ADAPTIVE CONTROL OF EXHAUST GAS RECIRCULATION AT NONROAD VEHICLE DIESEL ENGINE

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Abstract

At diesel engines with fuel direct injection, the problems with toxic exhaust compounds concern mainly nitrogen oxides (NO_x) and Particulate Matter (PM). For reduction of the NO_x's, the exhaust gases are feedback to the combustion chamber. This results with a lower combustion temperature and decrease the emission of NO_x gasses. The mass of the recirculated gases cannot be too high because it might lead to an increase in the PM emission. In nonroad vehicle engine the component responsible for the exhaust gases recirculation is most a two state (open/close) EGR Valve. Another problem in this type of combustion engines is volatility of its ecological parameters during exploitation. The reasons are various operation conditions of the engine, fuel quality ect. So, according to the proposed solutions, the engine controller must track these variations. The mass of recirculated gasses must also be corrected.

In the proposed solution the EGR valve is a prototype construction of an electronically controlled EGR. The openness of the valve is freely programmable and is controlled by adaptive algorithm saved in the ECU (Electronic Control Unit). As feedback signal to control the openness of EGR valve is used an NO_x sensor placed at engine outlet pipe. The paper describe an control circuit of EGR Valve and include research results of nonroad vehicle diesel emissions (NO_x and PM missions). The proposed adaptive control of EGR Valve shows potential to reduce especially NO_x emissions in aspect to fulfill further emission regulation TIER/Euro

Keywords: Exhaust Gas Recirculation, NO_x emissions reduction, adaptive control, EGR Valve

1. Introduction

Stricter requirements regarding emission of hazardous substances in nonroad vehicles require that a search be undertaken with an aim of finding solutions that offer benefits in terms of ensuring high reliability and guarantee of operation regardless of changing exploitation conditions. The fulfillment of the norms of exhaust gas emissions that are prospective in the near future brings a necessity of improvement of the engineering structure as well optimization of control algorithms and application of up-to-date solutions with regard to the elements involved in the limitation of exhaust gas emissions. The limitation of emission proves to be practical in terms of economy of use as a result of applying methods of optimizing combustion process in the engine [5-7, 9, 10]. One the possible and effective systems aimed at reduction of mainly NOx emission is associated with necessity of exhaust gas recirculation (EGR) in the engine. The application of the systems that limit the emissions becomes indispensable for the case of newest emission norms; however, their applicability is limited due to considerable increase in the cost of exploitation (connected with the need of periodic need of changing parts of the system, repletion of fluids, increase in fuel use, maintenance and service cost) as well as the ones related to production (catalytic converter, installation of DPF filter). For the case of nonroad vehicles Tier and Euro norms [2, 6, 8] limit the admissible emission levels of CO, HC, NOx and particulate matter (PM) enforcing their reduction by several orders.

