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An investigation of cold start and warm-up phases with a SI engine for meeting new European emissions regulations

PIOTR BIELACZYC, JERZY MERKISZ, ANDRZEJ SZCZOTKA

Automotive Research and Development Centre, BOSMAL, Bielsko-Biała, Poland

The European driving cycle, deleting the first 40 seconds of idle after the start up phase, and the US FTP 75 cycle are compared in this paper, presenting an analysis of emission tests for CO, HC, and NO_x, measured during tests performed on a chassis dynamometer under laboratory conditions. The tests are reviewed and the results discussed. The tests were undertaken on several vehicle types commonly found on the roads in Poland, the vehicles being of European manufacture.

The objective of the research was to determine the increases in the emissions of CO, HC and NO_x, and the changes to fuel consumption in the initial phase of engine operation. Differences in catalyst warm up rates when running FTP 75 and ECE+EUDC are demonstrated. Methods of reducing these harmful emissions, and the results of test with new technologies targeted at the reduction of CO, HC and NO_x under cold start are also discussed.

1. Introduction

Due to the ever-increasing attention which is being paid to the environment, manufacturers are required to produce internal combustion engines which are able to comply with the new stricter limits. In order to be able to decrease the amount of harmful emissions gradually, it is necessary to identify all the phenomena which influence these and, at the same time, to describe the mechanisms of their formation.

In implementing increasingly stricter requirements three principal regulatory groups for emissions standards world-wide: US (EPA and CARB), Europe (EU and ECE) and Japan are obtaining ever more reduction in vehicles exhaust emissions (figure 1).

Problem of cold start emissions has been an area of intense investigation for several years in order to meet new European standards called Euro III and Euro IV and US California LEV and ULEV requirements. As noted from the results of previous testing, SI engines equipped with a typical TWC (three-way-catalyst), operating under closed loop fuel and ignition control, with an oxygen sensor, emit more CO and HC during cold start and warm-up than in the other phases of controlled engine operation [1 – 5]. As the ambient temperature at engine start decreases to below zero and lower, the effect of this phenomenon becomes more marked, which is presented by authors [3 – 5] among others. It is necessary to enrich the fuel-air mixture under cold start conditions because fuel vaporisation at low

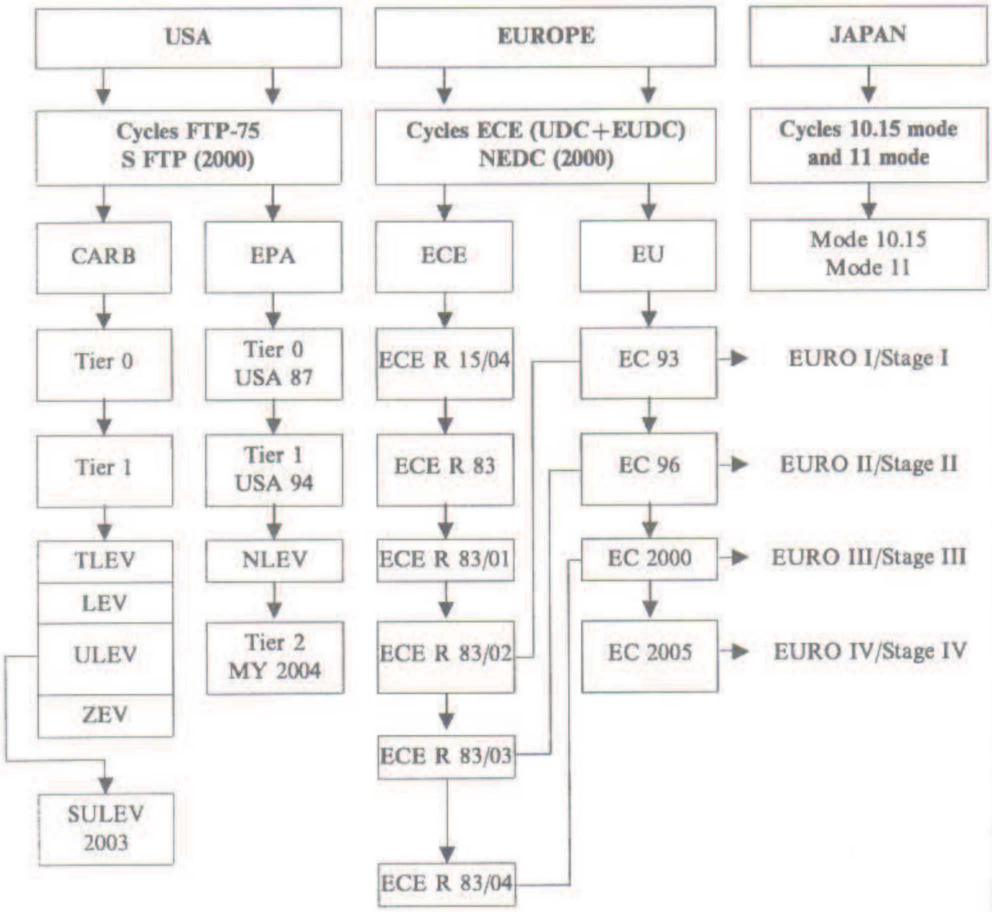


Fig. 1. Three principal regulatory groups for emissions standards world-wide: US (EPA and CARB), Europe (EU and ECE) and Japan

temperature is insufficient for effective combustion [1, 2, 6, 7]. Incomplete combustion with excess fuel leads to increased CO and HC levels. The increase in CO and HC emissions is accompanied by increased fuel consumption, caused by increased engine frictional losses and drive train losses, and an enriched fuel mixture essential for effective starting, stable idle and clean drive away [4, 5]. Principal parameters that affect the SI engine emission at start and warm up are as follows: engine calibration, fuel composition, introduction of fuel to the cylinders, A/F ratio enrichment necessary for a correct cold start, electronic engine control, catalyst light-off time [5, 8] (Fig. 2). The improvement of cold start performance through special attention paid to engine design, calibration and strategy is an important task.

As a consequence of more stringent exhaust emission limits detailed in the new proposed Euro III and Euro IV regulations, and possible new standards covering sub-zero tests within Europe, work to determine the causes of emissions and the development of new technologies for the reduction of CO and HC levels on the cold start phase has become a matter of prime importance.

The tests presented in this paper were carried out within a research program investigating the effect of cold start and warm-up at normal and low ambient temperatures upon emissions. The tests were completed at the BOSMAL Automotive Research and Development Centre in Bielsko-Biała, Poland.

