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Modelling Hydrocarbons Cold-start Emission from Passenger Cars

Piotr Laskowski[1*], Damian Zasina[2], Magdalena Zimakowska-Laskowska[3], Piotr Orliński[1]

[1] Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, ul. Narbutta 84, 02-524 Warsaw, Poland

[2] Faculty of Building Services, Hydro and Environmental Engineering, Warsaw University of Technology ul. Nowowiejska 20, 00-653 Warsaw, Poland

[3] Institute of Environmental Protection – National Research Institute, ul. Chmielna 132/134, 00-805 Warsaw, Poland

* Corresponding author's email: piotr.laskowski@pw.edu.pl

ABSTRACT

The aim of this paper is to present the results of mathematically modelling the influence of ambient temperature on hydrocarbons (HCs, comprised of methane and non-methane volatile organic compounds) in cold-start emissions from passenger cars (PCs) for different fuel types, vehicle segments including hybrid vehicles, and the Euro standard. In this article the simulations are performed using COPERT software, assuming ambient temperatures from 20 °C to +30 °C, with 5 °C intervals. The modelling results presented show that a change in ambient temperature has a significant effect on hydrocarbons in cold-start emissions. Furthermore, our results show that hydrocarbons emissions are sensitive to ambient temperature fluctuations, and dependent on fuel type, vehicle segment, and the Euro standard.

Keywords: hydrocarbons emissions, air pollution, road transport, cold-start.

INTRODUCTION

The road transport sector is a significant source of air pollutants' and greenhouse gases' emissions. These emissions, considered as the masses of particular substances released into the air, can be split into two groups: those that are regulated under EU road transport legislation and those that presently are not [8]. The 'regulated' pollutants include among others: hydrocarbons (HCs). The legislation on emissions regulates total hydrocarbons (THC/HCs) emissions, with no distinction between methane (CH_4) and non-methane volatile organic compounds (NMVOCs) [7].

According to the data presented in the EU's report [8], HCs belong to a larger group of chemicals known as volatile organic compounds (VOCs). HCs are compounds that chemically consist of hydrogen and carbon only, while VOCs may also contain another element, such as sulfur. NMVOCs also cover the homologous series such as aromatic compounds, aldehydes, alkenes, alkynes, ketones, and alkanes. They are produced by incomplete combustion of hydrocarbon fuels, and also by their evaporation. Due to the fact that there are many hundreds of different compounds, HCs and VOCs are groups of various chemical compounds displaying a wide range of proper-ties. Some of them, such as benzene, are carcinogenic; some are toxic, while others harmless to health [4, 8].

Hydrocarbons emitted by vehicles are products of either incomplete, or partial combustion, which are also toxic to human health [4]. HCs, and particularly the VOCs, contribute to the formation of ground-level ozone and photochemical ('Los Angeles' type) smog in the atmosphere, while methane (CH_4) is regarded as a greenhouse gas [8].

The vast majority of the HCs emissions come from vehicle exhaust systems. Cold-start emissions, defined as the total mass of a particular pollutant produced during an engine's thermally unstable operating conditions, occurring shortly after the engine's start, form a substantial part of total road emissions [14, 24]. Cold-start emissions can be defined as 'excess' emissions, i.e. they are significant compared to the emissions produced when an engine is in a fully warmed-up operational state. However, taking into consideration the duration of any period of driving, the significance of cold-start emissions decreases as the duration and distance of a period of driving increase. Cold- start emissions arise at the initial start-up when the engine is cold – starting from the ambient temperature (Ta), their value can be expressed as a mass of pollutant (s) per the vehicle start [1÷4, 6, 7, 14, 24]. During a hot start, the temperatures of the oil, coolant and all the elements of the engine are very close to those observed during a fully warmed-up operation (Tw). According to [3] the term cool start can be used to refer to an engine's start in the intermediate temperatures, i.e. Ta < T < Tw, where T is the temperature of a given engine.