2. Regulations regarding exhaust gas emissions of nonroad vehicles

With regard to land-based motorized vehicles that do not drive on roads and highways (offroad and nonroad vehicles) the Euro norms pertaining to them are the ones that are largely based on regulations contained in US Tier norms (EPA Nonroad Regulation, 40 CFR 89; 40 CFR1039; 40 CFR 1068) that are in force e.g. in the USA. The limitations imposed on emissions of nonroad vehicles in Europe are based on the laws listed in EU-Nonroad Directive 97/68/EC (2004/26/EC), additionally supplemented for agricultural vehicles by statements in EU directives no. 2000/25/EC and 2005/13/EC [8]. Detailed levels of admissible emissions of chosen substances contained in exhaust gases for engine with power range 75-130 kW according to EU -97/68/EC [8] are presented at Fig. 1.
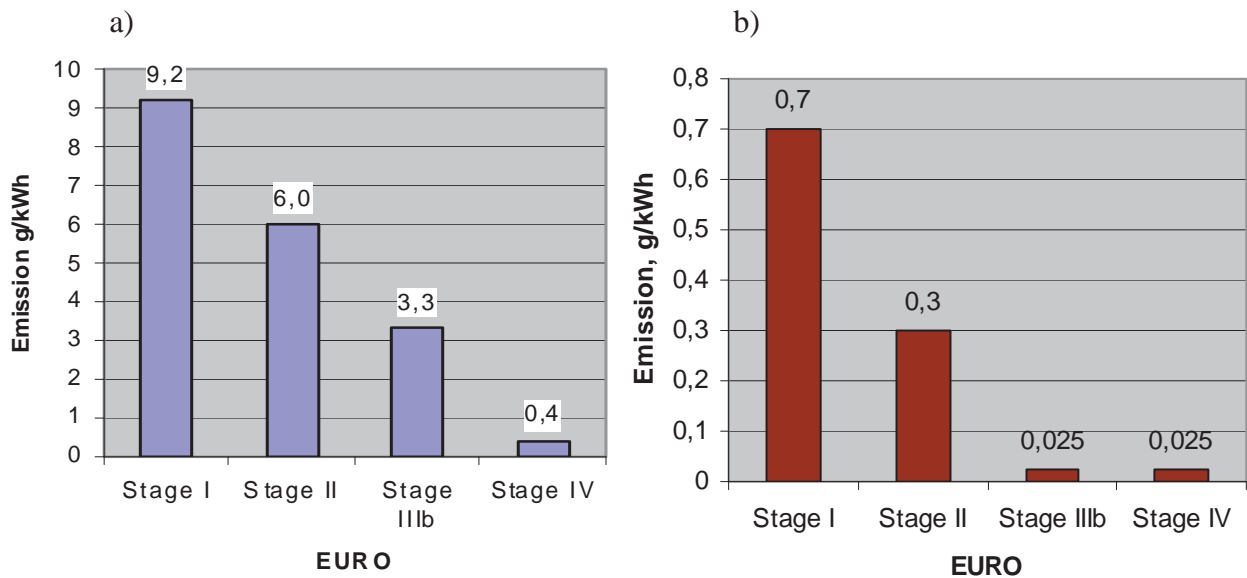

Fig. 1. Levels of admissible emissions of: a) NO_x and b) PM, according to EU -97/68/EC [8]

The measurement of emissions in the particular ranges of the maximum vehicle power is performed in accordance with guidelines in this directive and is based on steady state cycles ISO 8178 and ECE R49, ESC (European Steady State Cycle) and ECE R49 and NRTC (Nonroad Transient Cycle) [2, 6, 8].

3. Adaptive control of Exhaust Gas Recirculation System

The application of exhaust gas recirculation in a combustion engine results in reduction of NO_x emission. However, one has to consider the ratios of exhaust gas to fresh load. Too much mass of the exhaust gas to fresh air leads to a decrease of the power of the engine as well as a sharp increase in the emission of PM. As one can note, the issue of the reduction of emission of NO_x and PM in a diesel engine does not form a simple task. The reason for that are associated with variable operating conditions of the engine as well as wear of some of its elements due to exploitation, use of poor quality fuel (especially in nonroad vehicles) may lead to an increase in the emissions. Hence, an up-to-date control system should account for a number of unfavorable factors and offer a possibility of adapting to changing conditions. The central target should be associated with gaining a sensible compromise between emission and performance in a given vehicle. Not to disregard is the role of a solution that is reliable and economically justified in relation to the obtained results in terms of emission reduction.

In the consideration of the above problems a decision was made to implement advanced

algorithms of adaptive control of the system of exhaust gas recirculation in the controller of engine ECU of the nonroad vehicle. A choice of the algorithm was made with an additional aim that the system should contain the smallest possible number of additional sensors and/or other actuator subassemblies. Moreover, the algorithm needs to be simple in terms of the calculation structure to ensure that its execution will not take too much time for the ECU to perform since its major role is to supervise the correct operation of the diesel engine. One of the criteria for applicability is concerned with gaining the maximum beneficial parameters of engine operation accompanied by a limitation of hazardous substances. As a result of analysis of the system of exhaust gas recirculation, it is possible to consider it as a MIMO (Multi Input Multi Output) object, with the inputs of the object including: set load of the engine resulting from the depression of the acceleration pedal, while output data include: output power and emission of exhaust gases (Fig. 2).
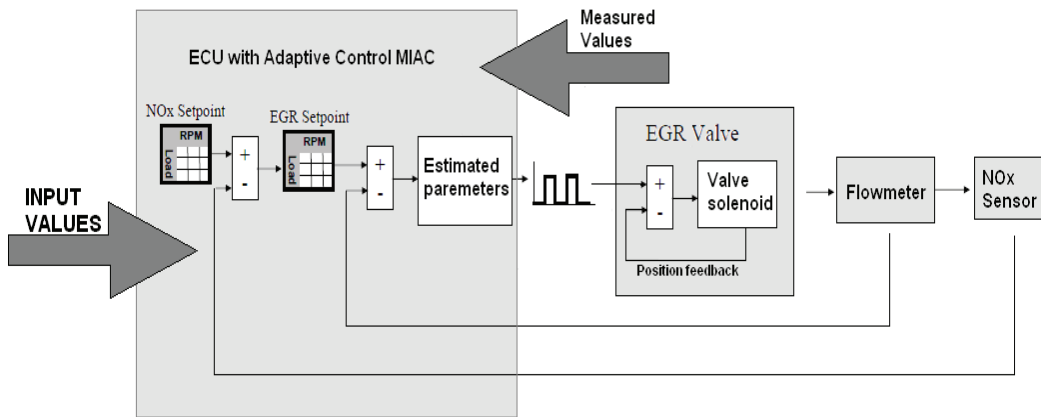

