ARCHIVES OF ENVIRONMENTAL PROTECTION
vol. 40 no. 3 pp. 86 - 100 2014

DE GRUYTER
PL ISSN 2083-4772
DOI: 10.2478/aep-2014-0026

COLD START EMISSIONS OF SPARK-IGNITION ENGINES AT LOW AMBIENT TEMPERATURES AS AN AIR QUALITY RISK

PIOTR BIELACZYC*, ANDRZEJ SZCZOTKA, JOSEPH WOODBURN

BOSMAL Automotive Research and Development Institute Ltd,
Sarni Stok 93, 43-300 Bielsko-Biała, Poland
*Corresponding author's e-mail: piotr.bielaczyc@bosmal.com.pl

Keywords: Cold start, low ambient temperature, direct and indirect injection spark ignition engine, exhaust emissions.

Abstract: SI engines are highly susceptible to excess emissions when started at low ambient temperatures. This phenomenon has multiple air quality and climate forcing implications. Direct injection petrol engines feature a markedly different fuelling strategy, and so their emissions behaviour is somewhat different from indirect injection petrol engines. The excess emissions of direct injection engines at low ambient temperatures should also differ. Additionally, the direct injection fuel delivery process leads to the formation of PM, and DISI engines should show greater PM emissions at low ambient temperatures. This study reports on laboratory experiments quantifying excess emissions of gaseous and solid pollutants over a legislative driving cycle following cold start at a low ambient temperature for both engine types. Over the legislative cycle for testing at -7°C (the UDC), emissions of HC, CO, NO_x and CO_2 were higher when tested at -7°C than at 24°C. Massive increases in emissions of HC and CO were observed, together with more modest increases in NO_x and CO_2 emissions. Results from the entire driving cycle showed excess emissions in both phases (though they were much larger for the UDC). The DISI vehicle showed lower increases in fuel consumption than the port injected vehicles, but greater increases in emission of HC and CO. DISI particle number emissions increased by around 50%; DISI particle mass by over 600%. The observed emissions deteriorations varied somewhat by engine type and from vehicle to vehicle. Excesses were greatest following start-up, but persisted, even after several hundred seconds' driving. The temperature of the intake air appeared to have a limited but significant effect on emissions after the engine has been running for some time. All vehicles tested here comfortably met the relevant EU limits, providing further evidence that these limits are no longer challenging and need updating.

INTRODUCTION

Vehicular Emissions and Their Impacts

Concern regarding the impact of the transport sector on air quality and greenhouse gas emissions remains high – particularly to legislators, but also to the public in general. Road transport remains one of the largest single sources of CO_2 emissions in the EU and a significant contributor to global emissions. In addition to CO_2, the emission of certain hydrocarbons and particulate matter can exert considerable impact on climate forcing, as well as air quality. Currently, both regulated emissions and greenhouse gases are considered to fall under the aegis of environmental protection.

From humble beginnings in California in the 1960s, legislative control of automotive exhaust emissions has evolved substantially, both in the USA and in other jurisdictions (e.g. the EU, Japan, China, India, etc.). In the EU, the introduction of Euro standards 1 to 5 (current) and 6 (planned) have dramatically reduced permissible emissions of various pollutants, and the range of regulated pollutants has also expanded over the years (NMHC and PN being two relatively recent additions). Separate limits are set for vehicles featuring SI (petrol) and CI (Diesel) engines, but for both types the trend has been one of substantial reductions over the past 20 years. Overall, in the last 13 years, maximum permissible emissions from SI engines have decreased by around 40%; emissions limits for CI engines are now roughly 80% lower than they were. (Note that these reductions are for regulated emissions and do not include CO_2, which has its own legislation).

While changes have been made to test procedures to attempt to quantify and limit cold-start emissions and emissions at low ambient temperatures, there is evidence that these measures are somewhat outdated. Furthermore, the EU limits currently apply only to emissions of HC and CO, and are relatively easily met. Irrespective of the legislation, increased emissions of pollutants other than HC and CO at low ambient temperatures have important implications for air quality and even the global climate.

Research conducted in the USA [7] has shown that air-quality models tend to underestimate cold-start emissions, such that actual VOC emissions from vehicles may be 12% to 38% greater than predicted by models. For all jurisdictions, ongoing research on the effect of low and sub-zero ambient temperatures is essential to ensure air quality models are as accurate as possible. Recent research [e.g. 20] has addressed some of the shortcomings and knowledge gaps, but ongoing testing is required for validation of these theoretical models and generalisations.