Optimizing the emissions associated with the engines' cold-starts phenomena is the example of multidisciplinary problem that engages also issue of forming combustible mixtures for simultaneous maintaining exhaust emissions and fuel consumption at environmentally and economically acceptable levels. This problem is exacerbated as ambient temperature decreases [2, 3, 5, 13, 21, 23, 24]. According to the information contained in [7], the cold-start VOC emissions occur not only in situations when the catalyst's conversion efficiency is low, but can also be caused by the fact that fuel enrichment is ongoing during cold-start conditions, which is typically necessary for the proper functioning of a cold engine. The enrichment's intensity depends on an engine's temperature during a cold start. For that's reason two different temperature ranges have to be de-fined for VOCs.

Generally, VOCs emissions associated with the cold-start effect become insignificant in ambient temperatures exceeding 30 °C. This is not only be- cause surfeit of emissions under ambient conditions are relatively small, but also because an engine cools down more slowly, while the real engine start-up temperature can remain high even after several hours of parking [7].

MATERIALS AND METHODS

In the 'EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019' [2] basic guidelines are given for the estimation of HCs emissions. In general, emissions are estimated using the following variables: emission factor and activity (rate) of the emission source [10, 18, 22]. The emission factors depend on technology, year of production, the style of driving, and many other variables. This means that the emission factors are widely applied to assess an engines' environmental properties. Activity of the emission source depends on the distance driven or the fuel combustion (dependent on the methodology used). According to [7], there are three vital methodologies (named Tiers) used for emission estimation: Tier 1 – default methodology using the international average values for the emission factors, Tier 2 – using country specific emission factors (i.e. derived from a country's own studies and analysis), and Tier 3 – based on mathematical modelling used for emission approximation [20].

For modelling purposes COPERT software was used for implementing the Tier 3 methodology [9, 12]. COPERT is a software tool, coordinated by the EEA, and widely used for the mathematical modelling of air pollutant emissions from the mobile sources.

Based on the applied methodology, driving is split into three types, due to the most frequent driving conditions: urban, rural, and highway. It is assumed that cold-start emissions are an additional emission which take place under all driving conditions, however the cold-start emissions occur most likely during urban driving, and rarely during rural driving. Highway driving conditions are characterized by the limited number of engine starts, and thus – also cold-start emissions [7, 16].

According to [7], and the assumptions introduced in the COPERT software, cold-start emissions are estimated as an additional emission with the assumption that all vehicles were only operated with hot engines and warmed- up catalysts.

In the COPERT software, the parameter β depends on the ambient temperature, and the driving conditions which can be described as the pattern of the vehicle use. The pattern can then be mathematically expressed using the average trip length, and incorporated to the model as the l_{trip} parameter. However, the information on the l_{trip}

Table 1. Types of the passenger cars considered in the simulation

Fuel	Segment	Euro Standard
Petrol	Mini, Small, Medium, Large-SUV-Executive	Euro 1 – Euro 6
Petrol Hybrid	Mini, Small, Medium, Large-SUV-Executive	Euro 4 – Euro 6
Petrol PHEV	Small, Medium, Large-SUV-Executive	Euro 6
Diesel	Mini, Small, Medium, Large-SUV-Executive	Euro 1 – Euro 6
LPG Bifuel	Mini, Small, Medium, Large-SUV-Executive	Euro 1 – Euro 6
Diesel PHEV	Large-SUV-Executive	Euro 6
CNG Bifuel	Mini, Small, Medium, Large-SUV-Executive	Euro 4 – Euro 6

parameter is scarce. According to the available statistical data, and the default value in the COPERT software, the default value of 12 km was taken into consideration [1, 7].

In this paper, we have investigated the impact of ambient temperature on hydro-carbons in cold-start emissions from PCs considered for different fuel types, vehicle segments, and the Euro standard (Table 1). Simulations are performed assuming ambient temperatures from −20 °C to +30 °C with 5 °C intervals. The types of vehicles considered in the simulations are shown in Table 1.

The simulations are performed for one passenger car in all combinations of fuel-vehicle segment-Euro Standard (indicated in Table 1), assuming a daily trip to work of 25 km. This distance is determined on the basis of Warsaw and Wrocław traffic research [22, 25]. In our article, it was assumed that the mileage share per road class is typical for Polish conditions [19].

The authors do realize that the mileage, the mileage share per road class, and number of vehicles can influence the results, however for modelling purposes the data remained constant (unchanged).

