ANALYSIS OF MEASUREMENT ERRORS OF CVS METHOD USED FOR TESTS OF POLLUTANT EMISSIONS FROM LIGHT-DUTY VEHICLES

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Abstract

The test procedure for the pollutant emissions from light-duty vehicles is currently under verification carried out at the international level. For this purpose, GRPE (Groupe des rapporteurs sur la pollution et energie) – the body developing UNECE regulations proposals - has set up a task group WLTP (Worldwide harmonized Light vehicles Test Procedure) which is supposed to prepare a new GTR (Global Technical Regulation) relating to this procedure.

The development of light-duty vehicles, leading to the reduction of pollutants emissions, caused the increase of the requirements for their test procedure. A large number of factors associated, inter alia, with the test equipment affects its accuracy, repeatability and reproducibility. In the ongoing analysis attention is paid even to factors, which affect test results in a relatively small way, and which have been overlooked yet.

One of the problems to which attention is paid is the impact of pollutant concentration in the dilution air in the CVS (constant volume sampler) system on test results. The CVS principle is accepted as the standard method to determine light-duty vehicle exhaust emissions on chassis dynamometer test cells worldwide. It was introduced in the early 1970s. One of its drawbacks is that it introduces an error resulting from the fact that the contractual DF dilution factor, rather than the actual dilution ratio DR, is used for the correction of concentration measurement results.

The article discusses this error for different type of engines used in light-duty vehicles and different pollutants subject to measurements.

Keywords: transport, road transport, combustion engines, air pollution, environmental protection

1. Introduction

The CVS system is a device, that takes the whole exhaust from vehicle exhaust system, dilutes it with air and prepares samples for analysis in order to determine the mass flow of examined pollutants.

The CVS system draws the air and exhaust gases of the tested vehicle in such a way, that the sum of the flow is constant. Thus, during the introduction of exhaust gases volume, which is varying in the time, the system will suck as much air, so that the flow rate was constant.

$$V_{CVS} = V_{dil} + V_{exh},$$ (1)

where:

V_{CVS} – volume of the diluted exhaust gas expressed in litres per test and corrected to standard conditions,

V_{dil} – volume of the ambient air aspirated by the CVS,

V_{exh} – volume of the exhaust gas.

After mixing gas with air, a mixture of gases is obtain, wherein the measured concentrations of the exhaust gas components are proportional to the mass flow of pollutants, introduced with the exhaust gases. This method of sample preparation allows the measurement of emissions during the given period of time.

In the case of vehicles with spark-ignition engines, diluted exhaust gases is collected in flexible

bags, from where they are collected for analysis of all controlled gaseous pollutants, covered by the provisions in the test Type I (CO, THC, NMHC, NO_x) and carbon dioxide (CO_2) in the measurement test of carbon dioxide emissions and fuel consumption. In the case of vehicles with compression-ignition engines the measurements of CO, NO_x and CO_2 concentrations are carried out in the same way as with spark-ignition engines, i.e. exhaust gases are collected to the analyser from the bags.

