International Journal of Occupational Safety and Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tose20

A Simulation Method of the Reduction of Nitrogen Oxides Over a Silver Aluminate Catalyst in Static Tests of Combustion Engines

Zdzisław Chłopek[a] & Andrzej Darkowski[b]
[a] Institute of Vehicles, Warsaw University of Technology, Poland
[b] Department of Chemistry, Warsaw University of Technology, Poland
Published online: 08 Jan 2015.

To cite this article: Zdzisław Chłopek & Andrzej Darkowski (2002) A Simulation Method of the Reduction of Nitrogen Oxides Over a Silver Aluminate Catalyst in Static Tests of Combustion Engines, International Journal of Occupational Safety and Ergonomics, 8:2, 161-182

To link to this article: http://dx.doi.org/10.1080/10803548.2002.11076522

INTERNATIONAL JOURNAL OF
OCCUPATIONAL SAFETY AND ERGONOMICS 2002, VOL. 8, NO. 2, 161–182

A Simulation Method of the Reduction of Nitrogen Oxides Over a Silver Aluminate Catalyst in Static Tests of Combustion Engines

Zdzisław Chłopek

Institute of Vehicles, Warsaw University of Technology, Poland

Andrzej Darkowski

Department of Chemistry, Warsaw University of Technology, Poland

The paper presents a proposition of simulation studies of nitrogen oxide catalytic reduction. The method enables estimating the influence of catalytic reactors on ecological properties of engines in static bench tests (e.g., ECE R49, United Nations Economic Commission for Europe [UN/ECE], 2000; Standard No. ISO 8178-4:1996, International Organization for Standardization [ISO], 1996; Merkisz (1998). An algorithm of simulation studies is shown. A model catalytic reactor for selective catalytic reduction is described. Silver aluminate deposited on steel substrate covered with aluminium phosphate is used as a catalyst. Propene is used as a reductant. The results of reactor studies in a chemical lab are presented. A simulation of the influence of catalytic reactor properties on ecological properties of an engine was done. Unitary emission conversion coefficients of nitrogen oxide in a static test ECE R49 were determined.

toxicity exhaust gases   combustion engines tests
nitrogen oxide reduction   silver aluminate catalyst

Correspondence and requests for offprints should be sent to Zdzisław Chłopek, Politechnika Warszawska, Wydział Samochodów i Maszyn Roboczych, Instytut Pojazdów, Zakład Silników Spalinowych, ul. Narbutta 84, 02-791 Warszawa, Poland. E-mail: <zchlopek@simr.pw.edu.pl>.

1. INTRODUCTION

Studies on a prototype of a catalytic reactor for purification of engine exhaust gases should be carried out in chemical labs instead of a real engine because that assures repeatable conditions. Model reactors are tested with synthetic gas mixtures. The composition of gas mixtures simulates exhaust gas of real engines. Such a method of studies maintains constant and repeatable conditions of measurements and is more sensitive to investigated characteristics of catalytic reactors than studies of real engines.

It is useful to learn how results from studies of model catalytic reactors estimate ecological properties obtained during typical bench engine studies. Certification tests are fundamental for determining ecological properties of combustion engines (AVL Consulting and Information, 1999; Cartellieri, Ospelt, & Landfahrer, 1989, as cited in Merkisz, 1994). The present paper deals with estimating ecological properties of combustion engines on the basis of chemical studies of model catalytic reactors.

The chemical reactor for nitrogen oxide selective reduction at oxygen presence is an object of chemical studies and the subject of this paper. The influence of the properties of a catalytic reactor on the ecological properties of combustion engines is studied assuming that there is a compression ignition engine, which determines the range of studies.

Certification tests in respect to ecological properties are carried out in two categories (AVL Consulting and Information, 1999; Merkisz, 1998; Merkisz & Chłopek, 1999; Walsh, 1996, as cited in Merkisz, 1998; Walsh, 1997):

- engines for cars (Personal Cars, PC), vans (Light Duty Vehicles, LDV), and the so-called Light Duty Diesel (LDD);
- engines for trucks (Heavy Duty Vehicles, HDV), buses, and the so-called Heavy Duty Diesel (HDD).

In the European Union LDD engines are tested in vehicles on an engine test bench according to the Economic Commission for Europe (ECE) R83.03 regulation (United Nations Economic Commission for Europe [UN/ECE], 2001). All compression ignition engines are tested according to ECE R49.03 (UN/ECE, 2000) in a 13-phase static test. According to American regulations also HDD engines are tested in dynamic conditions: on a engine test bench in the US-Heavy Duty-Diesel-Transient-Test (US-HD-D-T-T).

The results obtained in static tests, according to ECE R49.03 (UN/ECE, 2000) and other tests mentioned in section 2, are used to estimate ecological properties of engines. The bases of simulation studies of nitrogen oxide reduction in static tests are presented in section 3. The next section contains a description of a model reactor, the results, and methods. The results of simulation studies of nitrogen oxide reduction in static tests are presented in section 5. Conclusions (section 6) present suggestions how properties of the catalytic reactor affect ecological properties of engines.

2. STATIC TESTS OF COMBUSTION ENGINES

Static tests of combustion engines have been used to assess useful properties of combustion ignition engines, especially to assess their ecological properties. Useful properties of compression ignition engines in static and dynamic tests differ less than for spark ignition engines (Chłopek, 1999). The fundamental reason for this is the non-inertial fuel supply to the cylinders of compression ignition engines as opposed to the fuel supply of spark ignition engines (excluding fuel direct injection). The second reason why static tests are popular for compression ignition engines is the diversity of the applications of these engines, especially large HDD for applications other than automotive (e.g., construction machines). In such cases, dynamic tests, especially those based on time dependence of work conditions, are not adequate for different engine applications (AVL Consulting and Information, 1999; Chłopek, 1999; Merkisz, 1998).

Static test studies are done at determined working points of engines and conditions not depending on time, that is, at the thermal stabilisation of engines. In such cases the working point of the engine is determined by such characteristic values as the frequency of cycles—engine speed (revolution)—and load, measured as torque (or average useful pressure; Chłopek, 1999). The quality of the static test depends on the chosen working points and the time contribution of the work phases at particular points. Unitary emission—defined by Equation 1 in section 3—is a test quantity characteristic for ecological properties.

