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The Research Methodology for Performance Indicators of the Transport Diesel Engine in Exploitation Conditions

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Abstract

In article are considered the technological aspects of the transport diesel engine researches on the transient modes under operating conditions. The comparative analysis is made of pilot studies for ecological indicators of the transport diesel engine and the review of the measuring equipment used in the practice intended for measurement of exhaust gases emissions. For planned measurements was formed the equipment and their requirements to technologies.

Keywords: diesel engine; transient operation; research methodology; measuring equipments; ecological parameters.

1. Introduction

Environmental pollution from vehicles is the actual problem in our time therefore decrease in harmful substances emissions from diesel engines is one of the strategic tasks solved in the world. In Europe the environmental pollution from diesel engines is normalized by acts and standards of the EU. The last standards assume tests of engines which basis on the test cycles both on steady-state and on the transitional modes of the diesel engine operation.

The operating mode of the transport diesel is mean conditions under which working process is proceeds. The operating mode is characterizing by the load and frequency of rotation, and also nature of load change, frequency of

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rotation and other basic parameters of diesel engine's operation (torque, power, specific and hour fuel consumption, efficiency, etc.).

The operating mode of the diesel engine is changed depending on appointment and features of its use. The steady-state mode means constancy in time of basic working process parameters averages for a work cycle, also rotation frequency and the diesel thermal condition. This mode is characteristic in conditions when the diesel engine is brought to the set mode and works long time without its change. In transient mode the changes in time of functionally dependent parameters of the engine are happening because are changes the external operating conditions or control system parameters of diesel engines – for example, fuel feeding. Start-up, as well as the maneuvering operations, unexpected stops, the reversal operations (on ship engines) and change of loadings, belongs to the transient modes which often are the cause of the engines emergency damages.

Now for road vehicles are developed the cycles tests imitating operation of the diesel engine on the transient modes in the conditions for rural areas, also for the highway and city conditions. For off-road vehicles the standard included the transient test cycle for the engines which having electronic sensors for measurement of rotation frequency and a torque. The heavy transport diesels (heavy-duty diesels using, for example, on ships or locomotives) which don't have these sensors are tested only on the steady-state modes. However harmful substances emissions from the fulfilled gases depend on many parameters, for example, its depend for the used technologies, for emissions reduction, also for the used fuel, diesel engine management, environment conditions, etc. As a result indicators of the transport diesel engine under operating conditions significantly differ for the worse from the indicators of work established on the basis of official norms and standards.

For this reason research the operational indicators registration methodology aspects in the diesel engine on transient modes represents the actual and demanding the decision technological task.

In article are considered the methods of operational indicators measurement in the diesel engine on transient modes and their applicability for research of heavy transport diesel engines. The review of ecological indicators researches on heavy transport diesel engines and the comparative analysis of the used equipment is made. The common scheme of emissions assessment from diesel engine fulfilled gases on transient mode is represent.

2. Emission measurement in heavy-duty transport diesel engines

2.1. Test cycles and emission factors for heavy-duty transport diesel engines

An emissions test cycle (or driving schedule) is a predefined driving profile that the vehicle or engine under test has to follow. Test cycles are an integral part of all chassis and engine dynamometer tests, and their representativeness and completeness. The number of engine and vehicle dynamometer test cycles used worldwide for emission and fuel consumption measurements is continuously expanding to cover regulatory needs, while also trying to simulate real-world driving conditions (Franco et al. 2013).

There are two categories of test cycles, namely steady-state (or modal) and transient cycles. Steady-state test cycles involve running the engine or vehicle under a number of modes, each featuring constant engine speed and load. For each mode, the engine or vehicle is operated for a sufficient amount of time to produce relatively stabilized emission rates.

Transient test cycles include variations in the operating conditions as part of the test procedure, and they are regarded as more representative of real-world operation because they can be designed to account for real-world situations such as idling, acceleration, and deceleration. Detailed technical information on the most commonly used standardized driving cycles can be found in the literature or internet source (Emission Standards).

For an assessment of level of emissions of harmful substances from the engine define an emissions factor. The emissions factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per gram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category (i.e., a population average).

The general equation for emissions estimation is:

$$E = A \cdot EF \cdot \frac{1 - ER}{100}, \quad (1)$$

where: E = emissions; A = activity rate; EF = emission factor, and ER =overall emission reduction efficiency, % (USEPA).