2. The future of European emission requirements

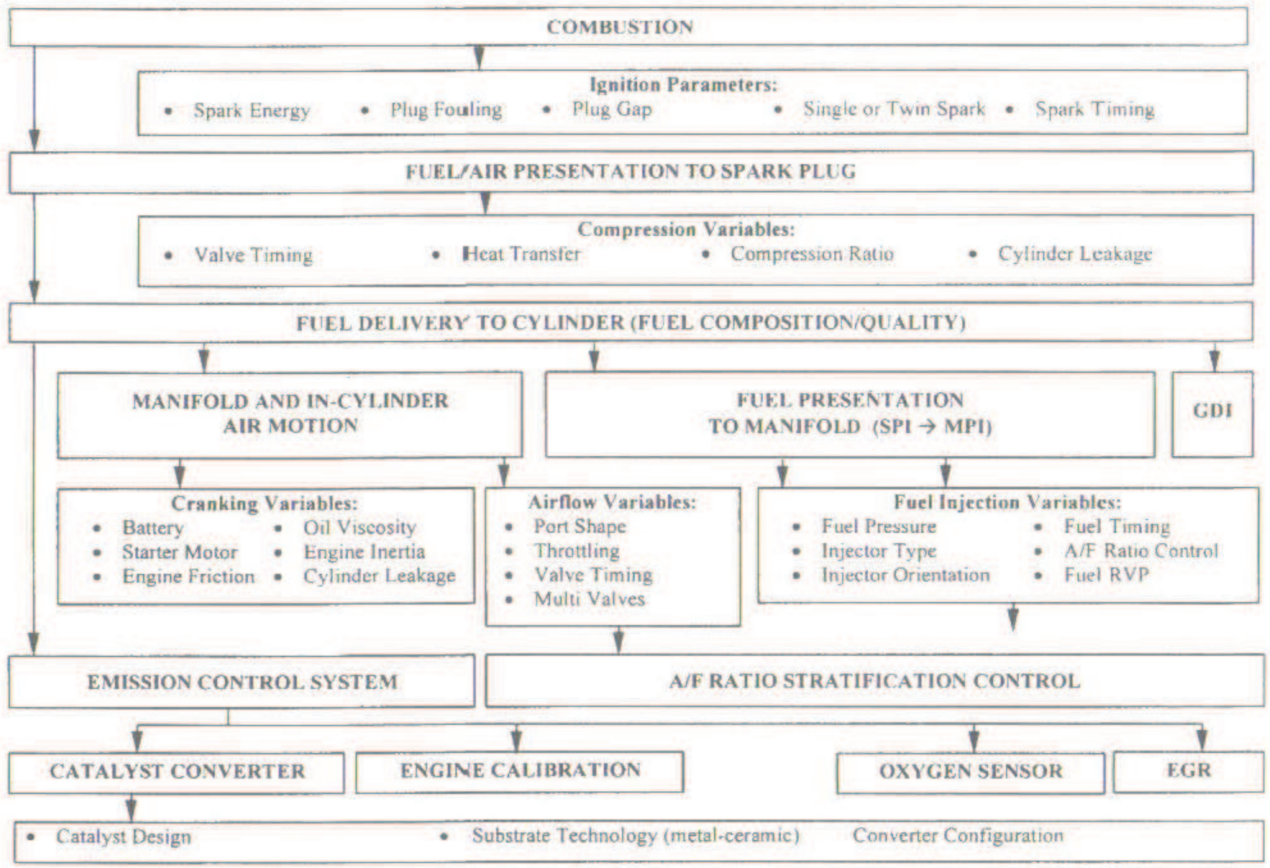
Surveys concerning the investigation of car emissions were conducted in the Europe as early as 1970. Based upon these findings, the EEC (European Economic Community) has developed procedures for car certification, and limits set for CO and HC emissions — Directive 70/220/EEC. Tables 1 outlines the history of European emission regulations and the progress of emission limits over this years. After entry into force emission standards called Euro II (Directive 94/12/EC and Directive 96/69/EC, Regulation ECE 83.03) further development in emission regulations has been taking place within the European Union. On the base of this work European Commission adopted a proposal for an improvement of requirements for passenger cars and quality of fuel. Commission proposed for passenger cars following elements [9]:

- Stage III — Euro III with application date for TA (Type of Approval): 01.01.2000 — expected reduction of tailpipe emission limits by up to 40%,
- Stage IV — Euro IV with application date for TA: 01.01.2005 — further reduction of emission limits.

Table 1. History of the European emissions standards

Directive EEC/EC	Emission limit				Driving Cycle
	CO	HC	NO_x	$HC+NO_x$	
70/220/EEC	152 [g/test]	10,1 [g/test]	–	–	ECE
74/290/EEC	122 [g/test]	8,6 [g/test]	–	–	ECE
77/102/EEC	122 [g/test]	8,6 [g/test]	14 [g/test]	–	ECE
78/665/EEC	99 [g/test]	7,6 [g/test]	11,9 [g/test]	–	ECE
83/351/EEC	76 [g/test]	–	–	22 [g/test]	ECE
88/76/EEC	30 [g/test]	–	–	8 [g/test]	ECE
89/458/EEC	19 [g/test]	–	–	5 [g/test]	ECE
91/441/EEC (EURO I)	2,72 [g/km]	–	–	0,97 [g/km]	ECE+EUDC
94/12/EC, 96/69 EC (EURO II)	2,2 [g/km]	–	–	0,5 [g/km]	ECE+EUDC
(EURO III)	2,3 [g/km]	0,2 [g/km]	0,15 [g/km]	–	NEDC
(EURO IV)	1,0 [g/km]	0,1 [g/km]	0,8 [g/km]	–	NEDC

In June 1988 the European institutions decided to accept requirements foreseen for the year 2000 (Euro III) and 2005 (Euro IV) (Figure 3, Table 2) [10]. This action has resulted in intensive efforts to develop new technologies to meet the new requirements. The most important innovation in the European emission standards is an exclusion of the introductory 40s phase. Other changes are as follows [9, 10, 11, 12]:



COMBUSTION
Ignition Parameters:
• Spark Energy • Plug Fouling • Plug Gap • Single or Twin Spark • Spark Timing
FUEL/AIR PRESENTATION TO SPARK PLUG
Compression Variables:
• Valve Timing • Heat Transfer • Compression Ratio • Cylinder Leakage
FUEL DELIVERY TO CYLINDER (FUEL COMPOSITION/QUALITY)
MANIFOLD AND IN-CYLINDER AIR MOTION
FUEL PRESENTATION TO MANIFOLD (SPI → MPI)
GDI
Cranking Variables:
• Battery • Starter Motor • Engine Friction • Oil Viscosity • Engine Inertia • Cylinder Leakage
Airflow Variables:
• Port Shape • Throttling • Valve Timing • Multi Valves
Fuel Injection Variables:
• Fuel Pressure • Injector Type • Injector Orientation • Fuel Timing • A/F Ratio Control • Fuel RVP
EMISSION CONTROL SYSTEM
A/F RATIO STRATIFICATION CONTROL
CATALYST CONVERTER
ENGINE CALIBRATION
OXYGEN SENSOR
EGR
• Catalyst Design • Substrate Technology (metal-ceramic) Converter Configuration