European, American, and Japanese manufacturers use static tests. The test that complies with the ECE R49 regulation (UN/ECE, 2000; Figure 1) is a basic classic study test (AVL Consulting and Information, 1999; Cartellieri et al., 1989, as cited in Merkisz, 1994; Chłopek, 1999; Cornetti, Klein, Fränkle, & Stein, 1988; Fränkle & Stein, 1988; Merkisz, 1998; Merkisz & Chłopek, 1999; Moser, Haas, & Schlögl, 1989; Moser, Haas, & Schlögl, 1990, as cited in Merkisz, 1998; Wachter & Cartellieri, 1987;

Walsh, 1996, as cited in Merkisz, 1998; Walsh 1997). Coordinates in Figure 1 are relative: The revolution in respect to nominal revolution, torque in respect to torque on the external characteristic for a given revolution rate (Chłopek, 1999). The circle surface area, corresponding to the working points is proportional to the time shares of particular phases. It is a 13-phase test performed at 11 working points and the idle working point is repeated twice.

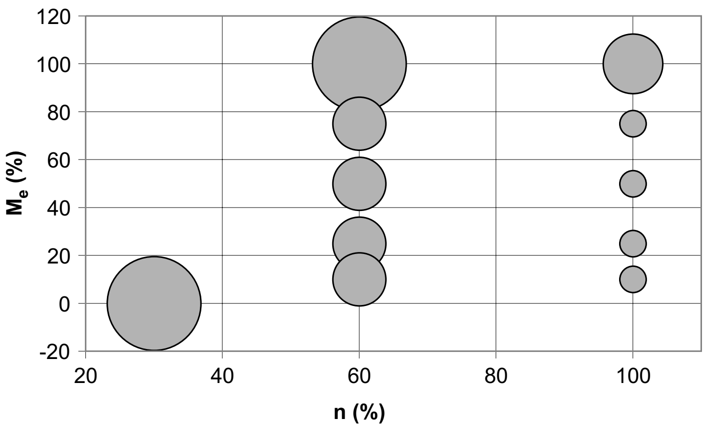

Figure 1. A 13-phase test according to the ECE R49 regulation (UN/ECE, 2000). *Notes.* M_e—torque, n—engine speed.

Tests for engines in non-automotive applications (non-road, off-road) are based on the ECE R49 regulation (UN/ECE, 2000) according to Standard No. ISO 08178-4:1996 (International Organization for Standardization [ISO], 1996). The basic test is an 11-phase one (the so-called universal test, marked B) identical with the ECE R49 (UN/ECE, 2000) test (without repeating the idle working phase and with a changed sequence of phases). For most engine applications (C, D, E, F categories) tests are defined by different time partition of engine work (excluding tests for water traction engines E3, E4, E5, whose working points are not the same as points of a universal test).

Static tests for non-automotive applications were developed in the USA, for example, CARB (California Air Resources Board) 6- and 8-phase tests (SAE Recommended Practice; Society of Automotive Engineers [SAE], 1993).

Since 1985, when the dynamic US–HD–D–T–T test was introduced in the USA, there has been a growing interest in developing static tests that simulate dynamic tests (Cartellieri et al., 1989, as cited in Merkisz, 1994; Chłopek, 1999; Cornetti et al., 1988; Fränkle & Stein, 1988; Moser et al., 1989; Moser et al., 1990, as cited in Merkisz, 1998; Wachter & Cartellieri, 1987). The theory of static tests synthesis is given by Chłopek (1999) according to the criterion of the similarity of the working state of engines and their useful properties.

Sample static tests for simulation dynamic US–HD–D–T–T tests were developed at AVL List (Anstalt für Verbrenungskraftmaschinen Prof. Dr H. List) (8- and 14-phase tests; Cartellieri et al., 1989, as cited in Merkisz, 1994; Cornetti et al., 1988; Fränkle & Stein, 1988; Wachter & Cartelieri, 1987) and at Steyer Daimler-Puch AG (11-phase test with points for a universal test; Moser et al., 1989).

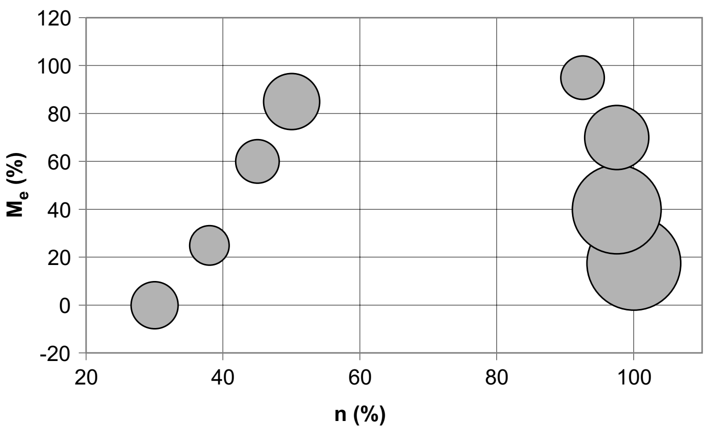

Figure 2. Schema of an 8-phase test developed according to the criterion of similarity of the unitary emission of nitrogen oxide. *Notes.* M_e—torque, n—engine speed.

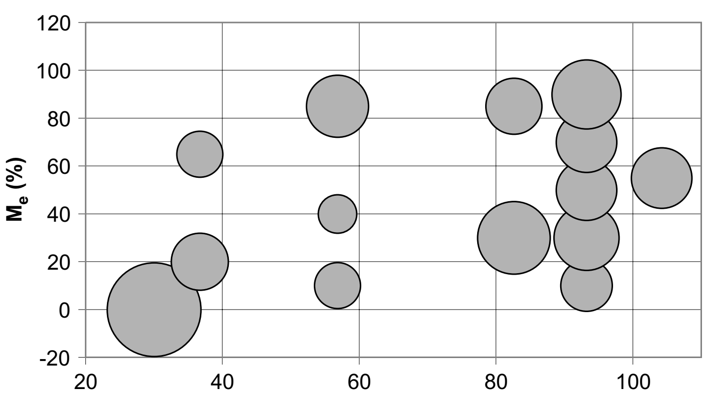

Figure 3. Schema of a 14-phase test developed according to the criterion of similarity of the work state of engines. *Notes.* M_e—torque, n—engine speed.

Figure 2 presents the 8-phase test developed according to the criterion of the similarity of unitary nitrogen oxide emission. Figure 3 presents the 14-phase test according to the criterion of the similarity of the working state of engines (useful power).