2.2. The emissions of harmful substances measurements in the laboratory

The heavy-duty diesel engines can be measured in controlled laboratory conditions. In this case all process of a test cycle is observed, and in the course of research is controlled the state of environment and other parameters necessary for repeatability of results. For harmful emissions measurement from heavy-duty diesel engines are using the engine dynamometers – inductive brake or hydraulic brake, the dynamometers of alternating current or a direct current (ECE/TRANS/WP.29/2009/120).

An engine dynamometer measures power and torque directly from the engine's crankshaft (or flywheel), when the engine is removed from the vehicle. These dynamometers do not account for power losses in the drive train, such as the gearbox, transmission, and differential.

Heavy-duty vehicle engines can be coupled to many different chassis and body types. Because it would be impractical to type-approve all the possible combinations, engine dynamometer testing is the regulated method for type-approval tests of heavy-duty engines. Emissions of the complete vehicle are not reflected in engine testing, although modern engine test benches can be made to run any real-world engine load test cycle by simulating the vehicle to get torque and engine speed curves, either offline or as hardware-in-the-loop simulation. In the past few years, the increasing technological sophistication of engine and after-treatment control systems of newer technology heavy-duty vehicle engines has made it cumbersome to perform engine dynamometer tests independently of manufacturers, which in turn continue to use this technique in engine and after treatment device development, both for heavy-duty and light-duty vehicles. Dynamometer testing thus became the primary source of emissions data both as well as road vehicles as heavy-duty vehicles (Franco et al. 2013).

Testing of the transport diesel engine at the stand – the most checked and standardized method of definition of harmful substances emission. For receiving reliable emission factors (i.e. emissions of such level which will hardly change when carrying out re-testing or modeling operation of the engine) requires a large number of vehicles which has to be repeatedly checked at various test cycles. The emission factors received at the stand are used for an assessment of total emissions of the fulfilled gases.

2.3. Emission measurements under real-world conditions

Measuring emissions under real-world conditions yields valuable data regarding the actual emissions behaviour of vehicles as they operate outside the boundaries of the emissions laboratory. The results of real-world techniques are typically less precise and repeatable than those of engine dynamometer studies, due to the absence of a standard test cycle and the presence of additional sources of variability such as environmental or traffic conditions, driver behaviour or highly transient operation. Moreover, real-world techniques exhibit other technical shortcomings. Still, the data produced by these measurements can play an important role towards the identification of gaps in emission models and the establishment of model development priorities. Real-world emission measurements are essential towards the validation of emission factors gained from laboratory testing (Franco et al. 2013).

2.3.1. Remote sensing

In measurement used that fact that all atoms of carbon in fuel will be converted in CO_2 during burning. Also it is supposing that sulphur oxidized to SO_2. It means that SO_2/CO_2 relation in a smoke plume of the fulfilled gases will be in direct ratio to S/C ratio in fuel with the corresponding correction of molecular weight. Also during researches is measured the quantity of NOx.

For emissions measurement from ships using remote sensing method the following equipment's are used: the fluorescent SO_2 analyzer, the chemiluminescence NOx analyzer and the analyzer of infrared absorption for CO_2 measurements. Analyzers are connected in system together with regulators of pressure, the stream, the pump and AIS (Automatic identification system for courts) respondent. All system is controlled by the computer. Researches are conducted at distance 100–200 m from a pollution source. (NordForsk, 2007)

Common concentration of a generic pollutant P can be estimated by means of the following equation (Franco et al. 2013):

$$[P]=\left(\frac{[P]/[\mathrm{CO}_2]_{remote}}{1+([\mathrm{CO}]/[\mathrm{CO}_2])_{remote}}\right)\cdot[\mathrm{CO}_2]_{stoich}, \quad (2)$$

where: $[CO_2]_{stoich}$ is the stoichiometric concentration of CO_2 for the fuel considered and the ratios of pollutant concentrations to CO_2 with the remote subscript are measured by the remote sensing instrument.

The emission factors estimated using a fuel-based approach become more uncertain for pollutants that are characterized by concentrations close to background levels (due to a low signal-tonoise ratio of the recorded concentrations), which in turn are affected by older, diluted exhaust plumes (Franco et al. 2013).