However, for THC the diluted exhaust gases are taken directly from the dilution tunnel and a continuous measurement of the concentration is carried out. The average value of emissions is determined by integration the instantaneous values. The system, which supply the diluted exhaust gases to FID analyser and the analyser itself are heated to a temperature of 190 ±10°C to prevent condensation of heavy hydrocarbons. The CVS system diagram is shown in Fig. 1.
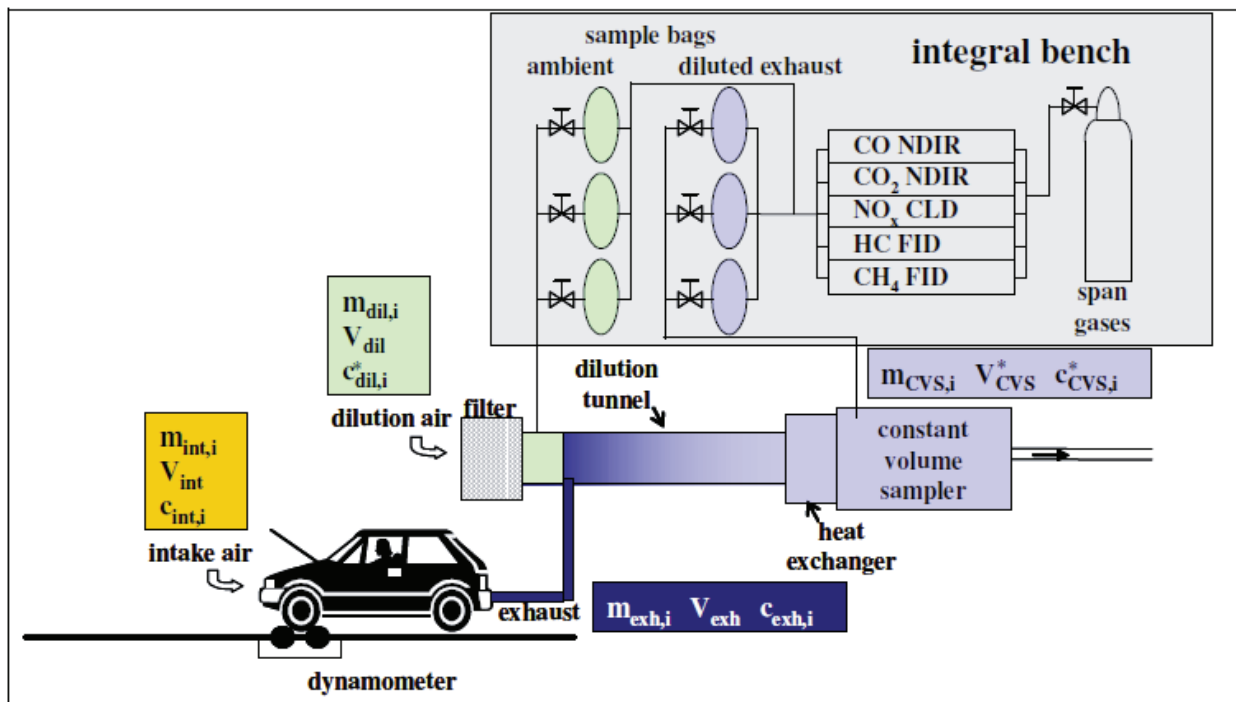

Fig. 1. Diagram of the CVS system [6]

2. The adopted procedure for emissions determining

Mass emissions of gaseous pollutants in test Type I is calculated by means of the following formula (2):

$$m_i = \frac{V_{CVS} \cdot \rho_i \cdot k_h \cdot C^c_{CVSi} \cdot 10^{-3}}{d},$$ (2)

where:
m_i – mass emission of the pollutant „i" in grams per kilometre,
V_{CVS} – volume of the diluted exhaust gas expressed in litre per test and corrected to standard conditions,
ρ_I – density of the pollutant „i" in grams per litre at normal temperature and pressure,
k_h – humidity correction factor used for the calculation of the mass emissions of oxides of nitrogen,
C^c_{CVSi} – concentration of the pollutant „i" in the diluted exhaust gas expressed in ppm and corrected by the amount of the pollutant „i" contained in the dilution air,
d – distance corresponding to the operating cycle in meters.

Parameters C_{CVS}, V_{CVS} and d are determined by measures and the density of the pollutant results from its physical properties, and for the purposes of type approval tests is specified in the regulations. In the calculations of the carbon monoxide, carbon dioxide and nitrogen oxides emissions, ρ values are adopted equally for all light-duty vehicles, and for the calculations of hydrocarbons emissions are used values, taking into account the type of applied fuel.

Adopted procedure is based on the assumption, that the contaminants in the air, drawn into the engine, does not have any effect on exhaust emissions from the vehicle.

Due to the fact that the CVS system draws air from the atmosphere, in which are contaminants, that are subject to measurements in the exhaust gases, it has an effect on the factor concentration in the dilution tunnel of the CVS system. Thus, to determine the emissions of analysed components from the exhaust system, it should be adjust the concentration in the dilution tunnel of the CVS system with the value, resulting from the amount of pollutants taken together with the atmospheric air.