Fig. 2. EGR Control system with MIAC

During the selection of the control strategy one has to take into account the conditions in which nonroad vehicles operate. A number of factor affect the total of hazardous substances emission into the environment, including: quality of fuel, atmospheric conditions, powertrain load and its wear. As a result of the analysis of the test object in this respect, it seems that an adaptive algorithm with MIAC (Model Identification Adaptive Control) identification of the object seems to be the most effective one. The proposed adaptive algorithm enables the correction of actuator setpoints (mainly EGR recirculation valve) for each of the operating points of the engine. The basic elements of the exhaust gas recirculation system include: prototype of EGR valve, NO_x sensor and a control unit with an adaptive algorithm. The applied EGR valve offers an possibility of adapting programming steps within the range of valve openings from 0 to 5mm with a step of about 0.1 mm. The programming and the control of the valve is performed over a common interface. The valve has a microcontroller and position sensor, which monitors the instantaneous opening over an closed feedback loop (Fig. 3).
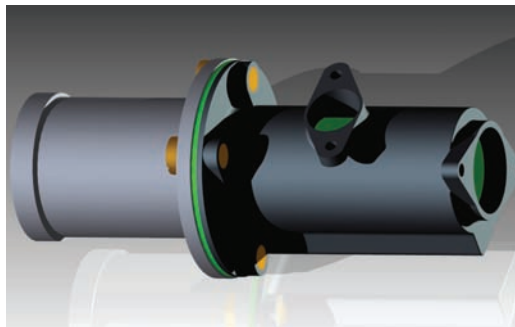

Fig. 3. Prototype EGR Valve with internal feedback including valve position sensor

For the case when a discrepancy is detected between an instantaneous valve opening from the setpoint, resulting e.g. from internal interference, microcontroller leads to the reduction of the deviation by adapting the current flowing through a valve solenoid. Additionally, in the exhaust system there is a sensor to measure the concentration of nitrogen oxides NOx and O_2 in the exhaust gases. This sensor operates in an external feedback loop and the measurement data are transferred to ECU by means of CAN bus (Fig. 4).
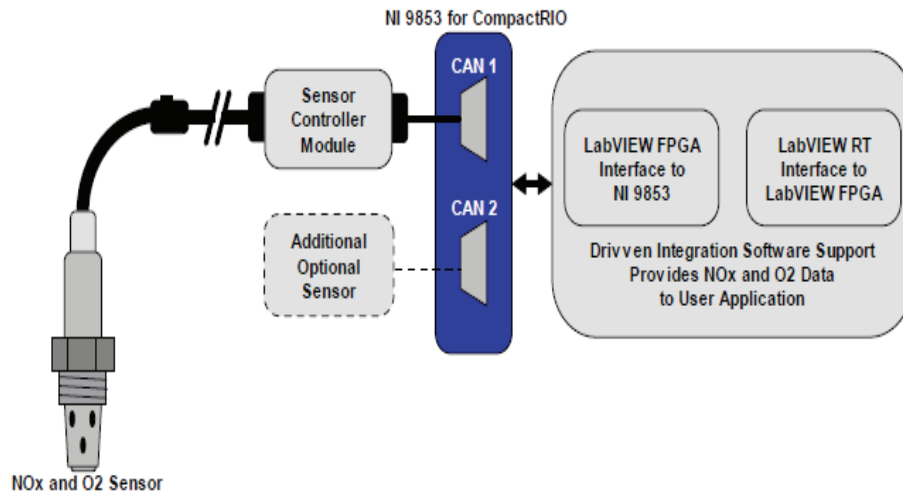

Fig. 4. Scheme of Drivven NO_x/O_2 Sensor Kit operating with LabView [11]