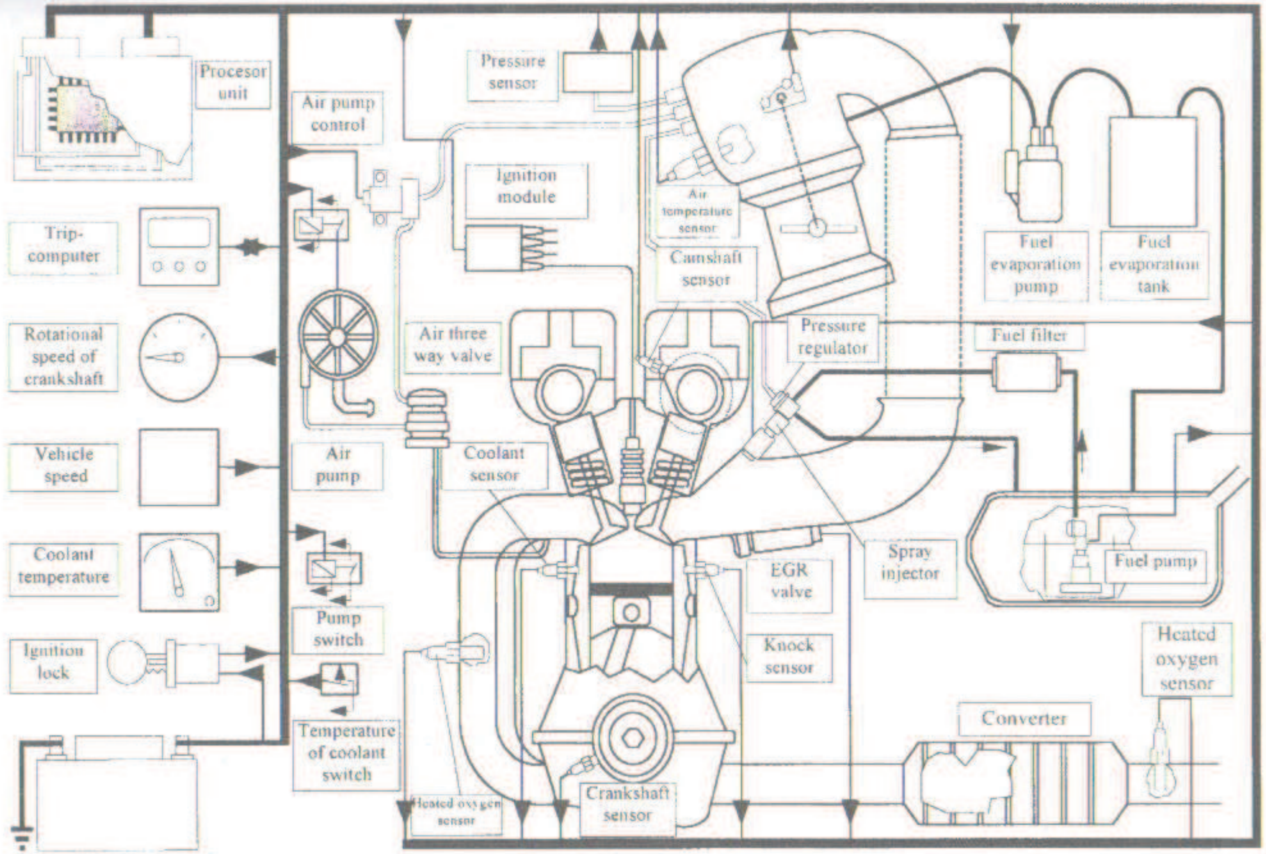


Fig. 2. Factors affected on exhaust emission during engine cold start and warm-up

- introduction of separate limits for HC and NO_x as in the US regulations — today a limit for the sum of HC and NO_x is accepted in Europe,
- condition of reliability of auxiliaries that reduces the emission to 80 000 km or 5 years with possibility of eventual increase to 100 000 km for Euro IV,
- introduction of sub ambient cold start test (at temperature of −7°C) in the year 2002
- introduction of the on-board diagnostics (OBD) for gasoline cars beginning from the year of 2000 (table 4),
- new standards of fuel quality, reduction of sulfur and aromatics contents in petrol (table 5) [10, 13],
- revision of evaporative emissions test sequence (VT SHED).

The final rules for Euro III/Euro IV (Stages 2000 and 2005) were presented in Directive 98/69/EC of the European Parliament and of the Council of 13 October 1998 and published in Official Journal of the European Communities — L350 of December 28, 1998.

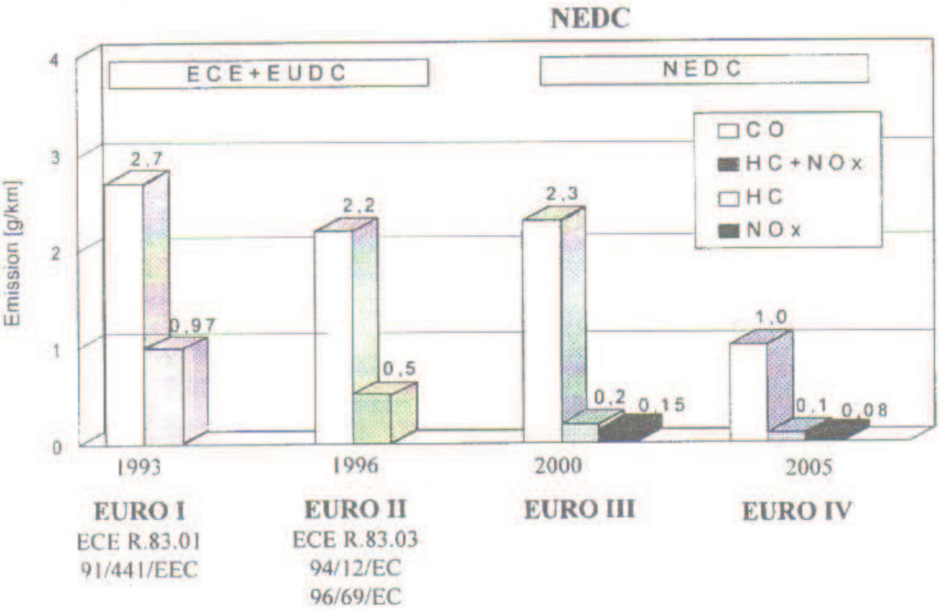


Fig. 3. Passenger car exhaust emission limit values in Europe (EURO I, EURO II) and new limit 2000/2005 (EURO III, EURO IV) for SI engines

T a b l e 2. EURO III and EURO IV emission limit values for light commercial vehicles

Class	Ref. Mass RW [kg]	CO [g/km]		HC [g/km]		NO_x [g/km]	
		2000	2005	2000	2005	2000	2005
I	RW⩽1250	2.3	1.0	0.20	0.10	0.15	0.08
II	1250<RW⩽1700	4.17	1.81	0.25	0.13	0.18	0.10
III	1700<RW	5.22	2.27	0.29	0.15	0.21	0.11