RESULTS

The comparison of cold-start emissions for CH4, depending on ambient temperature is shown in the Figures 1, 2, 3, and 4. The data is presented in Tables as well (2, 3 and 4).

In the Figures (5, 6, 7, 8, 9) and Tables (5, 6, and 7) are shown a comparison of cold-start emissions for NMVOC pollutants, depending on ambient temperature.

Table 2. The result of the simulation for CH_4 cold-start emission from Petrol, LPG and CNG PCs

Segment	Euro Standard	-20	-15	-10	-5	0	5	10	15	20	25	30
Petrol Mini	Euro 4 - Euro 6	0.66	0.62	0.58	0.54	0.51	0.47	0.43	0.39	0.36	0.32	0.28
Petrol Small	Euro 1	0.52	0.49	0.46	0.43	0.40	0.37	0.34	0.31	0.28	0.25	0.22
	Euro 2	1.09	1.02	0.96	0.90	0.84	0.77	0.71	0.65	0.59	0.52	0.46
	Euro 3	0.96	0.90	0.85	0.79	0.74	0.68	0.63	0.57	0.52	0.46	0.41
	Euro 4 - Euro 6	0.66	0.62	0.58	0.54	0.51	0.47	0.43	0.39	0.36	0.32	0.28
Petrol Medium	Euro 1	0.52	0.49	0.46	0.43	0.40	0.37	0.34	0.31	0.28	0.25	0.22
	Euro 2	1.09	1.02	0.96	0.90	0.84	0.77	0.71	0.65	0.59	0.52	0.46
	Euro 3	0.96	0.90	0.85	0.79	0.74	0.68	0.63	0.57	0.52	0.46	0.41
	Euro 4 - Euro 6	0.66	0.62	0.58	0.54	0.51	0.47	0.43	0.39	0.36	0.32	0.28
Petrol Large-SUV-Executive	Euro 1	0.52	0.49	0.46	0.43	0.40	0.37	0.34	0.31	0.28	0.25	0.22
	Euro 2	1.09	1.02	0.96	0.90	0.84	0.77	0.71	0.65	0.59	0.52	0.46
	Euro 3	0.96	0.90	0.85	0.79	0.74	0.68	0.63	0.57	0.52	0.46	0.41
	Euro 4 - Euro 6	0.66	0.62	0.58	0.54	0.51	0.47	0.43	0.39	0.36	0.32	0.28
Petrol Hybrid	Euro 4 - Euro 6	0.66	0.62	0.58	0.54	0.51	0.47	0.43	0.39	0.36	0.32	0.28
Petrol PHEV	Euro 6	0.49	0.47	0.44	0.41	0.38	0.35	0.32	0.29	0.27	0.24	0.21
LPG Bifuel Mini - Large-SUV-Executive	Euro 1 - Euro 6	0.92	0.87	0.82	0.76	0.71	0.66	0.60	0.55	0.50	0.45	0.39
CNG Bifuel Mini - Large-SUV-Executive	Euro 4 - Euro 6	3.88	3.33	2.82	2.34	1.91	1.52	1.17	0.85	0.49	0.20	0.00

Table 3. The result of the simulation for CH_4 cold-start emission from Diesel PCs

