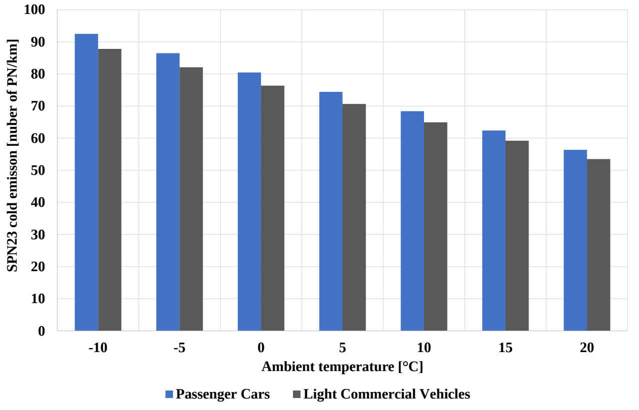

Fig. 8. The dependence of particle number (PN) emissions from cold start on the ambient temperature

Table 8. Change of particle number (PN) emissions in the cold start and hot phases depending on the ambient temperature

Temperature [°C]	PC PN emission [g/km]		LDV PN emission [g/km]	
	cold	hot	cold	hot
–10	91.736	0.000	82.627	0.000
–5	86.466	0.001	82.088	0.000
0	80.444	0.001	76.368	0.000
5	74.421	0.002	70.649	0.001
10	68.399	0.002	64.930	0.001
15	62.377	0.003	59.211	0.001
20	56.355	0.004	53.493	0.002
15	50.333	0.004	47.776	0.002
20	73.829	0.002	70.087	0.001

The hydrocarbons emission dependence for the cold start phase presented in Fig. 9 clearly shows that the emission decreases with increasing temperature.

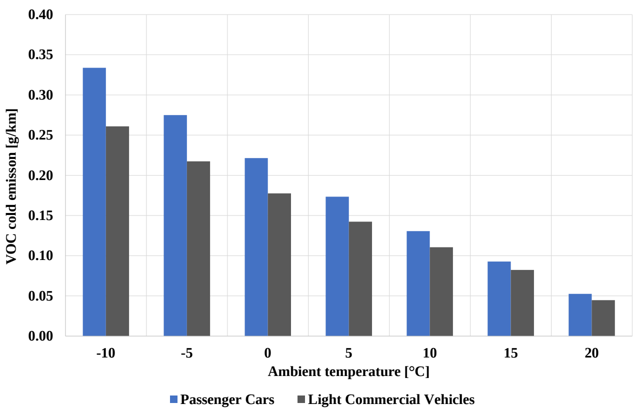

Fig. 9. The dependence of hydrocarbons (VOC) emissions from cold start on the ambient temperature

The difference between –10°C and +20°C is 536% for passenger cars and 485% for light duty vehicles.

Table 9 shows the impact of temperature on emissions in the cold and hot phases in urban areas. The difference is evident within urban settings, where emissions during cold start notably exceed those during warm phases. At temperatures of –10°C and –5°C, emissions during warm starts are virtually zero or negligible. Variations in hydrocarbon emissions between the two phases at other temperatures can reach up to 42 times for passenger cars and surpass 480 times for light duty vehicles at –5°C.

Table 9. Change of hydrocarbons (VOC) emissions in the cold start and hot phases depending on the ambient temperature

Temperature [°C]	PC VOC emission [g/km]		LDV VOC emission [g/km]	
	cold	hot	cold	hot
–10	0.332	0.000	0.250	0.000
–5	0.275	0.001	0.217	0.000
0	0.221	0.001	0.178	0.000
5	0.173	0.002	0.142	0.001
10	0.131	0.002	0.110	0.001
15	0.093	0.003	0.082	0.001
20	0.052	0.004	0.045	0.002
15	0.023	0.004	0.019	0.002
20	0.173	0.002	0.141	0.001

In Fig. 2–9 and are shown a comparison of a cold start emissions for CO_2, N_2O, CH_4, NO_x, NMVOC, VOC, TSP and SPN23, depending on the ambient temperature. The modelling showed that cold start emissions of all pollutants are highly influenced by variations in the ambient temperature. We can see that the levels of all modelled pollutants and cold start emissions have gone down. COPERT software was utilized to carry out the simulations, and the ambient temperatures ranged from –10°C to 20°C with 5°C intervals.

All of the simulations are conducted using COPERT software, assuming ambient temperatures from –10°C to +20°C, with 5°C intervals.