T a b l e 3. The main differences between the three emission test cycles

	NEDC	ECE+EUDC	FTP 75
Start of cranking	0 s	0 s	0 s
Start of sampling	0 s	40 s	0 s
Start of driving	11 s	51 s	21 s
First acceleration up to	18 km/h	18 km/h	40 km/h
The length of cycle	11.007 km	11.007 km	17.88 km
Total duration	1180 s	1220 s	1877 s
The average speed	33.6 km/h	33.6 km/h	34.1 km/h

T a b l e 4. Euro IV emissions limits and EOBD detection threshold — EU Common Position July 1997

NEDC	Vehicle tailpipe emissions [g/km]	EOBD detection threshold [g/km]
HC	0.1	0.4
CO	1.0	3.2
NO_x	0.08	0.6

The proposed Euro III/Euro IV standards are comparable to Californian LEV/ULEV standards with regard to exhaust gas after-treatment requirements [9, 10, 14] (Fig. 3). Table 2 shows the proposed Euro III and Euro IV limits for light commercial vehicles. Within the tightened limits of Euro III and Euro IV, the emission test cycle is also being modified. This change is made in order to eliminate the 40 seconds of idling in current ECE+EUDC cycle in which the engine and the exhaust system warms-up (Figure 4). Both the NEDC (New European Driving Cycle) and FTP 75 test cycles measure tail pipe emissions from start-up, with acceleration loading in 11 and 21 seconds respectively. In the new European cycle, engine crank and gas sampling simultaneously happen at the same time only 11 seconds before the

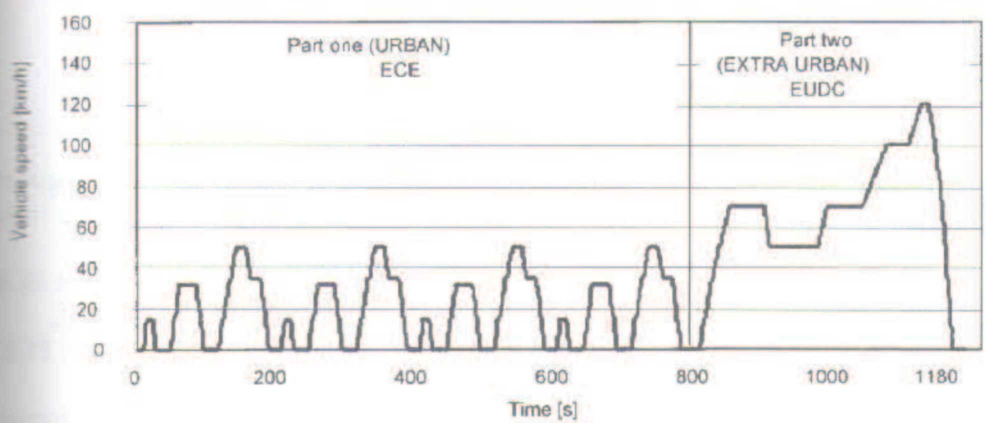


Fig. 4. Proposal of the New European Driving Cycle proceudre

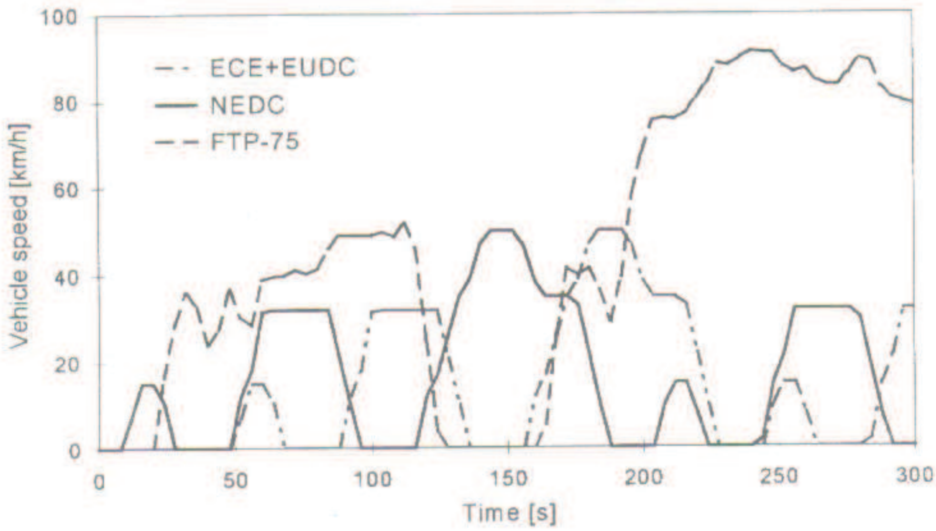


Fig. 5. Differences between initial phases of European: ECE+EUDC versus NEDC and USA: FTP 75 driving cycles

Table 5. Unleaded gasoline reference fuel limit values for EURO III and EURO IV

	Fuel limit values	
Gasoline Parameters	2000	2005
RVP Summer [kPa max.]	60	not defined
RVP [kPa max.] Arctic grade	70	not defined
Sulphur [mg/kg max.]	150	50
Benzene [% v/v max.]	1.0	not defined
Aromatics [% v/v max.]	42	35
Olefins [% v/v max.]	18	not defined
Oxygen content [% m/m. max.]	2.3	not defined
RON [min.]	95	not defined
MON [min.]	85	not defined
Evap 100°C [% v/v min.]	46	not defined
Evap 150°C [% v/v min.]	75	not defined
Trade lead [g/l max.]	0.005	not defined
Phosphorous [g/l max.]	0.0013	not defined

first vehicle acceleration. Figure 5 shows first 300 seconds of ECE and the proposed NEDC in comparison to the FTP 75 test. The main differences between the three emission test cycles are (table 3):

1) only 11 seconds warm-up in the NEDC versus 51 second in the current ECE cycle and 21 seconds in the FTP 75,
2) the first vehicle acceleration to only 18 km/h in the NEDC (and current ECE) versus approximately 40 km/h in the FTP 75 test,
3) the length of the NEDC is 11,007 km and total duration: 1180 s (in current ECE+EUDC: 1220 s).

3. Research project

3.1. Aims and methodology of the research

The tests presented in this paper were carried out within a research program investigating the effect of cold start and warm-up at normal and low ambient temperatures upon emissions. The tests were completed at the BOSMAL Automotive Research and Development Cenre in Bielsko-Biała, Poland. The objective of the research presented in this paper, was to determine the increase in emissions of CO, HC and NO_x in exhaust gases after engine cold start, following the ECE driving cycle, the removal of 40 seconds post start phase in new Euro III and Euro IV regulations, work to determine the cause of emissions and the development of the new technologies for the reduction in CO and HC levels on start up phase.). The tests were undertaken on four vehicle types designated as A, B, C, D. The vehicles were of European manufacture and commonly found on roads in Poland. The tests were done with lead-free petrol RON 95 according to CEC RF-08-A-85 requirements.