3. SIMULATION STUDIES OF NITROGEN OXIDE REDUCTION IN STATIC TESTS OF COMBUSTION ENGINES

Unitary substance emission e is defined as the ratio of the substance emission intensity E to the useful power of engines N_e (Chłopek, 1999)

$$e = \frac{E}{N_e}, \tag{1}$$

where emission intensity (Chłopek, 1999) is emission derivative m, the mass of emitted substance relative to time t

$$E = \frac{dm}{dt}. \tag{2}$$

Average unitary emission in a static test of a combustion engine is given by[1] AVL Consulting and Information (1999), Chłopek (1999), and Merkisz (1998)

$$e_{av} = \frac{\sum_{i=1}^{p} E_{(i)} \cdot u_{(i)}}{\sum_{i=1}^{p} N_{e(i)} \cdot u_{(i)}}, \tag{3}$$

where $E_{(i)}$—substance emission intensity (in exhaust gases), $u_{(i)}$—contribution of the work phase in points of static combustion engine test, p—number of work phases in points of static combustion engine test.

The conversion coefficient of substance concentration in exhaust gases k is defined by substance volumetric concentration in exhaust gases before purification S_0, and after purification S_1

$$k = 1 - \frac{S_1}{S_0}. \tag{4}$$

[1] To distinguish from other indexes, indexes in parentheses indicate the sequence of elements in vectors, matrixes, or sets.

The average unitary emissions in the combustion engine static test for non-purified exhaust gases e_{av0} and purified e_{av1} are given by equations

$$e_{av0} = \frac{\sum_{i=1}^{p} E_{0(i)} \cdot u_{(i)}}{\sum_{i=1}^{p} N_{e(i)} \cdot u_{(i)}}, \tag{5}$$

$$e_{av1} = \frac{\sum_{i=1}^{p} E_{1(i)} \cdot u_{(i)}}{\sum_{i=1}^{p} N_{e(i)} \cdot u_{(i)}}, \tag{6}$$

where $E_{0(i)}$, $E_{1(i)}$—substance emission intensity before and after the purification.

The conversion coefficient of unitary emission of the substance in exhaust gases in the static test of combustion engine K is determined as

$$K = 1 - \frac{e_{av1}}{e_{av0}}. \tag{7}$$

The emission intensity of the substance in exhaust gases can be expressed as a linear function of exhaust gas flow rate Q and volumetric substance concentration in the exhaust gas (AVL Consulting and Information, 1999; Chłopek, 1999; Merkisz, 1998).

$$E = S \cdot Q \cdot c_1, \tag{8}$$

where c_1—constant.

The volumetric intensity of exhaust gas flow is proportional to rotational speed n and volumetric efficiency η_v

$$Q = n \cdot \eta_v \cdot c_2, \tag{9}$$

where c_2—positive constant.

For compression ignition engines, as for engines with a quality regulation of mixture, it may be assumed that the volumetric efficiency is weakly dependant on rotational speed. A load, which can be expressed as torque M_e, is also weakly dependant on rotational speed

$$\frac{\partial \eta_v}{\partial n} \approx 0, \; \frac{\partial \eta_v}{\partial M_e} \approx 0. \tag{10}$$

As the following points in static engine tests are determined by co-ordinates n—M_e, it can be assumed that the emission intensity of the substance in exhaust gases is given by

$$\eta_{v(i)} \approx \text{const.} \tag{11}$$

So, it can be assumed that the substance emission intensity in exhaust gases is expressed by the relation

$$E = S \cdot n \cdot c, \tag{12}$$

where c is a positive constant.

The conversion coefficient of unitary emission of substance content in exhaust gases in the static engine test equals

$$K = 1 - \frac{\sum_{i=1}^{p} S_{1(i)} \cdot n_{(i)} \cdot u_{(i)}}{\sum_{i=1}^{p} S_{0(i)} \cdot n_{(i)} \cdot u_{(i)}}, \tag{13}$$

$$K = 1 - \frac{\sum_{i=1}^{p} S_{0(i)} \cdot (1 - k_{(i)}) \cdot n_{(i)} \cdot u_{(i)}}{\sum_{i=1}^{p} S_{0(i)} \cdot n_{(i)} \cdot u_{(i)}}. \tag{14}$$

The conversion coefficient of substance concentration content in exhaust gases, owing to purification systems, can be modelled as a function of substance concentration in exhaust gases, apparent temperature of the catalytic reactor T, and volumetric intensity of the exhaust gases flow through the catalytic reactor

$$k = f_1(S_0, T, Q). \tag{15}$$

The model of the conversion coefficient of substance concentration (Equation 15) assumes that there is no dependence on oxygen concentration in exhaust gases. This assumption is a result of low response of the conversion coefficient of nitrogen oxides to oxygen concentration in a typical static test of engines. This was proved during selective catalytic reduction by means of hydrocarbons.

It can be assumed that for the working points in the static test conversion, the coefficient of substance concentration in exhaust gases reads

$$k_{(i)} = f_1(S_{0(i)}, T_{(i)}, Q_{(i)}). \tag{16}$$

For catalytic reactors whose extensive parameters (size characteristics of a reactor) are properly chosen with respect to useful properties of engines (displacement volume, engine speed) the dependence of the volumetric exhaust gas flow rate on the conversion coefficient is weak. So, it can be assumed, with certain approximation, that the conversion coefficient is dependant on substance concentration in exhaust gases and the average exhaust gas temperature in the catalytic reactor space:

$$k = f_1(S_0, T), \tag{17}$$

$$k_{(i)} = f_1(S_{0(i)}, T_{(i)}). \tag{18}$$

The average exhaust gas temperature, similar to other quantities describing engine properties in conditions responding to the traction operation, in the static work condition of engine, depends on the parameters of the work state of an engine, that is, load and engine speed (Cornetti et al., 1988). As torque and engine speed determine univocally the working point in a static test, the average exhaust gas temperature depends only on the working point in a static test:

$$T_{(i)} = f_2(i). \tag{19}$$

For similar reasons substance concentration in exhaust gases depends only on the working point in a static test:

$$S_{0(i)} = f_3(i). \tag{20}$$

In connection with Equations 16, 19, and 20 the conversion coefficient of substance concentration in exhaust gases depends on the working point in a static test:

$$k_{(i)} = f_4(i). \tag{21}$$

As rotation rate in a static test depends only on the working points

$$n_{(1)} = f_5(i) \tag{22}$$

and the conversion coefficient of unitary emission of substance in exhaust gases in a static test of a combustion engine is given by Equation 14, so this coefficient is constant in this test.