Adaptive algorithms have been implemented in the ECU with a purpose of ensuring an adequate operation of the exhaust gas recirculation system. The basis for the control of EGR valve is made by two lookup tables stored in ECU memory. The lookup table for nitrogen oxides is the one that imposes the maximum admissible value of emissions relative to the rotational speed and engine load. In accordance with a subordinated lookup table defining opening steps of the EGR valve the ECU performs a correction of the valve opening. The adaptive algorithm has been configured in a manner that ensures that if the stored values vary too much from the actual emissions form the engine (measured by NOx sensor), an object identification is undertaken. On the basis of performed identification a correction of the lookup table of EGR valve settings is undertaken in accordance with which the ECU controls the valve. However, if the calculated new valve opening positions differ from the steps stored in the valve, the ECU orders a shift of the valve into programming mode and records the new opening steps. The algorithm configured in this manner makes it possible for the EGR system to adapt to the actual operating conditions of the engine, which in turn, are relative to a number of external circumstances.

4. Test object and research methodology

Initial testing was performed on a 4-cylinder diesel turbocharged engine of a nonroad vehicle with the power of over 75 kW. As a standard, this vehicle has a system of exhaust gas recirculation with their cooling and an EGR on-off valve and a by-pass channel. This system was equipped with a prototype EGR valve with an internal feedback and control based on a lookup table and an adaptation algorithm. A picture of the test object is found in Fig. 5. It was additionally supplemented with several sensors, including one for NO_x measurements.

The programming and control of the actuating system of EGR valve was performed on the basis of an original application developed by the authors in LabView environment. This application enables one to adapt basic settings affecting the operation of the EGR valve (Fig. 6).
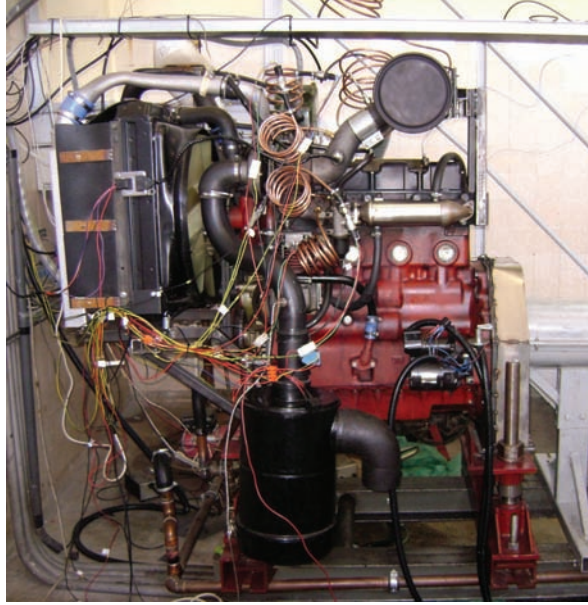
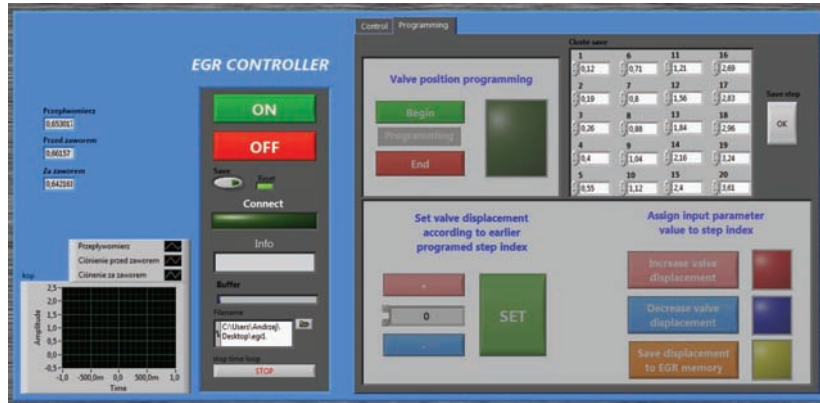*Fig. 5. Test object with cooled EGR and additional sensors*