In general case, the concentration of tested pollutant in the diluted exhaust gases is adjusted due to its content in the dilution air by the formula:

$$C_{CVSi}^{c} = C_{CVSi} - C_{dili}^{c} . \tag{3}$$

On the other hand, the impact of pollutants in ambient air on the concentrations in the CVS dilution tunnel is proportional to the product of the volume fraction of the incoming air in relation to the total flow rate and concentration of pollutant under consideration in the air (4).

$$C_{dili}^{c} = C_{dili} \times \frac{V_{dil}}{V_{CVS}} = C_{dili} \times \frac{V_{CVS} - V_{exh}}{V_{CVS}} = C_{dili} \times (1 - \frac{1}{DR}). \tag{4}$$

In formula (4) DR means the ratio of exhaust gases dilution (*dilution ratio*) in dilution tunnel equal V_{CVS}/V_{exh}.

It results from formulas (3) and (4), that the concentration of the pollutant in the diluted exhaust gases, corrected due to the presence of pollutants in the dilution air is equal to:

$$C_{CVSi}^{cDR} = C_{CVSi} - C_{dili} \times (1 - \frac{1}{DR}). \tag{5}$$

In accordance with the provisions, the actual ratio of dilution DR is not used for the calculation the corrected concentration values. Instead the conventional dilution factor DF is applied (6).

$$C_{CVSi}^{c} = C_{CVSi} - C_{dili} \times (1 - \frac{1}{DF}), \tag{6}$$

where:

C_{CVSi}^{cDR} – measured concentration of pollutant „i" in the diluted exhaust and corrected by the amount of pollutant „i" contained in the dilution air using the dilution ratio DR,

C_{CVSi}^{c} – measured concentration of pollutant „i" in the diluted exhaust and corrected by the amount of pollutant „i" contained in the dilution air using the dilution factor DF,

C_{CVSi} – measured concentration of pollutant „i" in the diluted exhaust gas, expressed in ppm,

$C_{dil\,I}$ – measured concentration of pollutant „i" in the air used for dilution, expressed in ppm,

$C_{dil\,I}^{c}$ – correction value resulting from the introduction of pollutant „i" together with the dilution air to the CVS system,

DR – dilution ratio,

DF – dilution factor.

The concentration of the pollutant in diluted exhaust gases, corrected due to the presence of pollutants in the dilution air, is determined on the basis of the following methodology:

The general formula for the determination of the dilution factor DF is as follows:

$$DF = \frac{a}{C_{CO2} + 10^{-4} \times (C_{THC} + C_{CO})}, \tag{7}$$

where:

DF   – dilution factor,
C_{CO2} – concentration of CO_2 in the diluted exhaust gas contained in the sampling bag, expressed in per cent volume,
C_{HC} – concentration of HC in the diluted exhaust gas contained in the sampling bag, expressed in ppm carbon equivalent,
C_{CO} – concentration of CO in the diluted exhaust gas contained in the sampling bag, expressed in ppm,
a   – coefficient

Coefficient „a" is the theoretical value of the carbon dioxide concentration in the raw (wet) exhaust, set by the following assumptions:
– the combustion is complete and perfect,
– fuel-air mixture in the engine is stoichiometric ($\lambda = 1$).

First assumption is never met in internal combustion engines, because besides the carbon dioxide in exhaust gases are also products of incomplete and imperfect combustion, in particular carbon monoxide, hydrocarbons, hydrogen and particulates. The adoption for analysis of so-called potential level of carbon dioxide, i.e. determined using the assumption, that the carbon and hydrogen contained in the fuel are completely oxidized to CO_2 and H_2O, enables the approximate compliance of this assumption.

The assumption of a stoichiometric composition of the fuel-air mixture also is never met, especially in compression-ignition engines, which effects on the concentration equalization (5) and (6), and therefore also on the result of pollutant emissions measurement.

Some data were collected, about the content of each pollutant in the air in a few research laboratories during research in the test Type I. Those data are included in the Tab. 1.

Tab. 1. Concentration of pollutants in the air in research laboratories

Pollutant	Unit	Concentration
Carbon monoxide	ppm	0.08-2.9
Methane	ppm	0.8-2.7
Non-methane hydrocarbons	ppm C_1	1.5-3.3
Nitrogen oxides	ppm	0.05-1.8
Dinitrogen monoxide	ppm	0.05-0.7
Carbon dioxide	% (v/v)	0.04-0.08

3. Method error resulting from the use of DF instead of DR

In order to assess the impact of dilution air pollution on the corrected concentration determined by the formula (3), there was applied the methodology, which is given below. The evaluation was performed separately for vehicles with SI and CI. The engines were divided into groups with similar values of excess air ratio. From each group a car was selected, for which there were on average the major differences between concentrations specified by formulas (5) and (6). These differences are calculated as a percentage as follows:

$$\Delta C = 100 * \left(\frac{C_{CVS}^{DF} - C_{CVS}^{DR}}{C_{CVS}^{DF}} \right). \tag{8}$$

ΔC smaller than 0 means, that the application of the calculation method set in provisions, results in underestimation the measured concentration in relation to the real concentration. In case, if ΔC is greater than 0, then this method results in overestimation of concentration.