The value of the conversion coefficient of unitary emission of substance is limited to K_{min} and K_{max}, corresponding in the particular working points of the static test to the average temperature of exhaust gases:

- the minimum conversion coefficient of unitary emission for K_{min},
- the maximum conversion coefficient of unitary emission for K_{max},

$$K \in [K_{min}, K_{max}]. \tag{23}$$

Equation 23 enables estimation of the conversion coefficient of unitary emission of substance content in exhaust gases in the static test in the case of an unknown relation between the average temperature of exhaust gases and the working point of the engine in Equation 19.

Knowledge of the relation between the conversion coefficient of substance concentration in exhaust gases and the concentration of substance in exhaust gases and the average temperature of exhaust gases in the catalytic reactor, determined by studies of the catalytic reactor by means of synthetic gases simulating exhaust gases, allows an estimation of the conversion coefficient of unitary emission of substance in the static engine test in conditions corresponding to the criterion of ecological estimation of the engines.

4. A MODEL OF A CATALYTIC REACTOR FOR A SELECTIVE REDUCTION OF NITROGEN OXIDES ON SILVER ALUMINATE

A catalytic reactor containing silver aluminate was used for nitrogen oxide reduction (Darkowski & Kruczyński, 2000).

Silver oxide decomposes to metallic silver at a temperature above 300 °C, therefore a synthesis of silver aluminate cannot be done by a simple reaction between metal oxides. Because of this, a reaction in oxidising flux was chosen. Silver aluminate has a Delafossite structure (Shannon, Rogers, & Prewitt, 1971). It can be prepared according to the following reaction:

$$AgNO_3(l) + LiAlO_2(s) \rightarrow AgAlO_2 + LiNO_3, \tag{24}$$

where (l)—liquid, (s)—solid.

The mixture of reagents was heated in 350 °C for 100 hrs. After the separation of aluminate by water washing, silver aluminate was deposited on a metallic substrate by means of the sol-gel technique in a silica matrix. The honeycomb structure had 46 channels per cm^2.

Laboratory studies of the catalytic reactor were done by means of a synthetic mixture of gases. The mixture contained nitrogen monoxide NO, nitrogen N_2, oxygen O_2, and propene as a reductant. The composition of the mixture was measured with an analyser with electrochemical cells. Propene concentration was determined by IR cell. The catalytic reactor was placed in the oven with regulated temperature. The rate of flow was 1.78 s^{-1}.

The variables in the studies were

- nitrogen oxide volumetric concentration in the gas mixture S_{NO},
- temperature of the synthetic gas mixture T_g,
- volumetric propene concentration in the synthetic gas mixture S_p.

Propene concentration was fixed in relation to nitrogen oxide concentration:

$$r = \frac{S_p}{S_{NO}} . \tag{25}$$

Studies were carried out for values of coefficient r that were components of a w_r-elements vector

$$\mathbf{r} = [0.5; 1.67; 3.33]^T. \tag{26}$$

Nitrogen oxide concentrations were fixed in following tests on levels of a w_n-elements vector $\mathbf{S}_{NO}$, formulated in ppm:

$$\mathbf{S}_{NO} = [50; 200; 400; 600; 800; 1000; 1200; 1400; 1600]^T. \tag{27}$$

The temperature of the synthetic mixture of gases was fixed on levels of a w_t-elements vector $\mathbf{T}_g$, formulated in degrees Celsius:

$$\mathbf{T}_g = [100; 350; 400; 450; 500]^T. \tag{28}$$

The number of independent variables is

$$w = w_r \cdot w_n \cdot w_t. \tag{29}$$

As a result of the studies a w-elements set of volumetric concentrations of nitrogen oxide after catalytic reduction by propene was obtained. The effect of this is a w-elements set of nitrogen oxide conversion coefficient $\mathbf{k}_p$, which is a function of elements of vectors $\mathbf{r}$, $\mathbf{S}_{NO}$, and $\mathbf{T}_g$,

$$\mathbf{k}_{p(j)} = \mathbf{f}_6(\mathbf{S}_{N0(j)}, \mathbf{T}_{g(j)}, \mathbf{Q}_{r(j)}), \tag{30}$$

where j = 1, 2, ... , w.

Sample dependence of nitrogen oxide conversion coefficient k_p on particular independent variables with remaining variables fixed is shown in Figures 4–6.

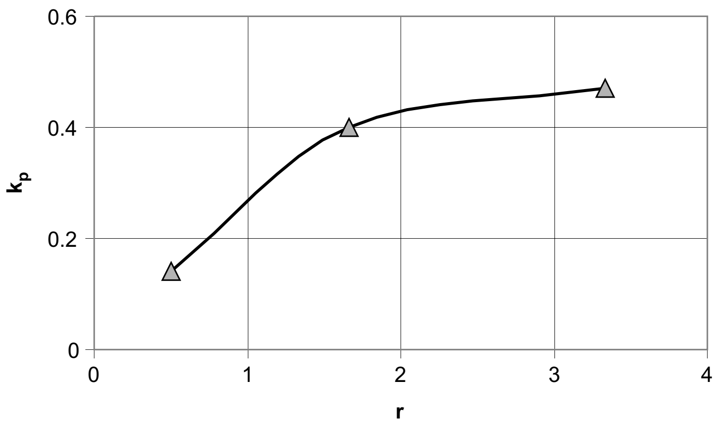

Figure 4. Dependence of the conversion coefficient of nitrogen oxide on the ratio of propene to nitrogen oxide concentration at fixed nitrogen oxide concentration S_{NO} = 800 ppm and temperature T_g = 450 °C. *Notes.* k_p—nitrogen oxide conversion coefficient, r—ratio of propene to nitrogen oxide concentration.

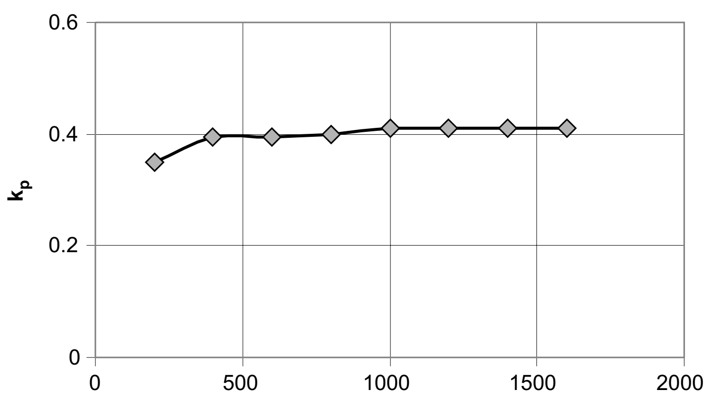

Figure 5. Dependence of the conversion coefficient of nitrogen oxide on nitrogen oxide concentration at a fixed ratio of propene to nitrogen oxide concentration r = 1.67 and temperature T_g = 450 °C. *Notes.* k_p—nitrogen oxide conversion coefficient, S_{NO}—nitrogen oxide concentration.