Fig. 6. View of EGR controls

The control and measurement system is based on Compact RIO platform with aid of LabView package.The applied integrated NO_x/O_2 sensor allow measure of the residual oxygen volume at exhaust gases. Lowering of oxygen concentration has an effect on increase of PM [5]. At this reason it is very important to control of the EGR rate X_{EGR} and is considerably to obtain advantageous rate between NO_x and PM emission [4, 7]. The relative NO_x emission rate E_{rNOx}, and relative PM rate E_{rPM} could be formulated as follows:

$$E_{rNO_x} = \frac{m_{NO_x}}{m_{NO_x \max}} ,$$ (1)

$$E_{rPM} = \frac{m_{PM}}{m_{PM \max}} .$$ (2)

The relative emission rate E_r could be formulated as:

$$E_r = nE_{rNO_x} \cdot (1-n)E_{rPM} .$$ (3)

The relative emission rate allow to compare different EGR systems and their control on research object. Include priorities factor *n* enable to find best engine emission rates in case of different emission priorities.

5. Analysis of initial research results

The testing was performed on a simulation test bench which simulates the input motor loads.

As indicated by the analysis of the research due to the control of EGR valve opening it is possible to affect the level of NO_x emission. As indicated by the chart summarizing the relation between the total emission in the steady state and degree of EGR valve opening, one can anticipate a considerable reduction in the emission levels especially of NO_x emission reduction (Fig. 7).
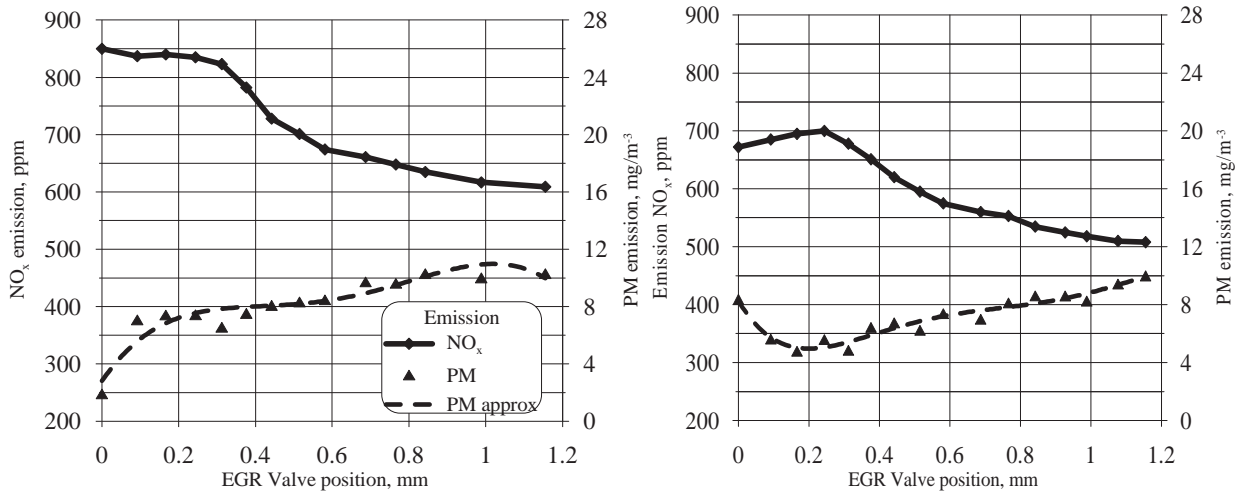

Fig. 7. Influence of EGR Valve position at emission of NOx and PM with load of 100 Nm at a) 900 rpm, b) 1100 rpm