The results presented in Tables 2–9 show that for temperatures from –10°C to –5°C in city traffic, there are only emissions from the cold start phase for both passenger cars and light duty vehicles, which indicates that with the model used l_{trip} parameter, even after driving 12 km, the engine still does not heat up to the optimal temperature. Only at a temperature of 0°C do emissions from the heated engine begin to appear, but they are over 41 (for PCs) and 486 (for LDVs) times lower than in the cold start phase.

4. Conclusions

Similarly, to the research conducted by [3, 13, 15], it can be seen that as the temperature increases, cold start emissions decrease for all pollutants, which was also proven by simulation tests.

As shown in Fig. 2–9, changing the ambient temperature reduces emissions of CO_2, N_2O, CH_4, NO_x, NMVOC, VOC, TSP and PN during cold start for each vehicle category.

The simulations show how important it is to reduce emissions from the cold start phase. Emissions in this phase are much higher than in the case of emissions from the engine heated to the appropriate temperature. This is especially important in cities, where these emissions have the greatest impact on human health.

In summary, ambient temperature significantly impacts cold start emissions under various driving conditions for passenger cars and light duty vehicles. Simulation results using COPERT software show that as temperature increases, emissions of carbon dioxide, nitrogen oxides, methane, nitrogen oxides, non-methane volatile organic compounds, hydrocarbons, total particle mass, and particle number decrease during cold start for both vehicle categories. The study highlights the importance of reducing emissions during the cold start phase, particularly in urban areas where these emissions significantly impact human health. Further testing on vehicles adjusted to appropriate temperatures is recommended to understand better and reduce cold start emissions.

It is therefore important to take effective action to reduce emissions during the cold start phase, especially in urban areas where these emissions significantly impact air quality and public health. It is essential to address cold start emissions to improve air quality and reduce negative impacts on health and the environment.

Further research and testing on vehicles is also recommended to confirm the simulation results and explore potential solutions to reduce cold start emissions. By addressing cold start emissions and implementing effective policies and regulations, we can work to minimise the impact of vehicle emissions on air quality and public health. Action is needed to reduce cold start emissions and improve air quality to benefit people and the environment. Additionally, continuous monitoring and regulation of vehicle emissions, particularly on cold start operations, is essential to achieving environmental goals and improving air quality in urban areas.

The authors also see the need to carry out tests on a real vehicle, which will be conditioned to an appropriate temperature and then tested on a chassis dynamometer and in real driving conditions.

Nomenclature

CH_4	methane
CO_2	carbon dioxide
COPERT	COmputer Programme to calculate Emissions from Road Transport
EC	European Commission
N_2O	nitrous oxide
NMVOC	non-methane volatile organic compounds
NO_x	nitrogen oxides
PN	particle number
RDE	real driving emissions
SCR	selective catalytic reduction
TSP	total particulate matter
VOC (HC)	hydrocarbons (treated as volatile organic compounds
WLTP	Worldwide Harmonised Light Vehicle Test Procedure