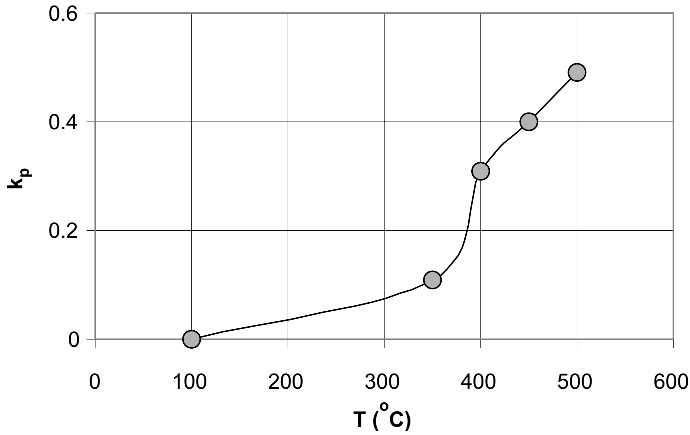

Figure 6. Dependence of the conversion coefficient of nitrogen oxide on gas temperature at a fixed propene to nitrogen oxide concentration r = 1.67 and nitrogen oxide concentration S_{NO} = 800 ppm. *Notes.* k_p—nitrogen oxide conversion coefficient, T—temperature.

5. RESULTS OF SIMULATION STUDIES OF NITROGEN OXIDE REDUCTION IN STATIC BENCH STUDIES OF COMBUSTION ENGINES

For simulation studies of nitrogen oxide reduction in static tests it is necessary to determine the nitrogen oxide conversion coefficient in working points of the engine in static test phases on the basis of conversion coefficients in laboratory test points.

Considering the effectiveness of nitrogen oxide reduction, the working points of an engine are characterised by the concentration of nitrogen oxide before conversion and the temperature of the gas taking part in a reaction.

A decrease of variables was achieved by optimising the propene to nitrogen oxide ratio with respect to the maximum conversion coefficient as a function of nitrogen oxide concentration and gas temperature. It was done by approximating the relation

$$k_{p(jr)} = f_7(r_{(jr)}) \text{ for } S_{NO\,(jn)} = \text{const}, \; T_{g(jg)} = \text{const}, \tag{31}$$

where jr = 1, 2, ... , w_r, jn = 1, 2, ... , w_n, jg = 1, 2, ... , w_g, by square terms and calculation of their maximum values in the region of the maximum values of independent variables region. As a result of this operation matrixes (dimensions $w_n \times w_g$) of the propene to nitrogen oxide concentration ratio were obtained, optimal with respect to the conversion coefficient of nitrogen oxide concentration (Figure 7) and maximum nitrogen oxide concentration conversion (Figure 8).

$$\mathbf{r}_{\mathrm{opt(jn,\ jg)}} = \mathbf{f}_8(\mathbf{S}_{\mathrm{NO\,(jn)}},\ \mathbf{T}_{\mathrm{g(jg)}}). \tag{32}$$

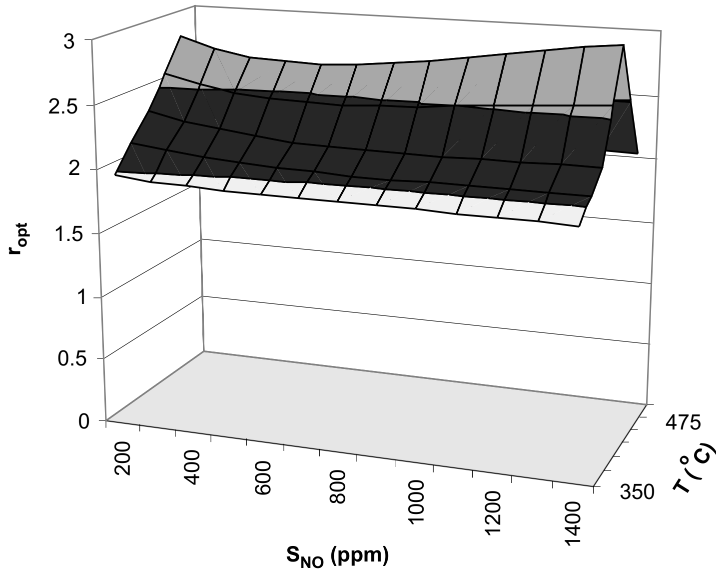

Figure 7. Dependence of the optimum propene to nitrogen oxide concentration ratio on nitrogen oxide concentration and gas temperature in laboratory studies of the reactor. *Notes.* r_{opt}—optimum propene to nitrogen oxide concentration ratio, S_{NO}—nitrogen oxide concentration, T—temperature.

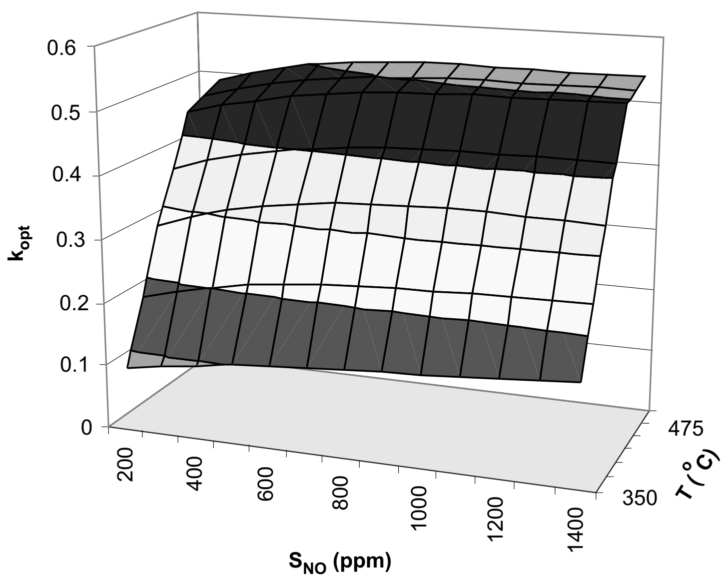

Figure 8. Dependence of the maximum conversion coefficient of nitrogen oxide on nitrogen oxide concentration and gas temperature in laboratory studies of the reactor. *Notes.* r_{opt}—optimum propene to nitrogen oxide concentration ratio, S_{NO}—nitrogen oxide concentration, T—temperature.