Cold Start Events and the Resulting Emissions

Start-up events are the most fundamental transient events experienced by automotive engines. This is related to the fact that engine speed and fuel consumption change from zero to non-zero values in a very short space of time, even before any power is transferred to the wheels [4, 6]. Both hot and cold start events can be classified as transient operation of an internal combustion engine [4, 6, 9]. Cold start can be defined as when an engine is started with the temperatures of the oil, coolant and all elements of the engine (T) at the ambient temperature (T_a) [3, 4, 6]. During hot start, the temperature of all these elements will be very close to those observed during fully warmed-up operation (T_w). The term 'cool start' can be used to refer to intermediate temperatures (i.e. $T_a<T<T_w$) [4, 6]. Cool and cold starts represent a significant challenge in terms of forming combustible air-fuel mixtures while keeping emissions and fuel consumption at reasonable levels. This problem becomes progressively worse with reducing ambient temperatures. Emissions of regulated exhaust gas components and carbon dioxide (CO_2) show measurable differences with varying T_a, with a general trend for worse emissions at lower temperatures [1–4, 6, 7, 10–14, 18–20].

Cold start emissions behaviour represents perhaps the greatest single issue for emissions control regarding passenger cars, and a key theme for the development of effective aftertreatment systems such as TWCs. Before an engine of any type can perform useful work, it must be started. In the case of passenger cars, each journey (or segment of a journey) necessitates a start-up event. For successful start-up, and acceptable drivability thereafter, fuel enrichment (use of a fuel-air mixture with 'excess' fuel) is necessary.

Additionally, due to the low temperature, CO and HC are not oxidized in the vehicle's TWC (aftertreatment) system during the period immediately following start-up. The result of these factors is that start-up events are significant in terms of emissions and fuel consumption, and there is a strong dependency on the temperature of the engine and the temperature of the ambient air.

The effect of low and sub-zero ambient temperatures on cold starts of internal combustion engines fitted to passenger cars has been widely reported and discussed in the literature [1–4, 6, 7, 10–14, 18–20]. The temperature range used globally for type-approval testing is typically 20°C to 30°C. Colder conditions a few degrees above zero cause greater emissions and fuel consumption and this trend continues as ambient temperatures fall below zero degrees centigrade. While the mathematical form of the response is variable [6], low ambient temperature cold starts lead to higher emissions of HC, CO and CO_2. Fuel consumption is greater and emission of NO_x can also be increased. Aftertreatment systems, such as a TWC, do not function properly during the first 20–100 seconds of engine operation following cold start, having not yet reached light-off, and this prevents effective mitigation of the increased tailpipe emissions of HC, CO and NO_x.

The main factors that affect emissions and fuel consumption, and thereby air quality and the climate, following cold start at low ambient temperatures are summarised graphically in Figure 1.

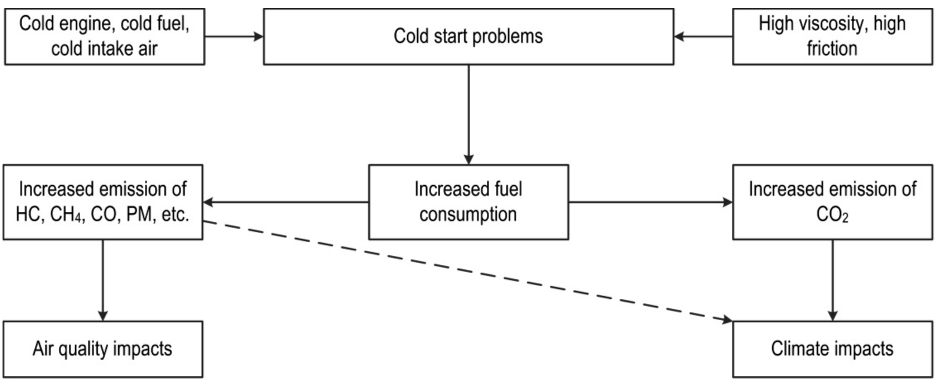

Fig. 1. Cause-and-effect diagram of the impacts of cold-start engine operation at low ambient temperatures on air quality and climate

Typically, one to two cold starts are experienced by each passenger car on most days; around 69% of all journeys begin with a cold or cool start [11]. Thus, in regions where T_a often falls below 0°C, a vehicle will typically experience one to two sub-zero cold starts on a significant number of days during any given year. There are many areas in North America, Europe and Asia where low and sub-zero ambient temperatures are common during the cooler months [4, 6].

Legal emissions limits and the results of emissions tests are expressed in units of g/km (or mg/km). However, after starting the engine, significant quantities of regulated and unregulated pollutants are emitted, even before the vehicle covers any distance. In terms of the requirements of the user of a private vehicle (passenger car), it is normally desirable to begin driving as soon as the engine has been started. Such a strategy is in fact the optimal strategy regarding emissions and excess fuel consumption – the best way to bring the engine and the TWC to T_w is to use the engine to drive the vehicle in a normal manner. However, under sub-zero conditions, the driver may find it desirable to leave the engine running while the windscreen clears and snow and ice are removed from the outside of the vehicle. Allowing the engine to "warm up" in this way in fact makes little sense for modern vehicles, since emissions and fuel consumption will be non-trivial, but no distance covered by the vehicle during this period. As far as minimising emissions and fuel consumption goes, the best strategy for light-duty automotive engine is to start driving as soon as the engine has been started. Another approach is to maintain the temperature T above T_a. This can be accomplished in three main ways: parking the vehicle within a heated garage or parking complex; using an electrical block heater to heat the engine and its fluids prior to start-up (a popular option in Scandinavia; see [12]); and linking trips together so that the engine does not have time to fully cool between journeys. Not all of these approaches are applicable in all cases, but in under certain circumstances a combination of all three approaches could potentially be used.