Segment	Euro Standard	-20	-15	-10	-5	0	5	10	15	20	25	30
Diesel Mini	Euro 4	-	-	0.011	0.011	0.010	0.009	0.008	0.008	0.007	0.006	0.005
	Euro 5 - Euro 6	-	-	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000
Diesel Small	Euro 1	-	-	0.184	0.172	0.160	0.148	0.136	0.124	0.112	0.100	0.088
	Euro 2	-	-	0.061	0.057	0.053	0.049	0.045	0.041	0.037	0.033	0.029
	Euro 3	-	-	0.031	0.029	0.027	0.025	0.023	0.021	0.019	0.017	0.015
	Euro 4	-	-	0.011	0.011	0.010	0.009	0.008	0.008	0.007	0.006	0.005
	Euro 5 - Euro 6	-	-	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000
Diesel Medium	Euro 1	-	-	0.184	0.172	0.160	0.148	0.136	0.124	0.112	0.100	0.088
	Euro 2	-	-	0.061	0.057	0.053	0.049	0.045	0.041	0.037	0.033	0.029
	Euro 3	-	-	0.031	0.029	0.027	0.025	0.023	0.021	0.019	0.017	0.015
	Euro 4	-	-	0.011	0.011	0.010	0.009	0.008	0.008	0.007	0.006	0.005
	Euro 5 - Euro 6	-	-	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000
Diesel Large-SUV-Executive	Euro 1	-	-	0.184	0.172	0.160	0.148	0.136	0.124	0.112	0.100	0.088
	Euro 2	-	-	0.061	0.057	0.053	0.049	0.045	0.041	0.037	0.033	0.029
	Euro 3	-	-	0.031	0.029	0.027	0.025	0.023	0.021	0.019	0.017	0.015
	Euro 4	-	-	0.011	0.011	0.010	0.009	0.008	0.008	0.007	0.006	0.005
	Euro 5 - Euro 6	-	-	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000
Diesel PHEV	Euro 6	-	-	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000

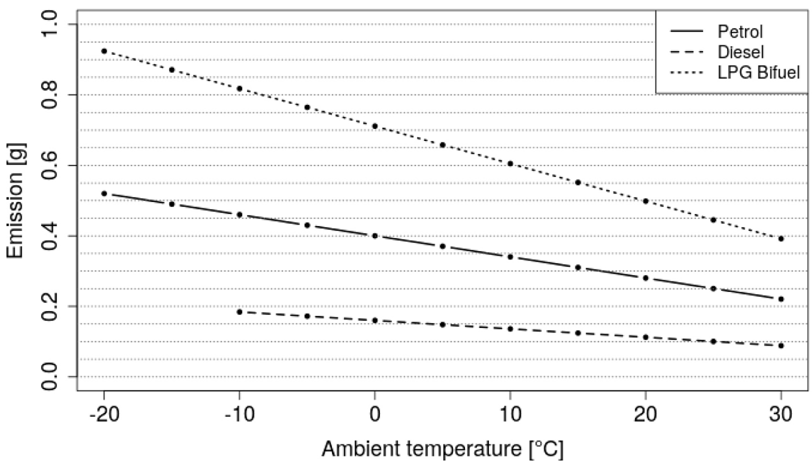

Fig. 1. The comparison of CH_4 cold start emission from Petrol, Diesel and LPG PCs Euro 1

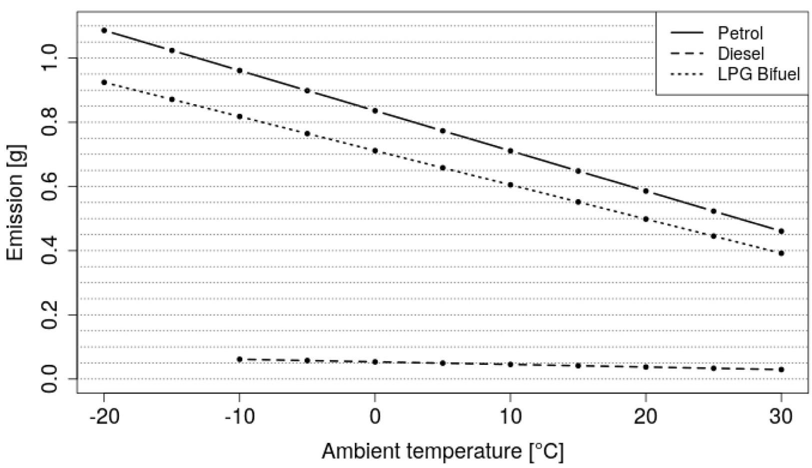

Fig. 2. The comparison of CH_4 cold start emission from Petrol, Diesel and LPG PCs Euro 2