Determination of the propene to nitrogen oxide ratio, optimal with respect to the conversion coefficient of nitrogen oxide for independent variables nitrogen oxide concentration and gas temperature as a result of static test measurements $\mathbf{S}_0$ and $\mathbf{T}$ was done by polynomial approximation of Equation 32 in three-dimensional space. $\mathbf{S}_0$ and $\mathbf{T}$ values were assumed on the basis of compression ignition (with direct injection) engine studies in the static test according to the ECE R49 regulation (UN/ECE, 2000; Figures 9 and 10)

$$\mathbf{S}_0 = [1000; 976; 795; 560; 430; 1350; 1200; 995; 646; 395; 130]^{\mathrm{T}}, \quad (33)$$

$$\mathbf{T} = [393; 311; 255; 212; 185; 385; 305; 275; 205; 180; 170]^{\mathrm{T}}. \quad (34)$$

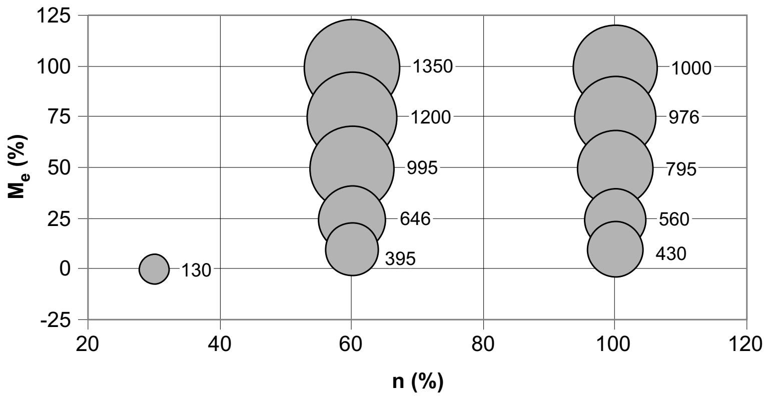

Figure 9. Values of nitrogen oxide concentration in static test points according to the ECE R49 regulation (UN/ECE, 2000). *Notes.* M_e—torque, S_{NO}—nitrogen oxide concentration, n—engine speed.

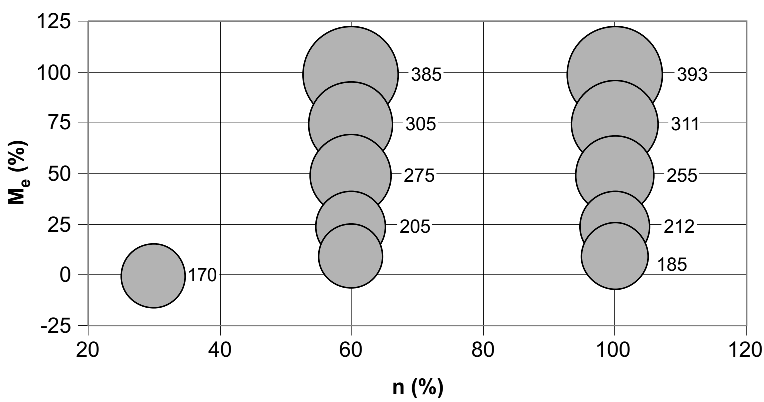

Figure 10. Values of gas temperature in static test points according to the ECE R49 regulation (UN/ECE, 2000). Notes. M_e—torque, T—temperature, n—engine speed.

As a result of this operation the values of the propene to nitrogen oxide concentration ratio $\mathbf{r}_p$ were determined. They are optimal with respect to the conversion coefficient of nitrogen monoxide for independent variables $\mathbf{S}_0$ and $\mathbf{T}$ (Figure 11).

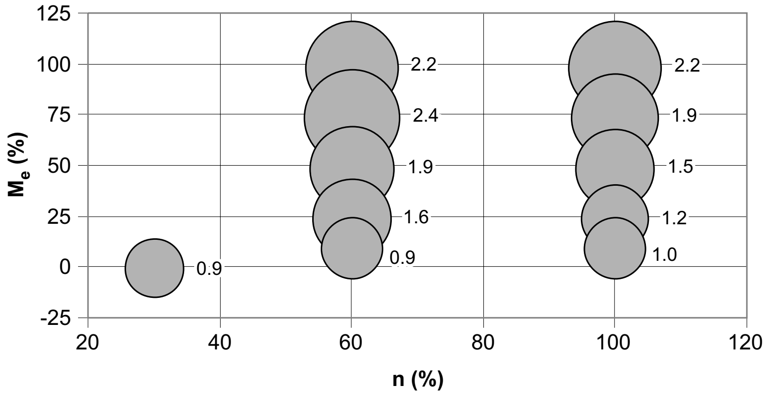

Figure 11. Values of the propene to nitrogen oxide concentration ratio, optimal with respect to the conversion coefficient of nitrogen oxide, in static test points according the ECE R49 regulation (UN/ECE, 2000). *Notes.* M_e—torque, r_p—propene to nitrogen oxide concentration ratio, n—engine speed.

Linear interpolation of Equation 30 is done by hyperplane in four-dimensional space. As a result, the nitrogen oxide conversion coefficients $\mathbf{k}$ were determined from the static test for variables $\mathbf{S}_0$, $\mathbf{T}$, and $\mathbf{r}_p$ (Figure 12).