Emission tests were undertaken in accordance with current ECE (UDC+EUDC) and NEDC cycles (Fig. 4). The tests were carried out utilising an emission chassis dynamometer, gases being collected with the bag analysis method (figure 6–8). The tests were undertaken on several vehicle types. The vehicle were equipped with typical antipollution device such as TWC, oxygen sensor and MPI (multi point injection) delivery systems. All the vehicles fulfilled the demands of regulations Directive 94/12/EC (Euro 2).

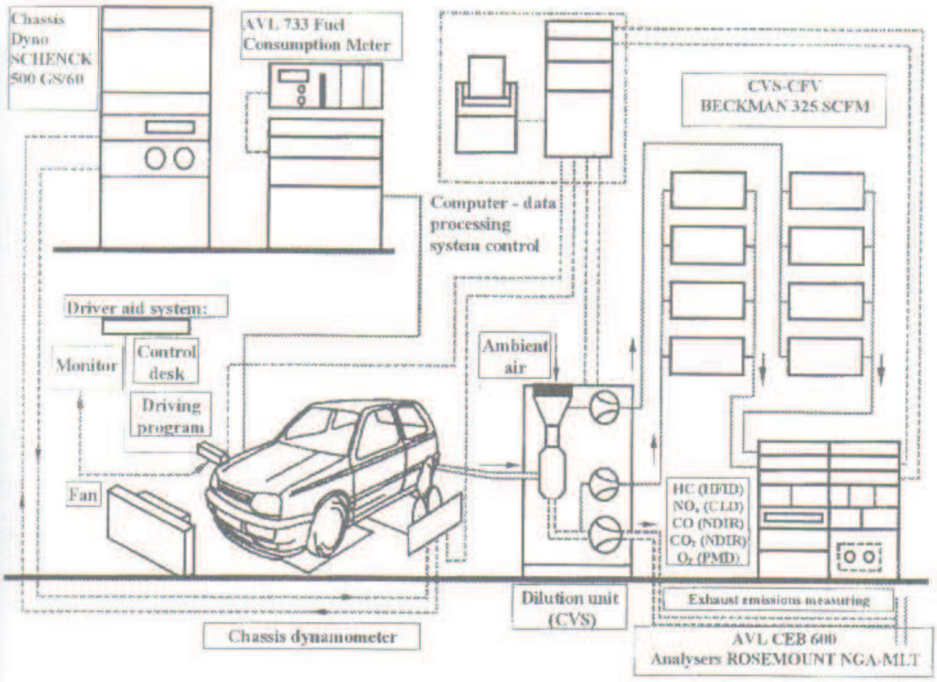


Fig. 6. Schematic diagram of the emission testing laboratory

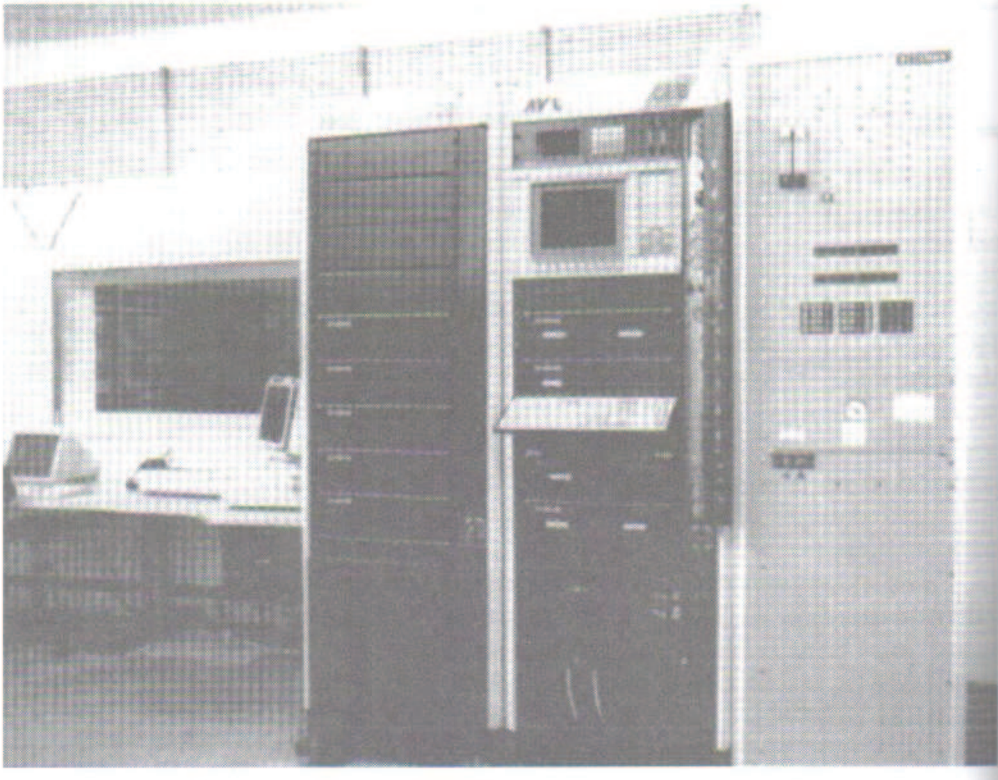


Fig. 7. View of the emission testing laboratory — anlayzers bench

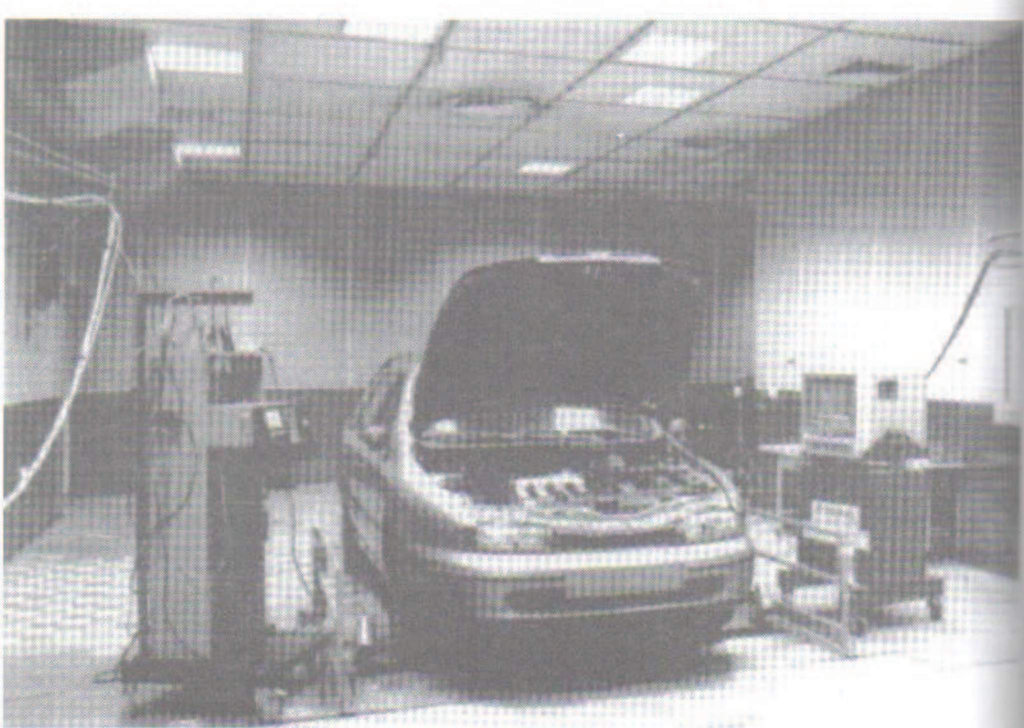


Fig. 8. View of the emission testing laboratory — testing cell with chassis dynamometer

3.2. Test results

The research project comprised a number of measurements taken during emission tests following actual and new European driving cycles and their parts as well as particular phases. Some types of tests and their results have been shown below.