Legislative Emissions Limits and Testing of Cold Start Emissions
Starting in the early 1990s, interest began to grow in cold start events and the attendant emissions and a number of studies and analyses were published. Various regulatory authorities have mandated emissions limits for testing of passenger cars at ambient temperatures below the standard 20–30°C range. These procedures and limits are summarised in Table 1.

Table 1. Low temperature emissions test limits for light-duty petrol vehicles

Legislation	Test temperature	Test cycle	HC [g/km]	CO [g/km]	NO_x [g/km]
European Union Cat M_1 and N_1 Cl. I	-7°C	UDC	1.8	15	–
European Union Cat N_1 Cl. II, M_1>6 seats	-7°C	UDC	2.7	24	–
European Union Cat N_1 Cl. III	-7°C	UDC	3.2	30	–
USA/EPA	-6.7°C	FTP-75		6.21	–
California/CARB	10°C	Unified Cycle	0.0124*	0.62	0.0124
California/CARB	-7°C	Unified Cycle	–	6.21	–

* NMOG limit; additional limit for aldehydes

Low temperature test and emissions limits were introduced for the first time in the USA's Code of Federal Regulations (CFR) legislation. Following analyses of automotive cold start emissions behaviour in the 1990s, testing at low ambient temperatures was introduced in 1994 in the USA from model year 1994 (Tier I) vehicles, with a limit to control CO emissions (10 grams/mile over the FTP 75 test cycle) at low ambient temperatures. There is also a cold CO limit which has to be met at all altitudes. The state of California developed its own test procedure; all non-diesel vehicles from model year 1996 onwards also need to meet a cold CO limit, an additional test performed at 10°C with limits for HC, CO and NO_x was introduced. Following these changes, in 2000 the EU firstly adapted the Euro 3 test procedure to synchronise sampling of the exhaust gas with the start of cranking (thereby eliminating the 40 second warm-up period which had previously existed). This change effectively forced manufacturers to mount catalytic aftertreatment systems in the close-coupled configuration, in order to minimise light-off time and ensure effective mitigation of the HC and CO emissions associated with start-up. Furthermore, from 2002 the EU introduced a test at -7°C for all SI vehicles. Measurement is performed in first part of the NEDC cycle – the UDC (780 seconds), with limits set for emissions of HC and CO. The Euro 5 regulations introduced additional requirements for SI flex-fuel vehicles, where measurement must be performed on two fuel types: petrol and E75 (Euro 5b). An additional requirement is now in place for type-approval testing of CI vehicles, which requires that the NO_x aftertreatment device reaches “a sufficiently high temperature for efficient operation” within 400 seconds following cold start at -7°C.

This paper discusses cold start events for SI engines, the dominant engine type for passenger cars in many (but not all) markets. Two types of SI engine are currently used in automotive applications, DISI currently having a smaller market share than indirect MPI SI engines. However, interest is growing in DISI engines in multiple markets, including in the EU. Ongoing research has indicated that cold start events continue to cause substantial excess emissions, and future test procedures may feature lower ambient temperature ranges, in an attempt to better quantify ‘real-world’ emissions and fuel consumption.

EXPERIMENTAL DETAILS

All work described here was carried out in the Euro 5/6-compliant vehicle emissions testing laboratory at BOSMAL Automotive R&D Institute (Poland). This laboratory is housed within a climatic chamber with the capability of creating stable temperatures covering the range -35°C to +60°C (see [5] for a detailed description of this test facility). Vehicles were tested on a chassis dynamometer located within this climatic chamber (Figure 3). Three experiments were performed. In the first experiment, the UDC was used to test a pool of MPI test vehicles at -7°C, according to EU legislative requirements [16]. Using a CVS, diluted exhaust gas was collected in emissions sampling bags for analysis of HC and CO emissions; CO_2 emissions were also measured. In the second and third experiments, an MPI vehicle and a DISI vehicle with approximately equal cylinder displacement and comparable unladen mass were tested over the NEDC at ambient temperatures of -7°C and -24°C. Emissions of HC, CO, NO_x and CO_2 were measured for both vehicles. For the DISI vehicle, PM emissions were quantified using gravimetric and condensation particle counter methods, according to the relevant EU legislation. For each of the cars tested, two or three emission tests were carried out (depending on the repeatability of the results). Only one emissions test per day was performed. The mean values of each measurement series were taken for further analysis. The maximum expanded uncertainties of the emission measurements were about 16% for HC, 11% for CO, 7% for NO_x and 4% for

PM, CO_2 and fuel consumption. For a thorough discussion of the uncertainties inherent in cold start chassis dynamometer emissions testing of passenger cars, see reference [21].