It is interesting to note the total emissions of NO_x and PM presented in relative reference scale (Fig. 8) in case of equal emission priorities defined with priorities factor *n*=0.5. The presentation of emissions in this manner enable one to assess a compromise between the content of specific substances in the exhaust gases. One of the important tasks in case of emission reduction is to find best compromise of NO_x and PM emission as lowest relative emission rate E_r. In this case also others indexes could be take into account. Very important is here specific fuel consumption and engine performance. High recirculation ratio X_{EGR} could decrease performance indexes and increase fuel consumption.
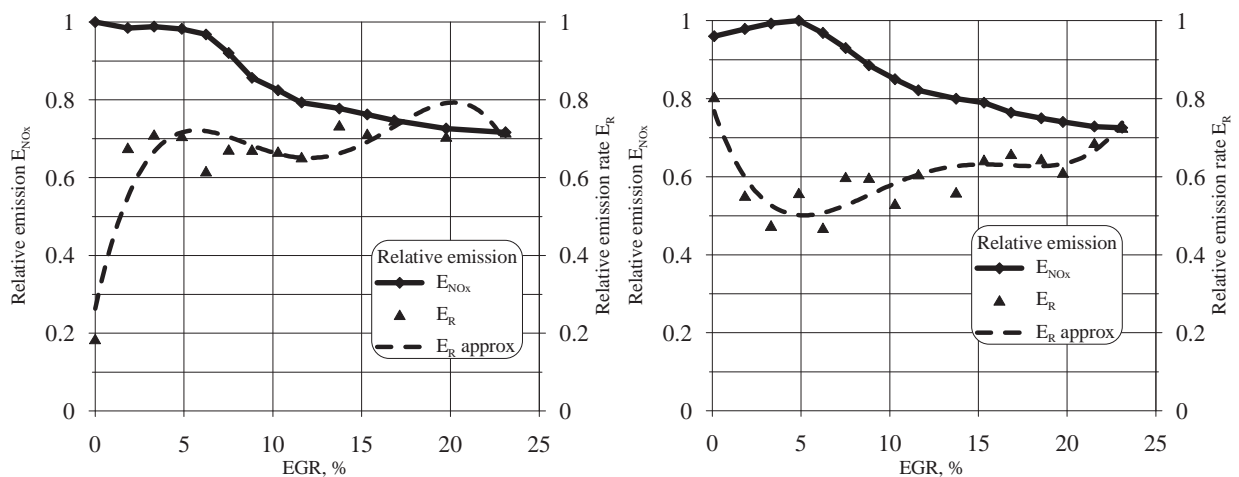

Fig. 8. Influence of EGR rate at relative emission rate at 100Nm load and: a) 900 rpm, b) 1100 rpm

The charts below contain a presentation of emission in a relative way by referring an instantaneous emission of particular substances to the composition of the same emissions at the same operating point with a standard system of exhaust gas recirculation.
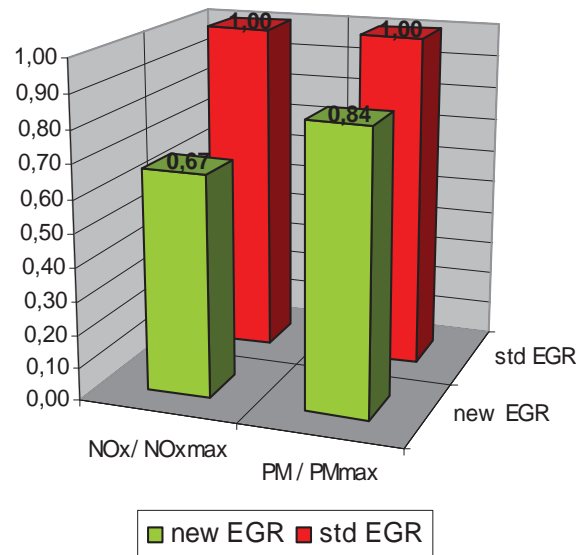
Fig. 9. Comparison between cumulative emissions of NO$_x$ and PM for standard and advanced control modes (1100 rpm, 100Nm)

Due to the control of valve opening it is possible to achieve a 33% drop in NO$_x$ emission accompanied by concurrent reduction of PM emission by over 10% (Fig. 9).

6. Conclusions

The conducted initial testing in the stationary state indicate an opportunity for finding a compromise between emissions of NO$_x$ and PM as a result of applying advanced ECU control of the system of exhaust gas recirculation with a feedback using signal from NO$_x$ sensor. As shows research results at stationary states NO$_x$ emission could be reduced of about 30% and PMs above 10%. Concurrently, a possibility of reducing mostly nitrogen oxide emissions has been indicated here. Analysis of transitional states shows possibilities for further EGR control algorithm optimization. The use of an adaptive algorithm using NO$_x$/O$_2$ sensor signal will make it possible to obtain improved parameters of operation regardless of the engine's point of operation.

Acknowledgments

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Appendix

E - emission properties factor,

E_r - relative emission rate,

$\dot{m}_p$ - inlet air stream of mass, g/s,

$\dot{m}_{EGR}$ - recirculated exhaust gas stream of mass, g/s

m_{NO_x} - unit mass of NO$_x$ emission, g/kWh,

m_{PM} - unit mass of PM emission, g/kWh,

$m_{NO_x\,max}$ - maximal unit mass of NO$_x$ emission, g/kWh,

$m_{PM\,max}$ - maximal unit mass of PM emission, g/kWh,

n - priorities factor $n \in \langle 0;1 \rangle$

X_{EGR} - rate of exhaust gas recirculation. %