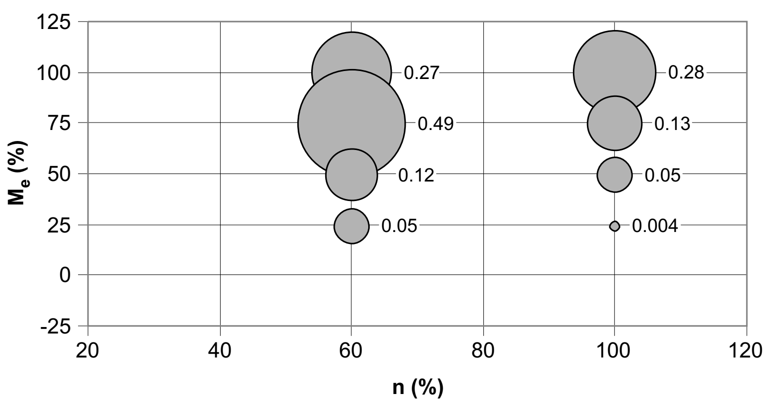

Figure 12. Dependence of the conversion coefficient of nitrogen oxide on nitrogen oxide concentration and gas temperature in static test points according to ECE R49 regulation (UN/ECE, 2000). *Notes.* M_e—torque, k—nitrogen oxide conversion coefficient, n—engine speed.

In agreement with Equation 14 it is possible to determine the conversion coefficient of nitrogen oxide unitary emission K in the combustion engine static test. The solution of this problem is described in this paper.

Contributions of work time in test phases in the ECE R49 (UN/ECE, 2000) test are included in the vector

$$\mathbf{u} = [0.1; 0.02; 0.02; 0.02; 0.02; 0.25; 0.08; 0.08; 0.08; 0.08; 0.25]^T. \quad (35)$$

On the basis of the procedure presented in this paper the conversion coefficient of nitrogen oxide unitary emission for the combustion engine static test was calculated as $\mathbf{K} = 0.233$.

Assuming that the conversion coefficient is an increasing function of gas temperature in the examined range of temperature, it is possible to determine the conversion coefficient of unitary emission for minimum and maximum temperatures in the particular working points in a static test. Simulation studies were done for the points of a static test equal to 100, 75, and 50% of the load. At the rest of the points the nitrogen oxide conversion is equal to zero because of the low gas temperature resulting from low load. For gas temperature 200 °C the conversion coefficient of unitary emission is $K_{min} = 0.098$, whereas for 500 °C it is $K_{max} = 0.479$.

The results of the conversion coefficients of nitrogen oxide unitary emission, according to the ECE R49 regulation (UN/ECE, 2000), are presented in Figure 13.

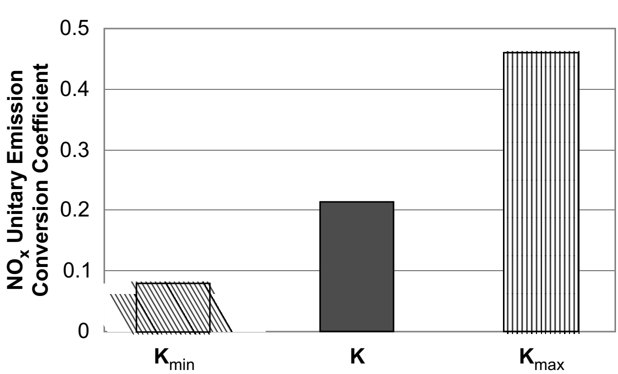

Figure 13. Conversion coefficients of nitrogen oxide unitary emission according to the ECE R49 regulation (UN/ECE, 2000). *Notes.* K_{min}, K, K_{max}—conversion coefficients of nitrogen oxide unitary emission.

6. CONCLUSIONS

The results of laboratory studies of a model catalytic reactor with silver aluminate show that in the examined range of nitrogen oxide concentration, gas temperature, and given propene to nitrogen oxide concentration ratio, the conversion coefficients of nitrogen oxide are between 0 and 0.5.

The dependence of the conversion coefficient of nitrogen oxide on the propene to nitrogen oxide concentration ratio is increasing. The susceptibility of the conversion coefficient of nitrogen oxide on the propene to nitrogen oxide ratio is low for ratios greater than 1.5. The relation of the conversion coefficient of nitrogen oxide to gas temperature is an increasing function. Large conversion coefficients of nitrogen oxide are obtained for temperatures greater than 400 °C.

The proposed method of studying the conversion coefficient of unitary substance emission was tested on the example of the reduction of nitrogen oxide. Silver aluminate was used as a catalyst.

The method is effective and sensitive to variables characteristic of the process of converting exhaust gases and the parameters of engine work.

The developed method of exhaust gases conversion studies allows estimation of the influence of catalytic reactor properties on ecological properties of engines in qualification studies of combustion engines.

LIST OF SYMBOLS

e — unitary substance emission

e_{av} — average unitary substance emission in a static combustion engine test

e_{av0} — average unitary substance emission in a static combustion engine test for non-purified exhaust gases

e_{av1} — average unitary substance emission in a static combustion engine test for purified exhaust gases

E — intensity of substance emission

$\mathbf{E}$ — p-elements vector of substance emission intensity in phases of a static test

$\mathbf{E}_0$ — p-elements vector of substance emission intensity in phases of a static combustion engine test for non-purified exhaust gases

$\mathbf{E}_1$ — p-elements vector of substance emission intensity in phases of a static combustion engine test for purified exhaust gases

i — phase number in static combustion engine test points
k — substance concentration conversion coefficient when the catalytic reactor is being used
k — p-elements vector of substance concentration conversion coefficient in phases of a static combustion engine test
$\mathbf{k}_p$ — w-elements vector of substance concentration conversion coefficients in laboratory studies
K — unitary emission conversion coefficient of substance contents in exhaust gases in a static combustion engine test
K_{min} — unitary emission conversion coefficient of substance contents in exhaust gases in a static combustion engine test corresponding to the minimum of conversion coefficient with respect to average temperature of exhaust gases in the catalytic reactor
K_{max} — unitary emission conversion coefficient of substance contents in exhaust gases in a static combustion engine test corresponding to the maximum conversion coefficient with respect to average temperature of exhaust gases in the catalytic reactor
M_e — torque
m — substance emission
n — engine speed
n — p-elements vector of engine speed in phases of a static combustion engine test
N_e — useful power of an engine
$\mathbf{N}_e$ — p-elements vector of useful power of a combustion engine in phases of a static test
p — number of work phases of a static combustion engine test
Q — flow rate
Q — p-elements vector of exhaust gases flow rates in phases of a static combustion engine test
r — ratio of volumetric propene concentration to nitrogen oxide volumetric concentration in exhaust gases before purification
r — w_r-elements vector of ratios of volumetric propene concentration to nitrogen oxide concentration before purification
S — volumetric concentration of substance in exhaust gases
S_0 — volumetric concentration of substance in exhaust gases before purification
$\mathbf{S}_0$ — p-elements vector of substance volumetric concentration in exhaust gases before purification
S_1 — volumetric concentration of substance in exhaust gases after purification