Fig. 2. Exhaust emissions laboratory at BOSMAL, showing the chassis dynamometer, windspeed fan and a vehicle, all within the climatic chamber

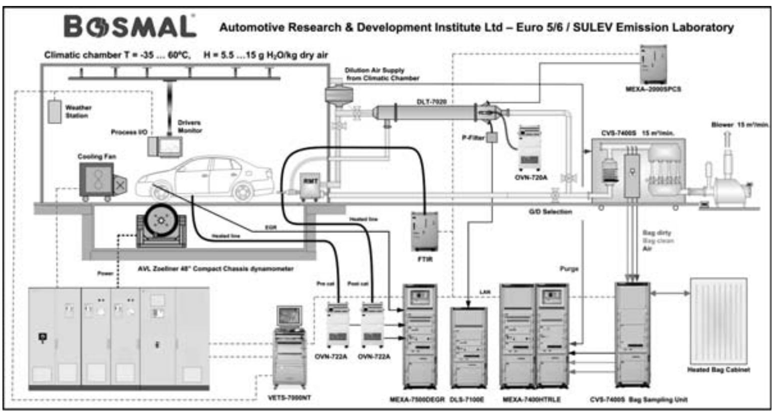

Fig. 3. Schematic diagram of BOSMAL's emissions laboratory, as used to measure emissions from the test vehicles

A T_a value of -7°C is in no way representative of the lower limit of operation for passenger cars. However, testing over the UDC at this temperature permits comparison to the EU's legislative limits, and also to results obtained in other studies.

Several pools of vehicles were tested. The first vehicle pool contained a total of 14 vehicles, all of which were passenger cars which met the EU's Euro 5 emissions standard. Twelve these vehicles featured MPI fuel delivery systems; the remaining two vehicles featured DISI engines. All vehicles tested in this study were European passenger cars featuring the latest SI engine technology, of displacement 1.0–1.4 dm³. Most vehicles were turbocharged. All vehicles featured close-coupled TWCs. No modifications whatsoever were made to the vehicles, in order to be representative of the on-road passenger car fleet.

All vehicles were fuelled with a standard European petrol fuel, whose key properties are shown in Table 2. This commercially available petrol fuel fulfilled the demands of the EN228:2009 standard.

Table 2. Key properties of the test fuel used

Parameter	Value
Research Octane Number [-]	95.5
Density [kg/dm^3]	0.7492
Benzene content [%v/v]	< 1.0
Aromatics [%v/v]	< 35
Olefins [%v/v]	< 18
Ethanol content [%v/v]	5.0
Sulphur content [mg/kg]	5.2

RESULTS & DISCUSSION

HC & CO Emissions Results from MPI and DISI Vehicles Obtained at -7°C Using the EU Legislative Test Procedure

The results of the first experiment, where test vehicles 1–14 were tested over the UDC for comparison to European legislative limits for HC and CO, are presented in Figure 4. HC emissions from all vehicles met the Euro 5 limit for testing at -7°C. Considerable variation was observed among vehicles 1–17, but 11 of the 12 MPI vehicles tested had HC emissions <1 g/km, and four emitted <0.5 g/km. Both DISI vehicles had very similar HC emissions of just over 0.5 g/km. CO emissions fell into three groups: very low emitters (<2 g/km) – vehicles 2, 4 & 5; low emitters (2–4 g/km) – vehicles 1, 3, 10, 11 & 12; and higher emitters (>5 g/km) – vehicles 6–9. Statistically speaking, there was no difference between the HC and CO emissions from the MPI vehicles and the DISI vehicles. Figure 5 shows a graphical comparison of HC and CO results obtained over the UDC at -7°C for all MPI test vehicles.

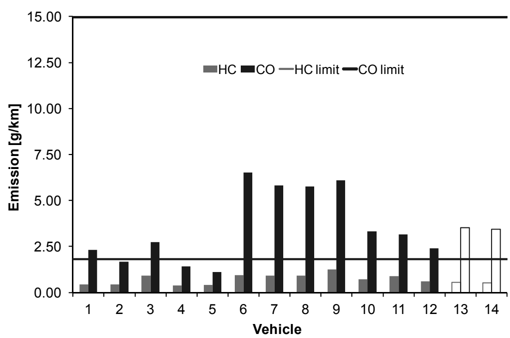

Fig. 4. HC and CO emissions results from test vehicles 1–14, tested over the UDC at -7°C, presented in comparison to the emissions limit. The solid bars (vehicles 1–12) are results from MPI vehicles; the hollow bars (vehicles 13 and 14) are DISI vehicles

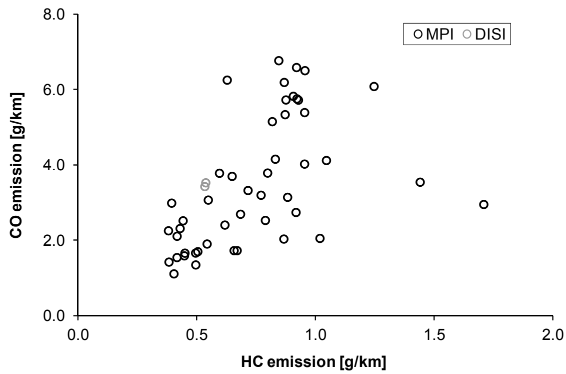

Fig. 5. A scatterplot of HC and CO emissions results for all test vehicles, tested over the UDC at -7°C