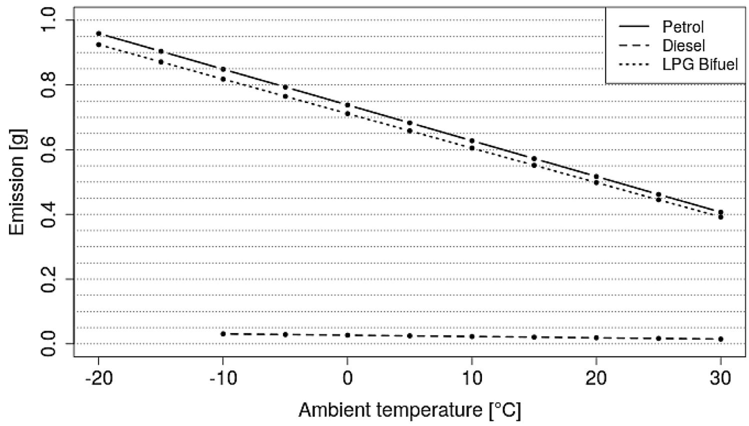

Fig. 3. The comparison of CH_4 cold start emission from Petrol, Diesel and LPG PCs Euro 3

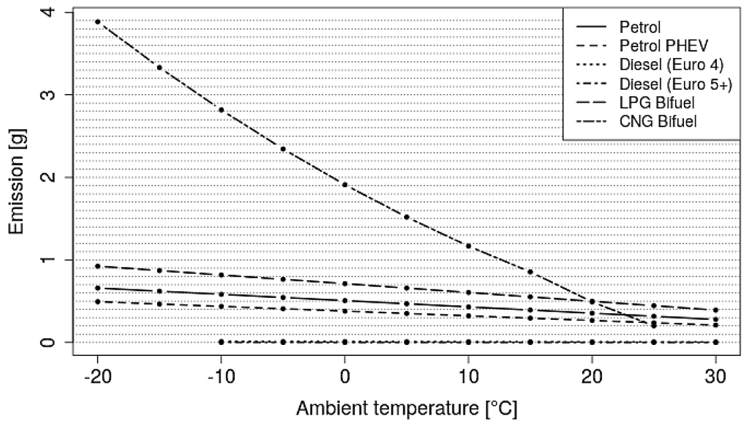

Fig. 4. The comparison of CH_4 cold start emission from Petrol, Diesel and LPG PCs Euro 4 and Diesel PCs Euro 5+

Table 4. The result of the simulation for NMVOC cold-start emission from Petrol, LPG and CNG PCs

Segment	Euro Standard	-20	-15	-10	-5	0	5	10	15	20	25
Petrol Mini	Euro 4 - Euro 6	5.65	4.83	4.06	3.36	2.72	2.14	1.62	1.16	0.60	0.15
Petrol Small	Euro 1	34.55	29.78	25.35	21.26	17.51	14.10	11.03	8.30	5.01	2.37
	Euro 2	18.55	15.93	13.49	11.25	9.20	7.33	5.66	4.18	2.38	0.95
	Euro 3	10.26	8.78	7.41	6.15	4.99	3.95	3.01	2.18	1.17	0.38
	Euro 4 - Euro 6	5.65	4.83	4.06	3.36	2.72	2.14	1.62	1.16	0.60	0.15
Petrol Medium	Euro 1	45.52	38.99	32.93	27.35	22.25	17.63	13.49	9.82	5.55	2.13
	Euro 2	24.70	21.08	17.74	14.66	11.85	9.31	7.03	5.03	2.68	0.81
	Euro 3	13.77	11.73	9.84	8.10	6.51	5.08	3.80	2.67	1.35	0.30
	Euro 4 - Euro 6	7.63	6.49	5.43	4.46	3.57	2.77	2.06	1.43	0.69	0.11
Petrol Large-SUV-Executive	Euro 1	31.35	26.89	22.76	18.95	15.47	12.31	9.47	6.96	3.82	1.36
	Euro 2	16.76	14.31	12.04	9.96	8.05	6.33	4.78	3.42	1.71	0.38
	Euro 3	9.24	7.86	6.58	5.41	4.34	3.37	2.51	1.75	0.79	0.05
	Euro 4 - Euro 6	5.08	4.31	3.60	2.94	2.35	1.81	1.34	0.92	0.38	0.00
Petrol Hybrid Mini - Small	Euro 4 - Euro 6	5.65	4.83	4.06	3.36	2.72	2.14	1.62	1.16	0.60	0.15
Petrol Hybrid Medium	Euro 4 - Euro 6	7.63	6.49	5.43	4.46	3.57	2.77	2.06	1.43	0.69	0.11
Petrol Hybrid Large-SUV-Executive	Euro 4 - Euro 6	5.08	4.31	3.60	2.94	2.35	1.81	1.34	0.92	0.38	0.00
LPG BifuelMini - Large-SUV-Executive	Euro 1 - Euro 6	7.36	6.23	5.19	4.24	3.37	2.58	1.88	1.27	0.55	0.00
Mini - Large-SUV-Executive	Euro 4 - Euro 6	2.37	2.04	1.72	1.43	1.17	0.93	0.71	0.52	0.30	0.12