Bibliography

1. Air quality in Europe – 2021 report. EEA – European Environmental Agency. Copenhagen, Denmark.
2. André J-M, Joumard R. Modelling of cold start excess emissions for passenger cars. 2005. https://hal.archives-ouvertes.fr/hal-00917071
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. P I Mech Eng D-J Aut. 2011; 225(9):1253-1264. https://doi.org/10.1177/0954407011406613
4. Bielaczyc P, Szczotka A, Woodburn J. Cold start emissions of spark-ignition engines at low ambient temperatures as an air quality risk. Arch Environ Prot. 2014;40(3):86-100.
5. Chu Van T, Zare A, Jafari M, Bodisco TA, Surawski N, Verma P et al. Effect of cold start on engine performance and emissions from diesel engines using IMO-compliant distillate fuels. Environ Pollut. 2019;255(2):113260. https://doi.org/10.1016/j.envpol.2019.113260
6. Daham B, Li H, Andrews G. Comparison of real world emissions in urban driving for Euro 1-4 vehicles using a PEMS. SAE Technical Paper 2009-01-0941. 2009. https://doi.org/10.4271/2009-01-0941
7. Dimaratos A, Toumasatos Z, Doulgeris S, Triantafyllopoulos G, Konstses A, Samaras Z. Assessment of CO_2 and NO_x emissions of one diesel and one bi-fuel gasoline/CNG Euro 6 vehicles during realworld driving and laboratory testing. Frontiers in Mechanical Engineering. 2019;5:62. https://doi.org/10.3389/fmech.2019.00062
8. European Commission: Regulation 2016/427. EC – European Commission. Official Journal of the European Union L 82, 1-98. EC (2016b): Regulation 2016/646. EC – European Commission. Official Journal of the European Union L 109, 1-22.
9. European Commission, Joint Research Centre, Vlachos T, Bonnel P, Weiss M. et al., Including cold-start emissions in the Real-Driving Emissions (RDE) test procedure – an assessment of cold-start frequencies and emission effects. Publications Office. 2017. https://data.europa.eu/doi/10.2760/70237
10. 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
11. Franco V, Zacharopoulou T, Hammer J, Schmidt H, Mock P, Weiss M et al. Evaluation of exhaust emissions from three diesel-hybrid cars and simulation of after-treatment systems for ultralow real-world NO_x emissions. Environ Sci Technol. 2016;50:13151-13159. https://doi.org/10.1021/acs.est.6b03585
12. Gis M. Assessment of exhaust emissions from vehicles in real traffic conditions. IOP Conf Ser: Earth Environ Sci. 2019; 214:012035. https://doi.org/10.1088/1755-1315/214/1/012035
13. Kurtyka K, Pielecha J. Cold start emissions from a gasoline engine in RDE tests at different ambient temperatures. Combustion Engines. 2020;181(2):24-30. https://doi.org/10.19206/CE-2020-204
14. Lairenlakpam R, Jain AK, Gupta P, Kamei W, Badola R, Singh Y. Effect of real world driving and different drive modes on vehicle emissions and fuel consumption. SAE Technical Paper 2018-01-5017. 2018. https://doi.org/10.4271/2018-01-5017
15. 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

16. McCaffery C, Zhu H, Li C, Durbin TD, Johnson KC, Jung H et al. On-road gaseous and particulate emissions from GDI vehicles with and without gasoline particulate filters (GPFs) using portable emissions measurement systems (PEMS). Sci Total Environ. 2020;710:136366. https://doi.org/10.1016/j.scitotenv.2019.136366
17. Ntziachristos L, Boulter P. EMEP/EEA Air pollutant emissions inventory guidebook 2019. 1.A.3.b.i-iv Road transport 2019. European Environment Agency: Copenhagen, Denmark. 2023. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view
18. Pielecha J, Merkisz J, Kurtyka K, Skobiej K. Cold start emissions of passenger cars with gasoline and diesel engines in Real Driving Emissions tests. Combustion Engines. 2019; 179(4):160-168. https://doi.org/10.19206/CE-2019-427
19. Prati M, Meccariello G, Della Ragione L, Costagliola MA. Real driving emissions of a light-duty vehicle in Naples. Influence of road grade. SAE Technical Paper 2015-24-2509. 2015. https://doi.org/10.4271/2015-24-2509
20. Ramadhas AS, Xu H, Liu D, Tian J. Reducing cold start emissions from automotive diesel engine at cold ambient temperatures. Aerosol Air Qual Res. 2016;16:3330-3337. https://doi.org/10.4209/aaqr.2015.11.0616
21. Regulation 2017/1154 – Amendment of Regulation (EU) 2017/1151 supplementing Regulation 715/2007 on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Regulation (EC) No 692/2008 and Directive 2007/46/EC as regards real-driving emissions from light passenger and commercial vehicles (Euro 6).
22. Suarez-Bertoa R, Valverde V, Clairotte M, Pavlovic J, Giechaskiel B, Franco V et al. On-road emissions of passenger cars beyond the boundary conditions of the real-driving emissions test. Environ Res. 2019;176:108572. https://doi.org/10.1016/j.envres.2019.108572
23. Varella R., Duarte, G., Baptista, P. Mendoza Villafuerte P, Sousa L. Analysis of the influence of outdoor temperature in vehicle cold-start operation following EU real driving emission test procedure. SAE Int J Commer Veh. 2017;10(2): 596-697. https://doi.org/10.4271/2017-24-0140
24. Williams R, Andersson J, Hamje H, Ziman P, Kar K, Fittavolini C et al. Impact of demanding low temperature urban operation on the real driving emissions performance of three European diesel passenger cars. SAE Technical Paper 2018-01-1819. 2018. https://doi.org/10.4271/2018-01-1819

Piotr Laskowski, DEng. – Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Poland.
e-mail: *piotr.laskowski@pw.edu.pl*

Jan Matej, DSc. DEng. – Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Poland.
e-mail: *jan.matej@pw.edu.pl*

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

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