A noticeable feature of Figure 5 is the scatter in the data – the correlation observed between emissions of HC and CO under these test conditions was weak. Both DISI vehicles and a fair number of MPI vehicles lie in the region where CO emission in numerically 4–8 times higher than HC emission (by mass), but there were several outliers. Interestingly, the DISI vehicles were relatively close to the mean of all MPI vehicles. Significantly, three of the test vehicles emitted well over 1 g/km of HC and the mean of all vehicles was around 50% of the Euro 5 limit. In contrast, regarding emissions of CO, the majority of vehicles emitted less than 5 mg/km and the mean value was around 30% of the Euro 5 limit. Any substantial reduction in the HC limit would likely require changes to the calibration, aftertreatment systems, etc, in order not to risk exceeding the new, lower limit. In contrast, if the CO limit were reduced by (say) 40–50%, all the vehicles tested in this study would still have had emissions under this lower limit. In the case of the DISI vehicles, both comfortably met the legislative limits by a wide margin.

Emissions deterioration factors are non-dimensional factors calculated by dividing emissions from a test conducted at -7°C by the equivalent emission from the test conducted on the same vehicle at 24°C. The value can range from 0 to infinity; a value of 1 implies the emission was exactly the same at -7°C and 24°C; a deterioration factor of 1.15 equates to a 15% increase. From this point onwards, this paper makes reference to deterioration factors, rather than raw results. Previous work has indicated that deterioration factors for SI engines can be very large at -7°C, particularly for HC and CO [1–4, 6, 7, 15, 18–20]. Since a total of 12 MPI vehicles were tested, it was possible to perform a brief statistical analysis of the deterioration factors calculated from the emission results, as shown in Table 3.

Table 3. A statistical analysis of excess emissions of HC, CO and CO_2 for MPI vehicles 1–12

(*n*=12)	HC	CO	CO_2
Mean [-]	9.486	6.780	1.214
Standard Deviation [-]	2.515	2.156	0.055
Coefficient of Variance [%]	26.51	31.79	4.51

For the pool of vehicles as a whole, the deterioration over the UDC was greatest for HC. The coefficient of variance for HC and CO was of a similar magnitude. For CO_2, the mean increase was relatively high (21%), but the variability was low. Despite these large deteriorations in emissions of HC and CO, all these vehicles easily met the relevant emissions limits for testing at -7°C – implying that these limits do not pose a challenge for and are easily met, at least for small engines.

A Comparison of Regulated Compounds and CO_2 Obtained over the NEDC at 24°C and at -7°C for an MPI vehicle

Deterioration factors varied greatly by pollutant type and according to the phase of the driving cycle, as shown in Figure 6.

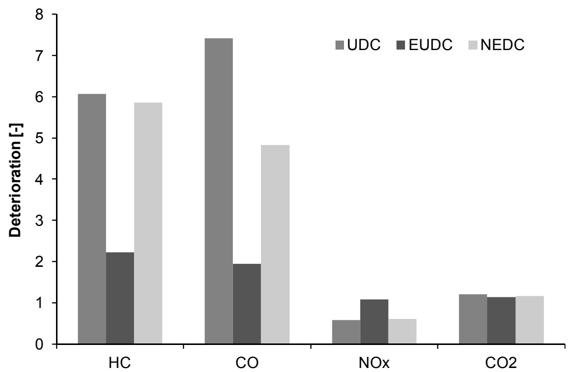

Fig. 6. Deterioration factors for a MPI vehicle tested over the NEDC at 24°C and at -7°C

Only HC and CO showed very large increases during both phases. For HC, CO and CO_2 emissions were markedly higher over the whole cycle. For NO_x, a slight decrease was observed for the first phase, counteracted somewhat by an increase for the second phase, meaning that overall emissions changed relatively little in response to the lower test temperature. The elevated emissions of HC and CO during the first phase strongly suggest combustion difficulties, the usage of a rich mixture and poor mixture formation. For this vehicle, the magnitudes of the deterioration for emissions of HC and CO were comparable, over both phases of the test cycle. Carbon dioxide emissions at cold start are markedly higher, as caused by higher rates of fuel consumption, due to the increased friction encountered when the engine's components and oil are at low temperatures [4, 6, 9]. Even oils designed for use in colder climates show massive increases in viscosity at sub-zero temperatures. This increases friction and consequently fuel consumption and CO_2 emissions. Therefore, the 16% increase in CO_2 emissions over the entire cycle is not an unexpected result. However, the excess emissions for the second phase (the EUDC) were around 13%, indicating that the ambient temperature still had an effect on fuel consumption (and therefore on CO_2 emissions), despite the engine being more or less fully warmed up by the time the second phase started.