Table 5. The result of the simulation for NMVOC cold-start emission from Diesel PCs

Segment	Euro Standard	-20	-15	-10	-5	0	5	10	15	20	25
Diesel Mini	Euro 4	-	-	0.442	0.350	0.266	0.192	0.126	0.069	0.021	0
	Euro 5 - Euro 6	-	-	0.035	0.028	0.021	0.015	0.010	0.006	0.002	0
Diesel Small	Euro 1	-	-	1.774	1.384	1.032	0.718	0.443	0.206	0.007	0
	Euro 2	-	-	1.227	0.966	0.731	0.521	0.336	0.176	0.041	0
	Euro 3	-	-	0.638	0.502	0.380	0.271	0.175	0.092	0.022	0
	Euro 4	-	-	0.442	0.350	0.266	0.192	0.126	0.069	0.021	0
	Euro 5 - Euro 6	-	-	0.035	0.028	0.021	0.015	0.010	0.006	0.002	0
Diesel Medium	Euro 1	-	-	1.774	1.384	1.032	0.718	0.443	0.206	0.007	0
	Euro 2	-	-	1.227	0.966	0.731	0.521	0.336	0.176	0.041	0
	Euro 3	-	-	0.638	0.502	0.380	0.271	0.175	0.092	0.022	0
	Euro 4	-	-	0.442	0.350	0.266	0.192	0.126	0.069	0.021	0
	Euro 5 - Euro 6	-	-	0.035	0.028	0.021	0.015	0.010	0.006	0.002	0
Diesel Large-SUV-Executive	Euro 1	-	-	2.687	2.109	1.588	1.123	0.713	0.360	0.063	0
	Euro 2	-	-	3.567	2.826	2.155	1.556	1.028	0.570	0.184	0
	Euro 3	-	-	1.415	1.120	0.854	0.615	0.405	0.223	0.069	0
	Euro 4	-	-	0.442	0.350	0.266	0.192	0.126	0.069	0.021	0
	Euro 5 - Euro 6	-	-	0.035	0.028	0.021	0.015	0.010	0.006	0.002	0
Diesel PHEV Large-SUV-Executive	Euro 6	-	-	0.026	0.021	0.016	0.011	0.008	0.004	0.001	0

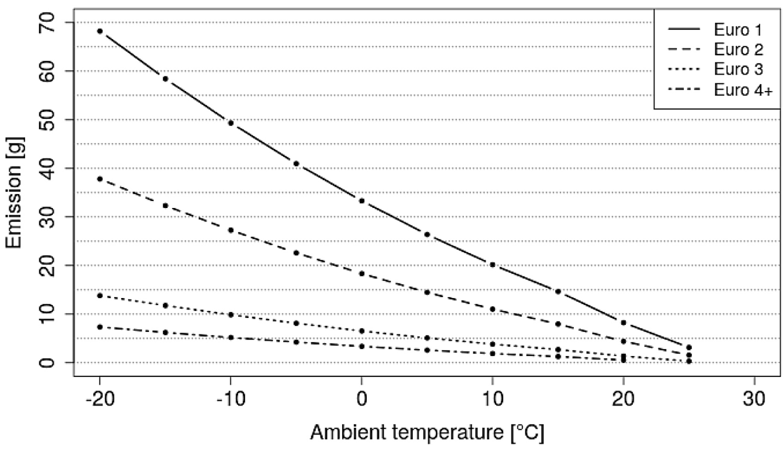

Fig. 5. The comparison of NMVOC cold start emission from Petrol, Diesel and LPG PCs all Euro standard