Figures 9, 10 and Table 6 show the results of the emission tests for HC, CO and NO_x. The measurements were taken in only elementary UDC 195 seconds phase in UDC cycle and complete ECE+EUDC test and for comparison in the same tests

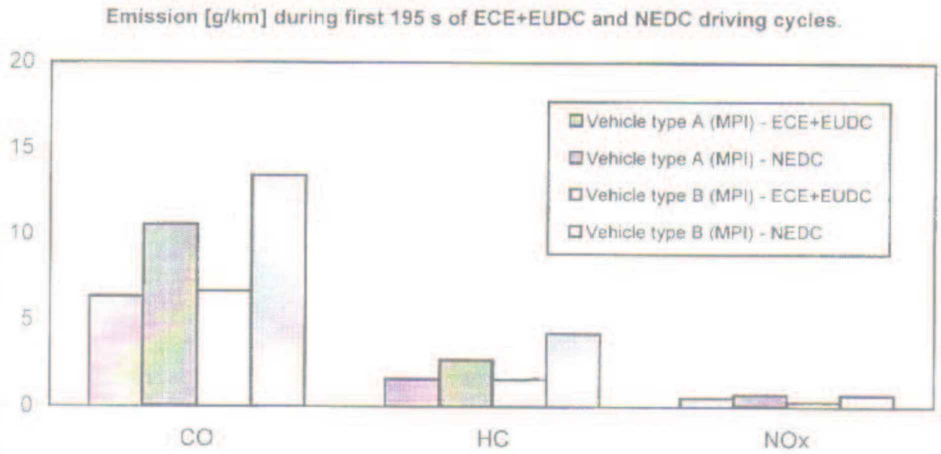


Fig. 9. CO, HC and NO_x emissions during 1st phase UDC, UDC and UDC+EUDC cycles tested according current and future procedure

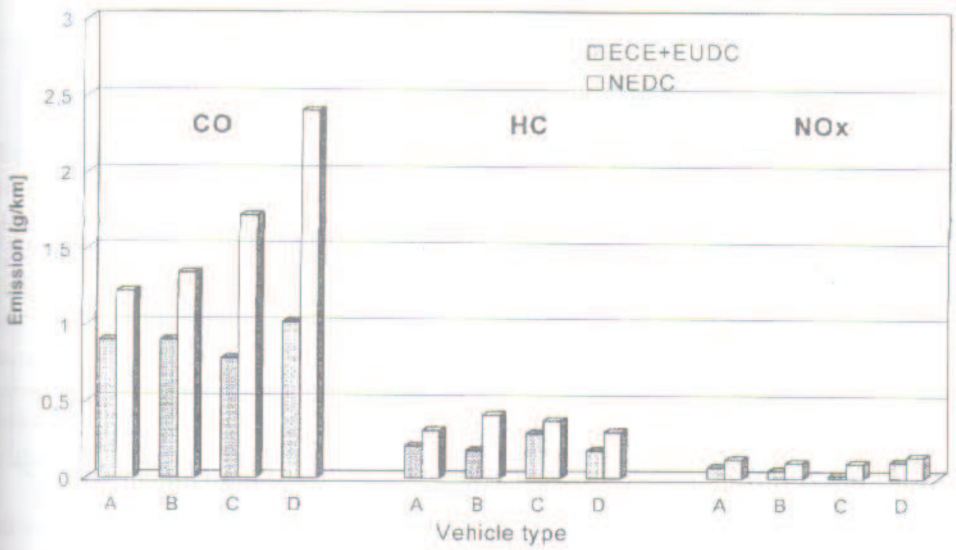


Fig. 10. CO, HC and NO_x emissions during ECE+EUDC and NEDC cycles for different types of car

T a b l e 6. Tailpipe CO and HC emissions for different vehicles types in ECE+EUDC and NEDC cycles

Vehicle		% of total cycle emission		
		I phase UDC ECE/NEDC	II–IV phase UDC ECE/NEDC	EUDC phase ECE/NEDC
Vehicle type A	CO	66.1 / 80.4	17.6 / 7.6	16.3 / 12
	HC	72.1 / 81.2	12.2 / 8.4	15.7 / 10.4
Vehicle type B	CO	68.0 / 92	16.7 / 0.6	15.3 / 7.4
	HC	82.7 / 94.1	6.9 / 2.1	10.4 / 3.8
Vehicle type C	CO	92.7 / 96.6	0.5 / 0.3	6.8 / 3.1
	HC	90.3 / 90.2	3.4 / 4.9	6.3 / 4.9
Vehicle type D	CO	94.8 / 90.7	0.6 / 7.5	4.6 / 1.9
	HC	81.4 / 71.7	7.5 / 22.5	11 / 5.8

following NEDC cycle procedure. The figures show great increase in CO and HC emissions in the first 195 seconds of UDC tests. During tests carried out accordin NEDC procedure CO and HC emissions were in the same phase about 30–40% higher than in tests following current ECE (UDC) cycle.

The results of CO_2 emission performed in ECE+EUDC and NEDC cycles fo different types of car are illustrated on figure 11. CO_2 emission is lower during test carried out according NEDC procedure. This is caused by the fact that enrichmen process necessary for proper start-up and stable combustion is continued by the fue injection control system until the coolant temperatures reaches the required value and during NEDC cycle coolant temperature rises more quickly, which makes shorte time the engine work on AFR richer than stoichiometric.