A Comparison of Regulated Compounds and CO_2 Obtained over the NEDC at 24°C and at -7°C for a DISI vehicle

Deterioration factors varied greatly by pollutant type and according to the phase of the driving cycle, as shown in Figure 7.

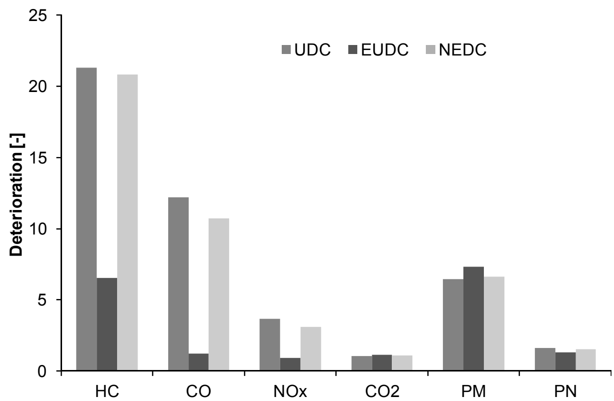

Fig. 7. Deterioration factors for a DISI vehicle tested over the NEDC at 24°C and at -7°C

HC and PM showed very large increases during both phases; CO and NO_x only showed a large increase during the first phase (the UDC); deterioration in emissions of CO_2 and PN and in the fuel consumption were less dramatic. The elevated emissions of HC and CO during the first phase strongly suggest combustion difficulties and rich operation. The deterioration observed for HC and CO is higher than for the MPI vehicles tested in this study. In a direct injection engine, uncombusted fuel can make contact with the cold cylinder wall, thereby leading to dramatically increased emissions of HC. The cylinder wall acts as a heatsink, limiting the efficiency of the oxidation reaction and increasing emissions of HC, CO and PM (and also PN). The poor distribution of fuel can result in increased NO_x emissions. During the second phase (the EUDC), emissions and fuel consumption were higher in all cases (particularly for HC and PM), apart from for NO_x, which was actually reduced. The efficiency of the fuel delivery process is hindered by low temperatures. When the injectors (and the fuel itself) are at low or sub-zero temperatures, fuel atomisation is impeded and a film of liquid fuel may accumulate on cold metal surfaces [3, 4, 6]. Impaired atomisation reduces the surface area to volume ratio of the droplets, making the air/fuel mixture less combustible. Despite these factors, over the whole cycle, fuel consumption increased by just under 12% – a small change, given the 31°C difference between the two test temperatures. This relatively small increase indicates that this engine did not dramatically increase fuel supply in response to the lower test temperature. Intriguingly, the observed deterioration was slightly higher for the second phase of the cycle, indicating that the deterioration was perhaps proportional to engine load (It should also be recalled that the legislative test method calls for the chassis dynamometer loading coefficients to be increased by 10% for testing at -7°C. This additional loading will also have an impact on CO_2 emissions and fuel consumption). Also of note was the fact that particle mass increased significantly, with a deterioration factor > 6 over the NEDC, while particle number emissions increased by around 50% only.

CONCLUSIONS

The emissions factors reported here from testing at -7°C over the UDC are broadly similar to those reported in other studies [4, 6]. The EU limits for testing at -7°C are evidently not particularly challenging for vehicles which meet the Euro 5 standard. Revision of these limits is under consideration [8] – and evidence presented here and elsewhere [e.g. 4, 6] suggests this revision is urgently required, as most European passenger cars comfortably meet the limits for emission of HC and CO, sometimes by a very wide margin. Results obtained from vehicles featuring DISI engines were similar to results from MPI engines. A graphical and statistical analysis of a pool of MPI vehicles revealed deterioration of emissions of HC and CO to be high, with HC showing the greatest increase. When tested over the NEDC, the MPI test vehicle showed similar responses and increased emissions during the second phase of the cycle, implying that the ambient temperature continued to have an effect, even after several hundred seconds' driving. For the DISI vehicle, PM emissions increased massively – by some 600%, but the increase in particle number was much smaller, at around 50%. The correlation between particle number and mass at low various ambient temperatures would be an interesting research direction. Additionally, these observations indicate that a particle mass and number limit would be appropriate for testing of DISI vehicles at -7°C. Such a requirement may feature in future EU legislation and research on this topic must continue. Continued interest in 'real world' emissions factors and realistic fuel consumption values, as well as air quality concerns, will ensure that the topic of cold start behaviour at low ambient temperatures remains an important research topic [4, 6, 7], particularly for automotive markets where sub-zero temperatures are common. The Republic of Poland is a good example of a jurisdiction where sub-zero ambient temperatures are very common and the impact of cold start emissions on air quality is substantial. This paper has confirmed that even modern vehicles emit much greater amounts of HC, CO (and PM) when started at low ambient temperatures. The high value of the emission deterioration factor for HC requires particular attention.