2.3.2. Remote sensing using mobile laboratory (infrared absorption method)

During on-road (also chase or plume chase) measurements, individual vehicles are followed by a mobile laboratory – usually on board a van or trailer – that is instrumented with gas and aerosol measurement equipment (ideally instruments with fast time response and high sensitivity, such as laser spectrometers), plus meteorological and positioning instruments, and even video recording equipment to monitor traffic situations (Franco et al. 2013). In a similar fashion as remote sensing studies, CO_2 is used as a tracer of combustion, and the results indicate the relative concentration of the pollutant of interest per CO_2 concentration value. These mobile laboratories are able to capture the exhaust plume of the vehicle being followed, thus providing real-world emissions data under a wide range of operating and environmental conditions. Mobile emission laboratories make it possible to study a statistically representative sample of vehicles for fleet characterization.

This method have shortcomings like remote sensing method (the measurements are influenced by physical characteristics of a place of sampling, an operating mode of vehicles, etc.), and also restriction that during research the minimum distance between mobile laboratory and a source of pollution is limited.

G. R. Johnson (Johnson et al. 2013) used this non-contact method for research of concentration of SO_2, NO_x, CO_2 and particulate matter (PM) on locomotives in the Australian port. Researches were conducted for the purpose of creation of a database of real emissions of the polluting substances. Distance between mobile laboratory and railway rails was 9 m, the receiver of a sample was at height 2.5 m. In total 56 trains were measured. Coefficients of emissions for each polluting substance were defined proceeding from the received measurements of CO_2, assuming that fuel in the engine burns down on stoichiometric reaction.

The mobile monitoring station was equipped with an SMPS (TSI 3934) for particle size distribution measurements, a condensation particle counter capable of detecting particles larger than 7 nm in diameter (TSI 3022 CPC) for particle number concentration measurements, a NOx analyzer (Ecotech ML9841A), an aerosol photometer (TSI DustTrak) fitted with a PM2.5 impactor and sensors for CO_2 (Sable instruments) and an SO_2 analyzer (Ecotech 9850).

The gaseous pollutant mass emission factor is calculated using the following equation (Johnson et al. 2013):

$$EF(x)=EF(CO_2)\cdot\frac{MW_x}{MW_{CO_2}}\cdot\frac{\Delta C_x}{C_{CO_2}}, \quad (3)$$

where: $EF(x)$ grams of pollutant (x) emitted per gram of fuel consumed; $\Delta C_x = C_x - C_x^{BG} =$ concentration enhancement in plume for pollutant (x); C_x or C_x^{BG} – volume or mole fraction (note v/v = mole/mole = ppm x 10^{-6})

of pollutant gas in plume or background (BG); MW_x = molecular weight (molar mass) of species x (Johnson et al. 2013).

2.3.3. On-board measurements (PEMS)

Portable emissions measurement systems (PEMS) are complete sets of emission measurement instruments that can be carried onboard the vehicle under study. Such systems can provide instantaneous emission rates of selected pollutants with satisfactory levels of accuracy. A PEMS unit is usually comprised of a set of gas analysers with heated sample lines directly connected to the tailpipe, plus an engine diagnostics scanner designed to connect with the OBD (on-board diagnostics) link of the vehicle and an on-board computer that provides data regarding emissions, fuel consumption, vehicle speed, engine speed and temperature, throttle position and other parameters. PEMS systems typically measure instantaneous raw exhaust emissions of NO_x, THC, CO_2 and CO. Portable particle mass analysers have become commercially available after extensive testing. Exhaust flow meters are attached to the tailpipe (alternatively, exhaust flow rate can be calculated from engine operating data, known engine and fuel properties, and measured CO2 concentrations in the exhaust gas) while a GPS and a weather station are normally installed on the external area of the vehicle. In some cases, other instruments may be used, such as accelerometers to record instantaneous acceleration, altimeters or video/photographic equipment to document traffic conditions during test runs (Franco et al. 2013).