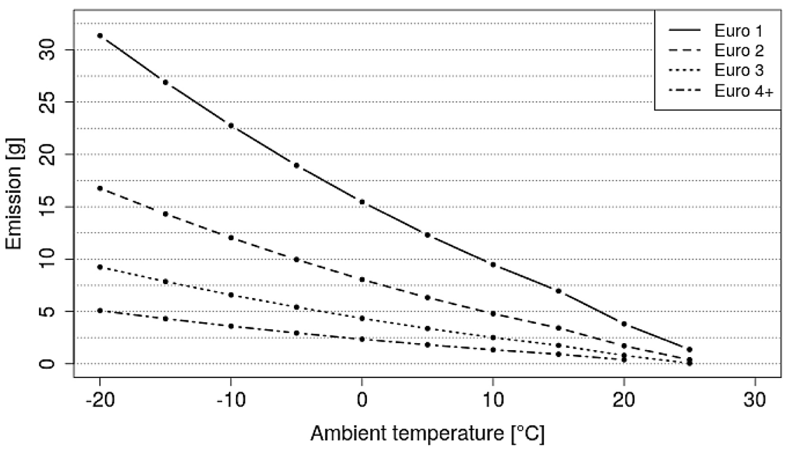

Fig. 6. The comparison of NMVOC cold start emission from Petrol Large – SUV PCs all Euro standard

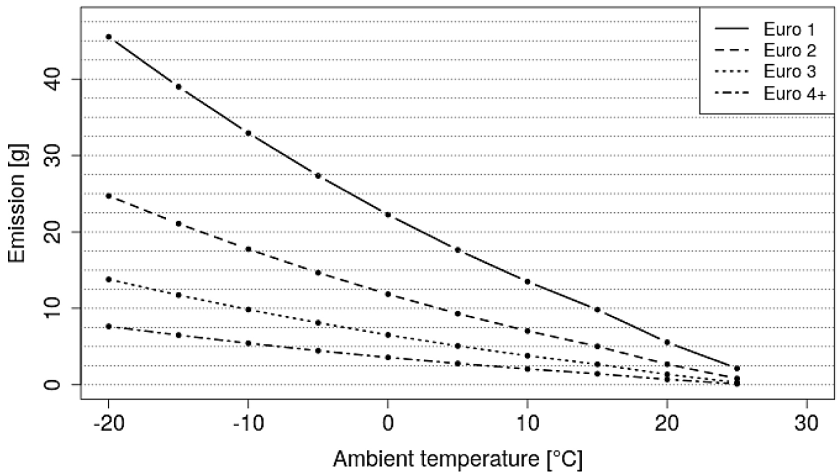

Fig. 7. The comparison of NMVOC cold start emission from Petrol Medium PCs all Euro standard

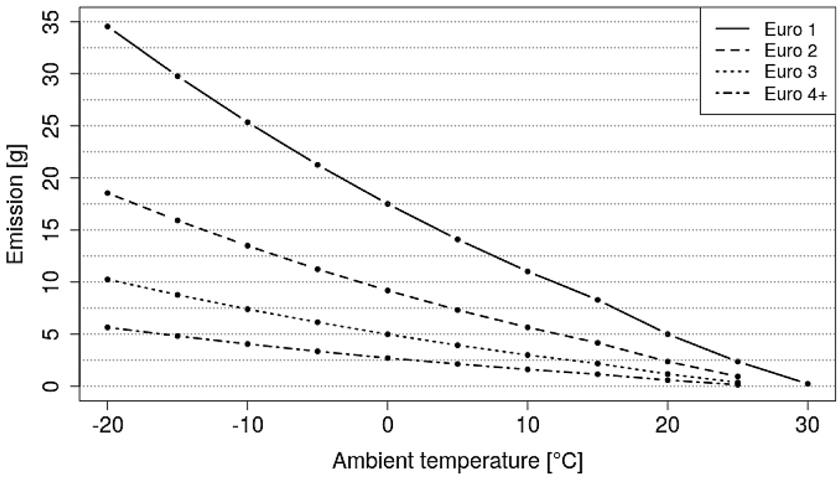

Fig. 8. The comparison of NMVOC cold start emission from Petrol Small PCs all Euro standard