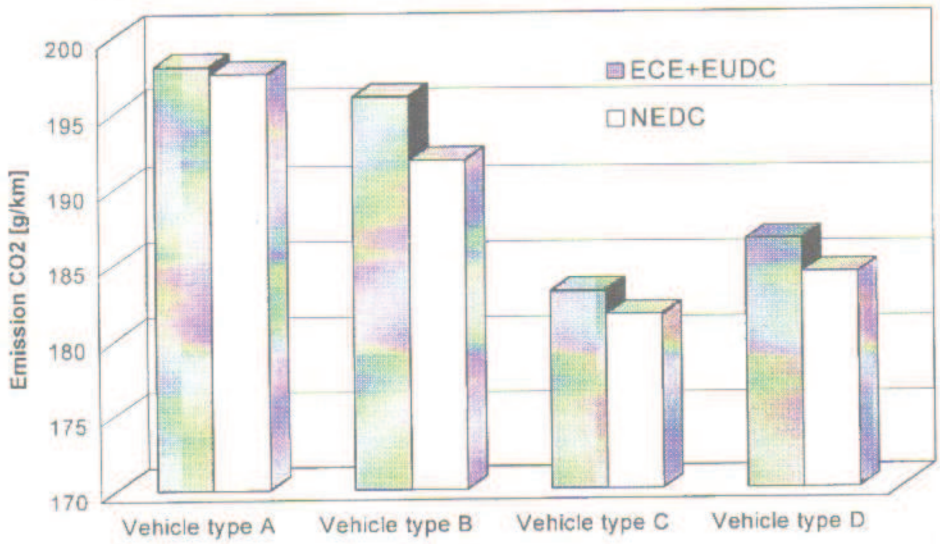


Fig. 11. CO_2 emission during ECE+EUDC and NEDC cycles for different types of car

In order to estimate the influence of catalyst light-off time on emission, catalyst temperatures were measured in various test cycles. The diagram in figure 12 presents a catalyst warm-up rate during tests performed according to the ECE+EUDC, NEDC and FTP 75 test procedures. It can be noticed that in the NEDC test an earlier start to driving entails quicker catalyst warm-up than in the ECE+EUDC test, but slower than in the FTP 75 one. Thus, catalyst reaches temperature of e.g. 300°C after *110 s in the ECE+EUDC test, after 82 s in the NEDC and after 53 s in the FTP 75* procedure. These time correspond to mileage of 0.2; 0.31 and 0.31 km, respectively.

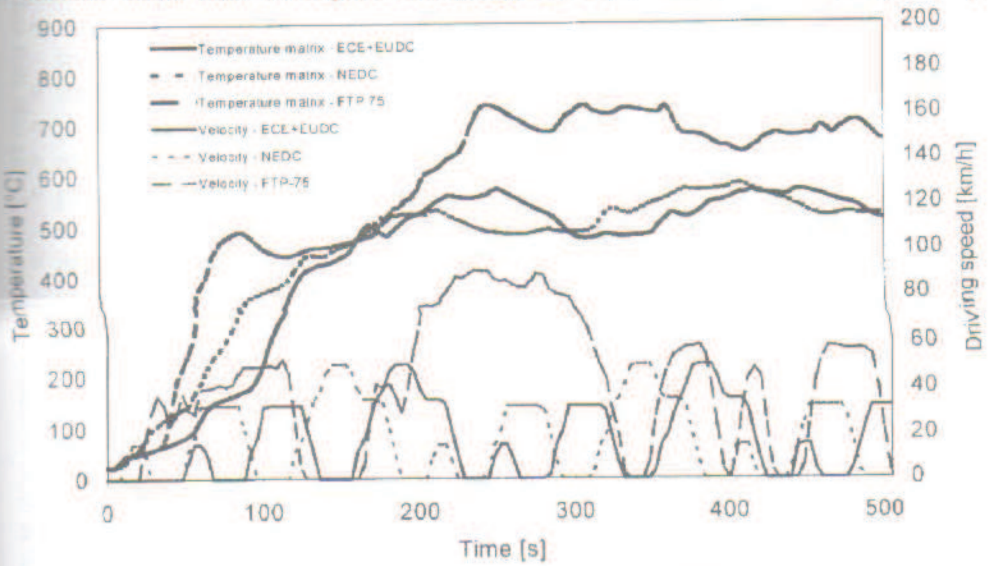


Fig. 12. Catalyst temperature distribution during 505 s of ECE+EUDC, NEDC and FTP 75 cycles

4. Discussion

The changes proposed in the NEDC European cycle for the Euro III requires emission reduction in the 40 seconds duration of heating-up of the engine after cold start; as early as in 11 seconds following crank initiation a car shall accelerate in the first gear in order to reach a speed of 18 km/h. With respect to the previous ECE (UDC) cycle, the changes require the necessity of higher enrichment of the mixture feeding an engine in the first seconds of operation after cold start. On the other hand this faster acceleration allows for more rapid catalyst light-off. It is reflected in increased CO limit for Euro III regulation from 2.2 to 2.3 g/km. Even a CO limit of 1.0 g/km, anticipated for Euro IV, involves the necessity of introduction of new technologies enabling significant reduction of CO emissions as well as HC emissions in the first phase of engine's operation.

A far quicker catalyst warm-up can be observed in the FTP 75 test procedure, actually after some 40 second it operates effectively, while in the ECE+EUDC test — depending on car type — some 100 to 150 second is necessary. Finally, in the FTP