Assuming that factors, other than air pollution, are constant, the concentration calculated according to equation (5) can be considered as real, and difference ΔC can be treated as an error of method established in the regulations.

Vehicles with spark-ignition engines are divided according to the used type of fuel on the vehicles powered by gasoline, LPG and natural gas, and then on:

– „pre Euro" fitted with carburettor system with petrol and a fuel or the mixing system with the gas supply, without catalytic converters,
– low-emission equipped with fuel injection system and three-way catalytic reactors.

In the case of vehicles „pre Euro", not equipped with catalytic converters, the excess air ratio λ in the majority of operating conditions that occur in a type I test is different, sometimes quite significantly, from 1. During operation of unheated engine after start and idling, the mixture is rich (λ < 1), and with average load is leaner than the stoichiometric (λ > 1). The average coefficient λ depends on many design and operating factors, such as engine cycle, the ratio of engine power relative to the weight of the car, adjusting the carburettor. The analysis was conducted for 4 cars powered by gasoline and 2 cars powered by LPG. For analysed petrol-fuelled vehicles, the average value of λ is contained in the range of 0.94-1.08. In Tab. 2 there were given an error of method established in the regulations (calculation based on a contractual DF according to formula (6) and not by the actual DR according to formula (5)) for vehicles powered by petrol ΔC is negative. Its value is very small. Error of method can be considered as totally negligible in this case. This is due to the relatively high concentration of pollutants in the exhaust of vehicles "pre Euro". This applies to all pollutants.

In the case of low-emission vehicles, equipped with fuel injection system and three-way catalytic converters, the air-fuel mixture is approximately equal to the stoichiometric, in most working conditions in the test Type I. The air excess ratio differs from 1 under the following operating conditions:

– starting the engine and warming after a cold start (λ <1),
– driving at high acceleration values (especially in cars with low power to weight ratio) (λ <1),
– braking with switched off fuel supply, in this case λ is theoretically equal to ∞.

The impact analysis of pollution of air that dilutes exhaust gases in CVS system on the measured concentration of pollutants was carried out for 5 cars powered by gasoline and 5 cars powered by LPG.

The analysis showed, that for vehicles powered by gasoline, which are equipped with fuel injection system and triple action catalytic converters for the whole type I test the excess air ratio is about 1.05. The error of the method is shown in Tab. 2 (car Euro 5). ΔC is negative. For these vehicles, its absolute value is greater than for cars "before Euro". This is due to the much lower concentration of pollutants in the exhaust gases. However, the error of the method is essentially negligible for all contaminants except methane. For nitrogen oxides, the value of this coefficient obtained for the extra-urban cycle is much higher than other values, but the outcome is the result of extremely low levels of this compound in the exhaust gases and the associated increase of error of sample analysis, but not discussed method error.

In the case of LPG fuel, the error is similar to gasoline error for all pollutants. In the case of natural gas supply, the difference occurs for hydrocarbon. The method error decreases repeatedly for methane due to its much higher concentration in the exhaust gases, and rises for non-methane hydrocarbons.

The service also includes vehicles with spark-ignition engines that not belong to any of the above basic groups, such as "before the Euro" equipped with a fuel injection system, low-emission with oxidation reactors. For these vehicles, the method errors has generally an intermediate value between values given in Tab. 2.

In the case of compression-ignition engines, the air excess factor is greater than 1 in the whole field of operation. There were conducted an analysis of vehicles powered by diesel fuel. They were divided into two groups:

– vehicles, where the switch off of the fuel supply when braking does not occur,
– vehicles, where the switch off of the fuel supply when braking does occur.