In the past few years, PEMS systems have experienced a remarkable technological development, with significant reductions in size, weight, and piping and cabling complexity, improved gas measurement principles, reduced analyser response times and an overall performance similar to conventional fixed laboratory equipment. The main advantage of on-board methods is that they can provide long series of emission values of a particular well-known vehicle driven under a wide range of traffic conditions, operational/duty cycles and ambient conditions, including some that would otherwise be difficult to replicate in the laboratory. The installation of PEMS on several vehicles of various categories can lead to a large database of emission values from vehicles of different technologies driven under different driving and environmental conditions. PEMS are relatively simple and inexpensive, and can be installed on a wide variety of vehicles. They can be especially convenient for heavy-duty vehicles, considering that dynamometer test beds have limitations in terms of vehicle size and become expensive for high engine power applications. PEMS are thus becoming an important regulatory tool for heavy-duty vehicles. US authorities have introduced additional emissions requirements based on PEMS testing and the ‘Not to Exceed’ (NTE) concept, whereby emissions averaged over a time window must not exceed specified values for regulated pollutants while the engine is operating within a control area under the torque curve. The corresponding test procedures and the portable instrumentation performance requirements are laid down in (Franco et al. 2013).

3. Comparative analysis of the measurement equipment for diesel engine on transient modes

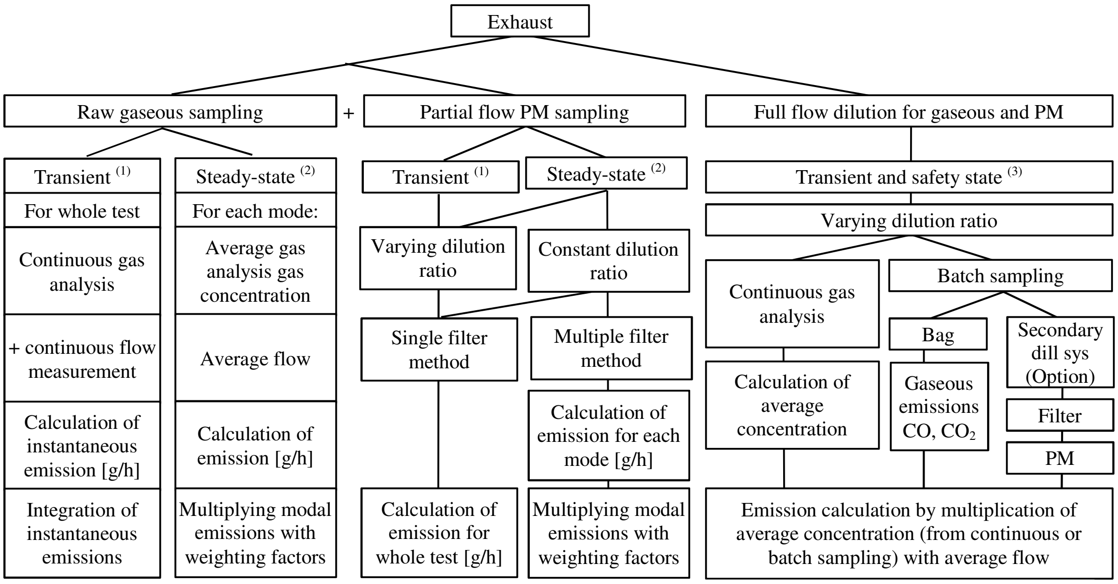
Measurement of the harmful substances content in the fulfilled gases is performed by means of selection of part of fulfilled gase and carrying out the chemical analysis of the specified test in various devices. That device can work as constantly (in the automatic mode), as periodically only in a holding time with its operator.

Selection of the chemical analysis method, realized in SI base unit depends on a type of substance which concentration have to measure. If the same substance is exposed to different types of the chemical analysis, results can both coincide, and to differ, and the difference can make hundreds of percent. Comparing results of measurements of the same substance concentration taken in the different organizations (interlaboratory researches) using both the same devices, or different devices, the various divergence admissible must be no more than 5% are considered (Кульчицкий 2004).

There are restrictions for measurement equipment (for gas analyzers) which are used in the diesel engine research on the transient mode. Those restrictions involve the use of the following methods of chemical analysis.

Non-Dispersive Infra-Red (NDIR) detectors are the industry standard method of measuring the concentration of carbon oxides (CO & CO_2). (ECE/TRANS/WP. 29/2009/120; Combustion).