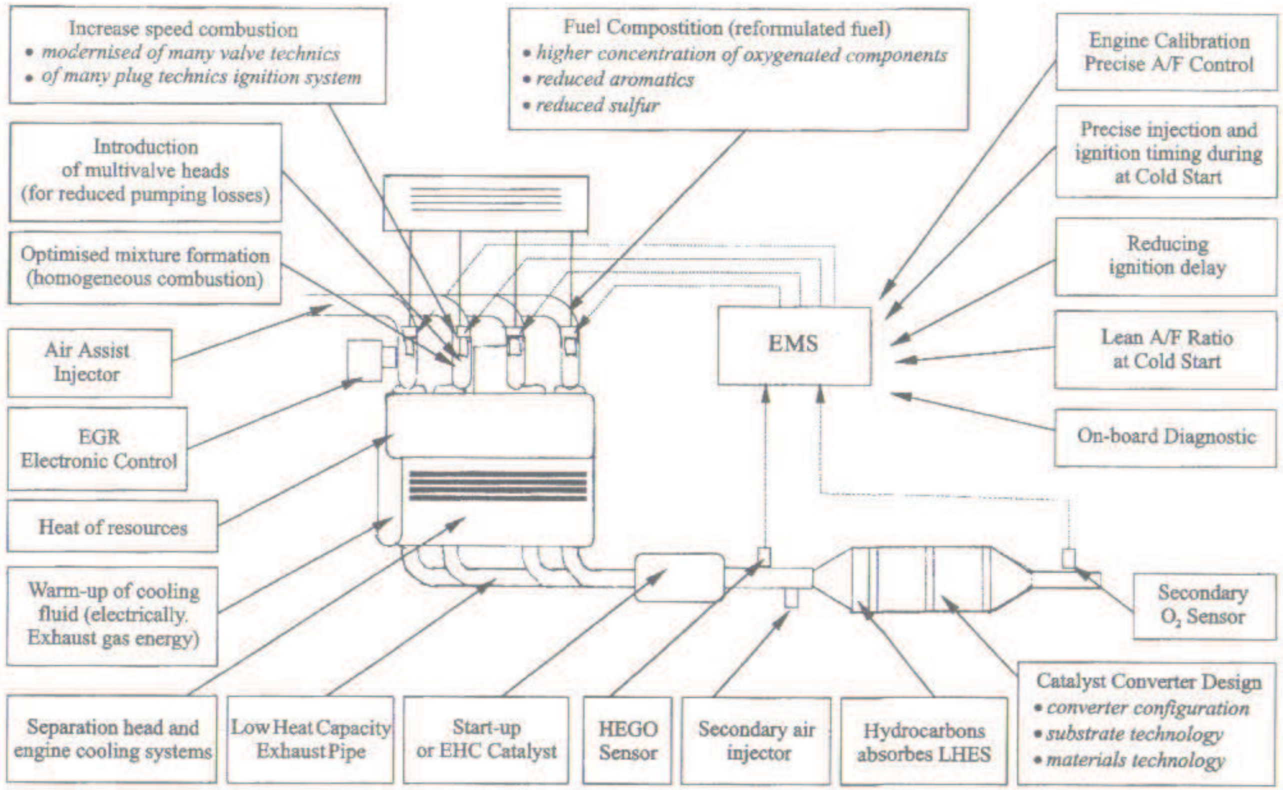


Fig. 13. The technologies should be applied in order to achieve low emissions during cold start and warm up

test it is a bit easier to manage a harmful emission before the main TWC catalyst commences its effective operation. In the NEDC test these differences decrease but there is still about 80 second left until the TWC reaches its full effectiveness and the engine emits perfectly untreated exhaust. It is clear that reduction in vehicle emissions in the cold phase of the cycles will be a key factor in meeting the required standards.

On the basis of performed tests and analysis of the results one can ascertain that in order to attain further reduction of CO emissions and to fulfill the demands of HC emissions, new designs aiming at the following should be set into practise:

- improvement of air/fuel mixture preparation (in order to reduce emissions of non-burnt HC),
- improvement of fuel atomization by use of air-assist injectors,
- proper formation of fuel spray, mixed with the air (reduced droplet size),
- modelling of complete induction system,
- preventing of fuel film generation in the inlet manifold (heating the plenum chamber),
- improved control of fuel injection — optimisation of timing and dosage of injected fuel, especially during start-up and the first tens of seconds of engine operation,
- implementing the new catalyst concepts such as close-coupled catalyst, pre-catalyst or start-up catalyst systems, actively heated systems and HC absorbers (also discussed at [7, 15]),
- implementing an insulated transfer pipe between exhaust manifold and catalytic converter,
- improved enigne calibration for cold-start.

The above specified acitvities should be set into practise in order to enabling a reduction of mixture enrichment, necessary for start-up and operation during warm-up and its operation during heating-up and prior reaching relevant operational temperature (light-off) by TWC converter.

To reduce emissions of NO_x with respect to fulfilment of Euro III and Euro IV it should be possible to implement heated lambda sensors with narrow field of tolerances or twin lambda sensor (before and after catalyst) and EGR (exhaust gases recirculation) systems.

Other emission control technologies necessary to introduce for fulfilling the emission requirements Euro III/Euro IV are presented in figure 13 [5, 7, 8, 16, 17].

Euro III and Euro IV regulations present a very serious problems for car manufacturers, especially becasue they are convergent with demands for the reduction of toxic emissions in range of hydrocarbons, together with higher durability of systems limiting HC emissions and the necessity of the monitoring of catalyst parameters.

5. Conclusions

On the base of the resutls achieved, as well as literature surveyed, the following conclusions can be drawn:

- The enrichment of the air-fuel mixture, necessary for correct cold start, cold transient operation and driveability is the main reason for the incrase in CO and HC emissions during engine cold start and warm-up,
- A change in the initial phase of emission test for Euro III/Euro IV procedure leads to increased by 30−40% emissions of CO and HC (for the same engine calibration), during initial, 195 seconds phase, these emissions are higher by about 60−80%,
- The primary TWC begins its operation during NEDC cycle after about 80−100 seconds,
- The technologies which are to be introduced in order to regulate cold start emissions, should be based mainly upon the methods of supplying of additional heat to the engine (for warming-up of oil, coolant and fuel) and the improvement of fuel atomisation in order to reduce the necessary enrichment of fuel-air mixtures during engine cold starts and warm-ups,
- It is necessary to introduce a technology of emission reduction at that initial stage, for instance a start-up catalyst or close-coupled catalyst and reduce time when catalyst reaches light-off temperature.

Abbreviations

AFR	Air Fuel Ratio
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ECE	Economic Commission for Europe, subgroup of United Nations
EEC, EC	European Economic Community; (now EU)
EGR	Exhaust Gas Recirculation
EOBD	European Onboard Diagnostic
EPA	Environmental Protection Agency US
EU	European Union
EUDC	Extra Urban Driving Cycle
FTP-75	Federal Test Procedure
GDI	Gasoline Direct Injection
HC	Hydrocarbons
HEGO	Heated Exhaust Gas Oxygen (sensor)
LEV	Low Emission Vehicles
MPI	Multi Point Injection
MY	Model Year
NEDC	New European Driving Cycle
NO_x	Nitrogen Oxides
O_2	Oxygen
RVP	Reid Vapour Pressure
SFTP	Suplemental FTP
SI	Spark Ignition Engines

SPI	Single Point Injection
SULEV	Super Ultra Low Emission Vehicle
TA	Type of Approval
TLEV	Transitional Low Emission Vehicles
TWC	Three-Way Catalyst
UDC	Urban Driving Cycle
ULEV	Ultra Low Emission Vehicle

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Contact: Pior Bielaczyc is a Manager of Exhaust Emission Testing Lab at BOSMAL R&D Centre. He can be reached for further information at the address: BOSMAL Automotive Research and Development Centre, Sarni Stok 93, 43-300 Bielsko-Biała, Poland, Phone: +48 33 813 04 98, Fax: +48 33 812 50 38, E-mail: obrsm @ bosmal.com.pl

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Badania faz zimnego startu i nagrzewania silnika OZI pod kątem spełnienia europejskich standardów emisji

Streszczenie

W artykule przedstawiono wpływ zmian w europejskim cyklu jezdnym (wyeliminowanie obecnie nie mierzonej, 40 sekundowej fazy wstępnej) w porównaniu z cyklem stosowanym w USA — FTP 75, na poziom emisji CO, HC i NO_x w testach realizowanych w warunkach laboratoryjnych, na hamowni podwoziowej. Badania, których celem było określenie wpływu tych zmian na wzrost emisji związków szkodliwych w spalinach oraz zużycia paliwa w początkowej fazie testu, przeprowadzono dla kilku typów samochodów produkcji europejskiej, często eksploatowanych w Polsce. Przedstawiono również różnice w nagrzewaniu się katalizatora w czasie realizacji europejskich i amerykańskich cykli jezdnych. Omówiono metody obniżania emisji CO, HC i NO_x w początkowej fazie testów jezdnych, po rozruchu zimnego silnika.