Tab. 2. Method error resulting from using DF instead DR for tested vehicles with spark-ignition engines powered by gasoline

Pollutant	Method error [%]		
	„pre Euro" car (NEDC cycle)	Euro 5 car	
		urban cycle	extra-urban cycle
Carbon oxide	-0.001	-0.008	-0.02
Methane	-0.02	-0.30	-1.7
Non-methane hydrocarbons	-0.003	-0.04	-0.2
Total hydrocarbons	-0.004	-0.08	-0.4
Nitrogen oxides	-0.001	-0.04	2.0

We analysed two vehicles of the first group and three vehicles of the second group.

The first group includes vehicles "pre Euro" and part of Euro 1 and Euro 2. In fact, all the cars that meet the requirements of Euro 3 and then are fitted with power supply system with switch off the fuel supply when braking, which causes an increase in the average air excess ratio. It should be noted, that the effects of disabling fuel supply on the excess air coefficient in compression-ignition engines is significantly greater than in spark-ignition engines due to the higher coefficient of cylinders filling in comparable work conditions. Tab. 3 shows the maximum error of the method.

In the case of vehicles with compression-ignition engines fuelled by diesel fuel, the error of method is, as in the case of spark-ignition engines, negative. Its absolute value is much higher for cars switch off the fuel supply when braking does occur, which is due to the lower concentration of pollutants in the exhaust gases of this vehicle group. For all the controlled pollutants, with the exception of nitrogen oxides, it takes relatively large, non-negligible values. The highest value of the error occurs for hydrocarbons. This is due to the fact that the concentrations of these compounds in the diluted exhaust gases and the dilution air are only slightly different from each other. This applies in particular for methane.

Tab. 3. Method terror resulting from using DF instead DR for tested vehicles with compression-ignition engines powered by diesel oil

Pollutant	Method error [%]			
	vehicles without switch off the fuel supply (Euro 2)		vehicles with switch off the fuel supply (Euro 4)	
	urban cycle	extra-urban cycle	urban cycle	extra-urban cycle
Carbon oxide	-0.14	-0.96	-0.7	-27.1
Methane	-2.6	-5.0	-14	-30.4
Non-methane hydrocarbons	-0.4	-1.9	-1.7	-20.9
Total hydrocarbons	-0.8	-2.9	-5.3	-24.5
Nitrogen oxides	-0.02	-0.02	-0.1	-0.1

The method error given in Tab. 2 and 3 were determined for cases, where the concentration of certain pollutants in the dilution air was lower, sometimes quite significantly, than the maximum measured concentration in the laboratory (Tab. 1).

Table 4 shows the results of coefficient ΔC simulation in case, when the concentration of pollutants in the dilution air would be equal to the maximum value specified in Tab. 3.1.

The simulation was performed for:

– Euro 5 car with spark-ignition engine powered by gasoline, for which the method error, resulting from using DF instead DR is given in Tab. 3,

– Euro 4 car with compression-ignition engine powered by diesel oil, for which the method terror, resulting from using DF instead DR is given in Tab. 4.

Tab. 4. Maximum method terror (%) resulting from using DF instead DR for tested vehicles, depending on the degree of dilution air pollution

Pollutant	Euro 5 car with spark-ignition engine				Euro 4 car with compression-ignition engine			
	urban cycle		extra-urban cycle		urban cycle		extra-urban cycle	
	a	b	a	b	a	b	a	b
Carbon oxide	-0.003	-0.02	-0.008	-0.06	-0.7	-1.2	-27	-35
Methane	-0.3	-0.5	-1.4	-2.0	-14	-21	-30	-45
Non-methane hydrocarbons	-0.05	-0.09	-0.3	-0.5	-1.7	-2.9	-21	-33
Total hydrocarbons	-0.1	-0.11	-0.4	-0.6	-5.3	-6.6	-24	-29
Nitrogen oxides	-7.3	-5.1	-0.5	-3.1	-0.1	-0.2	-0.1	-0.2

$a - C_{dil\,i}$ equal to real one during tests, $b - C_{dil\,i}$ equal to the maximum one, given in Tab. 2.

4. Conclusions

The analysis found that the CVS test method, adopted in the legislation results in measurement errors of all gaseous pollutants arising from the fact, that the conventional dilution factor DF, but not the actual dilution ratio DR is used for the correction of the measurement results, due to the concentration of pollutants in the dilution air.

In particular, a big method error occurs in the case of compression-ignition engines, which are powered with lean mixtures.

The method error increases, if tested vehicle is characterized by low gas emissions,

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