Each constituent gas in a sample will absorb some infra red at a particular frequency. By shining an infra-red beam through a sample cell (containing CO or CO_2), and measuring the amount of infra-red absorbed by the sample at the necessary wavelength, a NDIR detector is able to measure the volumetric concentration of CO or CO_2 in the sample.



(1) Transient and Ramped Modal Test Cycle; (2) Discrete Mode Steady State Cycle; (3) Transient, ramped modal and discrete mode Steady-State Cycles

Fig. 1. Requested operations to calculate the engine emissions in steady-state and transient test cycles.
Note on figure 1: The term "Partial flow PM sampling" includes the partial flow dilition to extract only raw exhaust with constant or varying dilution ratio (ECE/TRANS/WP.29/2009/120).

A chopper wheel mounted in front of the detector continually corrects the offset and gain of the analyser, and allows a single sampling head to measure the concentrations of two different gases (Combustion).

A chemiluminescence detector (CLD) is the industry standard method of measuring nitric oxide (NO) concentration (ECE/TRANS/WP.29/2009/120; Combustion).

The reaction between NO and O_3 (ozone) emits light. This reaction is the basis for the CLD in which the photons produced are detected by a photo multiplier tube (PMT). The CLD output voltage is proportional to NO concentration.

The light-producing reaction is very rapid so careful sample handling is important in a very rapid response instrument (Combustion).

The flame ionisation detector (FID) is the auto-motive emissions industry standard method of measuring hydrocarbon (HC) concentration (ECE/ TRANS/WP.29/ 2009/120; Combustion). The sample gas is introduced into a hydrogen flame inside the FID. Any hydrocarbons in the sample will produce ions when they are burnt. Ions are detected using a metal collector which is biased with a high DC voltage. The current across this collector is thus proportional to the rate of ionisation which in turn depends upon the concentration of HC in the sample gas.

The ionisation process is very rapid, so the slow time response of conventional FIDs is mainly due to sample handling. A typical slow analyser might have a response time of 1–2 seconds (Combustion).

Emissions measurement equipment requirements under controlled conditions for non-road engines regulated by World Forum for Harmonization of Vehicle Regulations documents. The common scheme for estimating emissions of a diesel engine on transient modes are presented in Fig. 1 (ECE/TRANS/WP.29/ 2009/120).

4. Conclusions

1. The exhaust gas emissions from heavy-duty diesel engines on transient mode can be measured in controlled conditions at the stand or under real-world conditions with remote sensing, plume chase or PEMS measurement methods. Emissions of exhaust gases dependence from many parameters, such as, for example, technologies used to reduce emissions, the fuel used, the environmental conditions of operation, etc., In the study of the environmental performance of diesel engines under transient conditions on the test bench are created controlled conditions the environment, and other parameters needed for repeatability. However, the tests do not reflect the actual level of emissions of a complete vehicle, although modern test benches can be made to perform any real load on the engine by simulating the operating conditions of the vehicle. The implementation of this method is also associated with significant financial costs and the availability of expensive equipment, which makes this method unattractive for scientific research.
2. In the study of environmental parameters of the diesel engine in real conditions for the measurement of transients used equipment, using the most suitable technology measuring various toxic components:
- for NOx measurements used the chemiluminescence detector method;
- for CO and CO_2 measurements used Non-Dispersive Infra-Red (NDIR) detectors method;
- and for CH measurements used the flame ionisation detector (FID) method.
3. In some cases, research on transients, when it is technologically impossible to measure all the parameters of the engine in certain modes, the calculation method is used determine the level of emissions - NTE. According to the NTE concept, emissions averaged over a time window must not exceed specified values for regulated pollutants while the engine is operating within a control area under the torque curve.
4. From all the discussed methods for KU MEF Maritime institute research program about transients from diesel engine the most affordable and rational from a scientific point of view is a method of research using portable equipment PEMS.

An emission test consists of measuring emissions and other parameters for the test cycles. A qualitative assessment of the emissions level depends on the chosen method of measurement and used equipment. The measurement of specific emissions requires the determination of the mass of pollutants in the exhaust (i.e. HC, NMHC, CO, NO_x and PM) and the corresponding engine work. Thus, for the research heavy-duty engines with the PEMS method and for successes assessment of the emissions level we have to adhere NTE concept, whereby emissions averaged over a time window must not exceed specified values for regulated pollutants while the engine is operating within a control area under the torque curve.

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