$\mathbf{S}_1$ — p-elements vector of substance volumetric concentration in exhaust gases after purification
S_{NO} — volumetric concentration of nitrogen oxide in the synthetic mixture
$\mathbf{S}_{NO}$ — w_n-elements vector of nitrogen oxide volumetric concentration in the synthetic mixture
S_p — volumetric concentration of propene in the synthetic mixture
$\mathbf{S}_p$ — w_p-elements vector of propene volumetric concentration in the synthetic mixture
S_r — volumetric concentration of reductant in exhaust gases
t — time
T — average exhaust gases temperature in the catalytic reactor
T — p-elements vector of average exhaust gases temperature in the catalytic reactor in the points of engine static test phases
T_g — temperature of the synthetic mixture
$\mathbf{T}_g$ — w_t-elements vector of the synthetic gas mixture temperature
u — p-elements vector of the contribution of work time in phases of a static combustion engine test
w — number of independent variables in laboratory studies of the catalytic reactor
w_r — dimensions of the vector of propene to nitrogen oxide concentration ratio before purification
w_n — dimensions of $\mathbf{S}_{NO}$ vector of volumetric concentration of nitrogen oxide in the synthetic mixture of gases
w_t — dimensions of vector of temperature of the synthetic gases mixture
η_v — volumetric efficiency
$\boldsymbol{\eta}_v$ — p-elements vector of volumetric efficiency in phases of a static combustion engine test

REFERENCES

AVL Consulting and Information. (1999). *Current and future exhaust emission legislation*. Graz, Austria: AVL List.

Chłopek, Z. (1999). *Modelowanie procesów emisji spalin w warunkach eksploatacji trakcyjnej silników spalinowych* [The modelling of exhaust emissions in conditions of traction exploitation of internal combustion engines] (Prace Naukowe. Series: Mechanika, No. 173). Warsaw, Poland: Oficyna Wydawnicza Politechniki Warszawskiej.

Cornetti, G.M., Klein, K., Fränkle, G.J., & Stein, H.J. (1988). *US transient cycle versus ECE R49 mode cycle* (SAE Paper No. 880715). Warrendale, PA, USA: Society of Automotive Engineers (SAE).

Darkowski, A., & Kruczyński, S. (2000). Properties of silver catalyst for nitrogen oxides reduction in exhaust gases at oxygen presence. *Polish Journal of Environmental Studies, 9*(Suppl. I), 27–30.

Fränkle, G., & Stein, H.J. (1988). Instationäre oder stationäre Abgasprüfverfahren für Nutzfahrzeug-Dieselmotoren [Nonstationary or stationary exhaust gases measurment technique for light duty diesel engines]. In *8. Internationales Motorensymposium* (VDI Fortschritt Berichte, Series 12, No. 86; pp. 1–34). Düsseldorf, Germany: Verein Deutscher Ingenieure (VDI) Verlag.

International Organization for Standardization (ISO). (1996). *Reciprocating internal combustion engines—Exhaust emission measurement—Part 4: Test cycles for different engine applications* (Standard No. ISO 8178-4:1996). Geneva, Switzerland: Author.

Merkisz, J. (1994). *Wpływ motoryzacji na skażenie środowiska naturalnego* [The influence of motorization on natural environment pollution]. Poznań, Poland: Wydawnictwo Politechniki Poznańskiej.

Merkisz, J. (1998). *Ekologiczne problemy silników spalinowych* [Ecological problems of combustion engines]. Poznań, Poland: Wydawnictwo Politechniki Poznańskiej.

Merkisz, J., & Chłopek, Z. (1999). Metody kontrolnych badań silników spalinowych obowiązujące w Polsce ze względu na emisję zanieczyszczeń [Inspection methods of combustion engines (obligatory in Poland) in respect to pollution emission]. In J. Pasynkiewicz (Ed.), *Konferencja Naukowo-Techniczna "Ograniczenie niskich emisji w dużych aglomeracjach miejskich"* (pp. 47–57). Warsaw, Poland: Polskie Towarzystwo Inżynierii Ekologicznej.

Moser, F.X., Haas, E., & Schlögl, H. (1989). Die Partikel-Hürde U.S. 1991: Vergleich der Testverfahren für Nutzfahrzeugmotoren—Bewältigung mittels innermotorischer Maßnahmen [1991 US limitation of particulates: comparison of tests for light duty engines—overwhelmed by means of inside engine methods]. In H.P. Lenz (Ed.), *10. Internationales Wiener Symposium* (VDI Forschritt Berichte, Series 12, No. 122; pp. 270–295). Düsseldorf, Germany: Verein Deutscher Ingenieure (VDI) Verlag.

Society of Automotive Engineers (SAE). (1993). *Test procedure for the measurement of gaseous exhaust emissions from small utility engines* (SAE Recommended Practice SAE No. J1088). Warrendale, PA, USA: Author.

Shannon, R.D., Rogers, D., & Prewitt, C. (1971). Chemistry of noble metal oxides. Syntheses and properties of ABO_2 delafossite compounds. *Organic Chemistry*, *10*(4), 713–718.

United Nations Economic Commission for Europe (UN/ECE). (2000). *Uniform provisions concerning the approval of compression-ignition (C.I.) and natural gas (NG) engines as well as positive-ignition (P.I.) engines fuelled with liquefied petroleum gas (LPG) and vehicles equipped with C.I. and NG engines and P.I. engines fuelled with LPG, with regard to the emissions of pollutants by the engine* (ECE Regulation No. 49). Geneva, Switzerland: Author.

United Nations Economic Commission for Europe (UN/ECE). (2001). *Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements* (ECE Regulation No. 83). Geneva, Switzerland: Author.

Wachter, W., & Cartellieri, W. (1987). Wege zur Erfüllung zukünftiger Emissionsgrenzwerte bei LKW Dieselmotoren [Obtaining future emission limits by heavy duty diesel engines]. In H.P. Lenz (Ed.), *8. Internationales Motorensymposium* (VDI Fortschritt Berichte, Series 12, No. 86; pp. 206–239). Düsseldorf, Germany: Verein Deutscher Ingenieure (VDI) Verlag.

Walsh, M.P. (1997). *Global trends in diesel emission control—A 1997 update* (SAE Paper No. 970179). Warrendale, PA, USA: Society of Automotive Engineers (SAE).