Despite the decrease of benzene content in gasoline aromatics in fuel still constitute a risk resulting from the high toxicity of benzene. In addition, homologues of benzene are harmful because they contribute to the formation of ozone and photochemical smog. In earlier studies [22] it was shown that benzene and its alkylated derivatives profiles in gasoline, engine exhaust gases and in air in the vicinity of communication arteries show striking similarities. For all countries and regions with such climatic conditions, cold start emissions will form an important part of emissions inventories and projections and any studies which fail to take cold start behaviour into consideration will tend to paint too optimistic a picture. However, cold start emissions depend on various factors, not least ambient temperature and engine type. Furthermore, real usage of vehicles does not follow an established 'procedure' and extended idling, extensive use the cabin heating system, etc. may cause even greater deteriorations in emissions performance at low ambient temperatures. The need for data on these subjects and answers to questions surrounding the operation of passenger cars at low and sub-zero ambient temperatures makes experimental work of the type presented in this paper a research priority.

DEFINITIONS/ABBREVIATIONS

CARB	California Air Resources Board
CO	carbon monoxide
CO_2	carbon dioxide
CI	compression ignition
CVS	constant volume sampler
DISI	direct injection spark ignition
EU	European Union
EUDC	Extra Urban Driving Cycle
EPA	Environmental Protection Agency
FTP	Federal Test Procedure
HC	hydrocarbons
LCV	Light Commercial Vehicle
MPI	Multi-Point Injection
NEDC	New European Driving Cycle
NMHC	non-methane hydrocarbons
NO_x	oxides of nitrogen
PC	passenger car
PM	particle mass
PN	particle number
SI	spark ignition
T	conceptual mean temperature of the coolant, oil and all engine elements
T_a	ambient temperature
T_w	temperature of the oil and coolant when the vehicle is fully warmed up
TWC	three-way catalyst
UDC	Urban Driving Cycle
USA	United States of America
VOC	volatile organic compounds

REFERENCES

[1] Andrews, G.E., et al. (2005). Influence of Ambient Temperature on Cold-start Emissions for a Euro 1 SI Car Using In-vehicle Emissions Measurement in an Urban Traffic Jam Test Cycle, *SAE Technical Paper*: 2005-01-1617, DOI:10.4271/2005-01-1617.

[2] Andrews, G.E., et al. (2004). The Effect of Ambient Temperature on Cold Start Urban Traffic Emissions for a Real World SI Car, *SAE Technical Paper*: 2004-01-2903, DOI:10.4271/2004-01-2903.

[3] Bielaczyc, P. & Merkisz, J. (1998). Cold Start Emissions Investigation at Different Ambient Temperature Conditions. *SAE Technical Paper*: 980401, DOI:10.4271/980401.

[4] Bielaczyc, P., Szczotka, A. & Woodburn, J. (2012). Excess Emissions and Fuel Consumption of Modern Spark Ignition Passenger Cars at Low Ambient Temperatures, *SAE Technical Paper*, 2012-01-1070, DOI:10.4271/2012-01-1070.

[5] Bielaczyc, P., Szczotka, A. & Woodburn, J. (2011). Development of vehicle exhaust emission testing methods – BOSMAL's new emission testing laboratory, *Combustion Engines*. 1, 144, 3–12.

[6] Bielaczyc, P., Szczotka, A. & Woodburn, J. (2011). The effect of a low ambient temperature on the cold-start emissions and fuel consumption of passenger cars. *Journal of Automobile Engineering*, 225, 9, 1253–1264, DOI:10.1177/0954407011406613.
[7] Cook, R., et al. (2007). Impact of Underestimating the Effects of Cold Temperature on Motor Vehicle Start Emissions of Air Toxics in the United States, *Journal of the Air & Waste Management Association*, 57, 12, DOI: 10.3155/1047-3289.57.12.1469.
[8] Dardiotis, C., et al. (2012). JRC's contribution to the revision of the European type approval procedure for light-duty vehicles. Current and Future Trends in Automotive Emissions, Fuels, lubricants and Test Methods – 2012, proceedings from the 3rd International Exhaust Emissions Symposium, 24–25 May 2012, Bielsko-Biala, Poland, *Combustion Engines*, 2, 149.
[9] Heywood, J.B. (1988). Internal Combustion Engine Fundamentals, McGraw-Hill, New York 1988.
[10] Joumard, R. & Serie, E. (1999). French National Institute for Transport and Safety Research, Report LTE 9931, available from http://www.inrets.fr.
[11] Joumard, R. & Serie, E. (2005). French National Institute for Transport and Safety Research, Report LTE 0509, available from http://www.inrets.fr.
[12] Laurikko, J. (1995). Ambient temperature effect on automotive exhaust emissions: FTP and ECE test cycle responses. *The Science of the Total Environment*, 169, 195–204.
[13] Laurikko, J. (2008). Cold-Start Emissions and Excess Fuel Consumption at Low Ambient Temperatures – Assessment Of EU2, EU3 and EU4 Passenger Car Performances. FISITA paper: F2008-06-049.
[14] Smokers, R., et al. (2004) Expert judgement on the long term possibilities of conventional emission abatement technologies for passenger cars, *Topics in Catalysis*, 30/31, 439–443, DOI: 10.1023/B:TOCA.0000029787.60870.49.
[15] Tribulowski, J., et al. (2002). Influence of Atomization Quality on Mixture Formation, Combustion and Emissions in a MPI-Engine Under Cold-Start Conditions, Part II. *SAE Technical Paper*: 2002-01-2806, DOI: 10.4271/2002-01-2806.
[16] UNECE Regulation no 83 – Annex 8.
[17] Vehicles in use: key figures (2008). ACEA (European Automobile Manufacturers' Association), available from http://www.acea.be.
[18] Weilenmann, M., et al. (2005). Regulated and nonregulated diesel and gasoline cold start emissions at different temperatures, *Atmospheric Environment*, 39, 2433–2441, DOI: 10.1016/j.atmosenv.2004.03.081.
[19] Weilenmann, M., et al. (2009). Cold-start emissions of modern passenger cars at different low ambient temperatures and their evolution over vehicle legislation categories, *Atmospheric Environment*, 43, 2419–2429, DOI: 10.1016/j.atmosenv.2009.02.005.
[20] Weilenmann, M., et al. (2013). The cold start emissions of light-duty-vehicle fleets: A simplified physics-based model for the estimation of CO_2 and pollutants, *Science of The Total Environment,* DOI: 10.1016/j.scitotenv.2012.11.024.
[21] Bielaczyc, P. & Szczotka, A. (2007). Analysis of Uncertainty of the Emission Measurement of Gaseous Pollutants on Chassis Dynamometer, *SAE Technical Paper* 2007-01-1324, DOI: 10.4271/2007-01-1324.
[22] Żak, M. & Konieczyński, J. (2008). Comparison of benzene and its alkylated derivatives profiles in car's fuels, engines exhaust gases and in air in vicinity of communication arteries, *Archives of Environmental Protection*, 34, 2, 3–11.