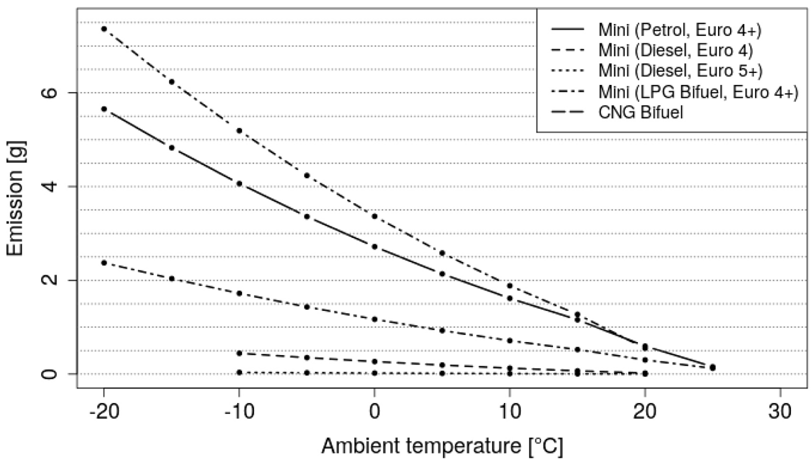

Fig. 9. The comparison of NMVOC cold start emission from Mini PCs all Euro standard

Results are presented using the language of statistical computing R [17].

In the Figures (Fig. 5– 9) and Tables (Table 4–5) are shown a comparison of a cold-start emissions for NMVOC pollutants, depending on the ambient temperature.

The results of modelling indicate that in the case of CH_4 and NMVOC cold-start emissions are very sensitive to the changes in ambient temperature (Ta).

For all modelled pollutants and cold-start emissions we can observe similar de-creasing trends. It should, therefore, be noted that along with the change of the fleet structure of the higher Euro standards, also the emission of cold- starts are decreasing.

All of the simulations are conducted using COPERT 5 software, assuming ambient temperatures from −20 °C to +30 °C, with 5 °C intervals. Simulations were performed for PCs for different fuel types: Petrol (incl. Hybrid and PHEV), Diesel (incl. PHEV), LPG, and CNG, segment (Mini, Small, Medium, Large-SUV-Executive), and the Euro standard (Euro 1–Euro 6). The article presents the results of modelling changes in the ambient temperature assuming that simulation is performed for one vehicle in each category generating the constant mileage, the constant mileage share per road class, as well as constant number of vehicles.

CONCLUSIONS

As shown in Figures 1–9, changing the ambient temperature affects the reduction of cold-start emissions of CH_4 and NMVOC for each vehicle category. The highest CH_4 cold-start emissions are for PCs Petrol for Euro 1–3, Euro 4–6, PCs CNG, and next for Petrol PCs Euro 4+, while for PCs Diesel emissions are much smaller than for other fuels (see Tables 2-4).

For the Diesel PCs at an ambient temperature −20 °C and −15 °C there was no emission factors available to calculate emissions, and for ambient temperature +25 °C, as shown in Table 4 and 5, the highest NMVOC cold-start emissions occur for PCs Petrol. The highest NMVOC cold-start emissions occur for Petrol PCs Euro 1 vehicles. Comparing between the Euro 1, and post-Euro 1 (Euro 2+) vehicles, the strong reduction of NMVOCs emissions can be explained by appearing of a catalytic systems, and their gradual reduction in time to reach the light-off temperature along with increasing Euro standard. This reduction in time causes the decrease of distance travelled with a partially warm engine which may cause exhaust emissions after the catalytic system.

There is also a noticeable difference in emissions between Euro 1–3 and Euro 4+, which is due to the technical solutions used in engines.

Acknowledgements

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Abbreviations

- CH_4 - methane;
- COPERT - Computer Programme to calculate Emissions from Road Transport;
- EEA - European Environment Agency;
- EMEP - European Monitoring and Evaluation Programme;
- HC(s) - hydrocarbons;
- NMVOC(s) - non-methane volatile organic compounds;
- PC(s) - passenger cars;
- PHEV - Plug-in Hybrid Electric Vehicle.

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