EMISJA SPALIN PODCZAS ROZRUCHU ZIMNEGO SILNIKA ZI PRZY NISKICH TEMPERATURACH OTOCZENIA JAKO ZAGROŻENIE CZYSTOŚCI POWIETRZA

Samochodowe silniki spalinowe o zapłonie iskrowym (ZI) charakteryzują się zwiększoną emisją związków szkodliwych spalin podczas rozruchów przy niskich temperaturach otoczenia, co ma duży wpływ na jakość powietrza. Różnice w emisji związków szkodliwych spalin (w tym również różnice w nadmiernej emisji podczas rozruchów w niskich temperaturach otoczenia) silników benzynowych o wtrysku bezpośrednim w porównaniu do silników o wtrysku pośrednim wynikają w znacznej mierze z odmiennej strategii zasilania silnika paliwem. Proces bezpośredniego wtrysku paliwa prowadzi również do formowania się cząstek stałych (PM). Silniki o zapłonie iskrowym z bezpośrednim wtryskiem paliwa charakteryzują się znacznie większą emisją cząstek stałych przy niskich temperaturach otoczenia. W niniejszym artykule przedstawiono wyniki badań laboratoryjnych zwiększonej emisji gazowych związków szkodliwych spalin i cząstek stałych dla obu typów silników podczas

homologacyjnych cykli jezdnych na hamowni podwoziowej, poprzedzonych zimnymi rozruchami w niskich temperaturach otoczenia. Podczas fazy UDC (ustawowy cykl jezdny przeprowadzany w temperaturze -7°C) emisja węglowodorów (HC), tlenku węgla (CO), tlenków azotu (NO_x), a także dwutlenku węgla (CO_2) była wyższa przy badaniu w temperaturze otoczenia -7°C niż przy 24°C. Zaobserwowano znaczący wzrost emisji węglowodorów i tlenku węgla, a także niewielki wzrost emisji NO_x i CO_2. Wyniki z całego cyklu jezdnego NEDC wykazały nadmierną emisję w obu fazach cyklu (choć znacznie większą podczas fazy UDC). Dla samochodu z silnikiem ZI z wtryskiem bezpośrednim stwierdzono mniejszy wzrost zużycia paliwa oraz znacznie większą emisję HC i CO w porównaniu do samochodu z silnikiem ZI z wtryskiem pośrednim. Dla samochodu z silnikiem z wtryskiem bezpośrednim emisji cząstek stałych była o wyższa o około 50%, jeżeli chodzi o ich liczbę, a masa wyemitowanych cząstek była wyższa o 600%. Zaobserwowany wzrost emisji związków szkodliwych spalin był zmienny w zależności od typu silnika i badanego pojazdu. Największy wzrost tej emisji występował w trakcie rozruchu zimnego silnika i stan ten trwał nawet kilkaset sekund po uruchomieniu silnika. Temperatura zasysanego powietrza po nagrzaniu silnika wydaje się mieć ograniczony, ale widoczny wpływ na emisję. Wszystkie badane pojazdy bez problemów spełniały odpowiednie unijne normy emisji, co dowodzi, że aktualne wymagania homologacyjne nie stanowią już wyzwania i wymagają zaktualizowania.