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Mobile system for on-road measurements of air pollutants

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The paper presents a prototype of a mobile monitoring system for measuring the levels of the main traffic air pollutants (C_6H_6, NO_2, NO_x, CO, and CO_2,) in cities. The novelty of the proposed system lies in the fact that it can be utilized to monitor emissions from urban traffic along roads and areas where traditional monitoring stations cannot be placed. In the proposed system, the monitoring device can be mounted on any moving vehicle (such as a car, bus, or truck) rather than be attached to a dedicated van, as most systems of this kind found in literature are. Analyzers used in this system are small portable structures that contain an electronic instrument to measure, record, and transmit relevant data on concentrations of the pollutants to a website. The model outcome for carbon monoxide obtained in functional tests in real conditions is also presented here. Data on temporal changes of carbon monoxide concentration are compared against meteorological parameters and speed of the vehicle. Spatial interpolation techniques are applied to obtain a nonplanar visualization of carbon monoxide and benzene concentrations in the main arteries of a city. © *2010 American Institute of Physics.* [doi:10.1063/1.3356076]

I. INTRODUCTION

Most of the existing automatic and manual systems monitoring gaseous pollutants in atmospheric air and ambient aerosols usually perform stationary measurements, i.e., they are connected directly to a specific point or space in the vicinity of that point.[1] Basing on data obtained from a single monitoring site, it is not possible to assess spatial and temporal variations in concentrations of air pollutants. Experimental results published in the past decade[2–9] have confirmed reliability of mobile systems in obtaining information about spatial and temporal distribution of atmospheric trace gases, without the need to construct a complex network of stationary stations. Most of the described systems involve application of mobile laboratories[2–4] equipped with appropriate monitors. In the system proposed here, measurements of pollution are carried out among moving vehicles with the aid of a unit that can be installed on any vehicle rather than be attached to a dedicated van.

The prototype of the monitoring system consists of an original device, further called ARPOL (the acronym stems from ARMAAG—Agency of Regional Monitoring of the Atmosphere of Gdańsk Agglomeration, and Gdańsk POLytechnic), designed to measure in motion concentrations of C_6H_6, NO_2, NO_x, CO, and CO_2 in atmospheric air. The device can be installed on any mobile vehicle such as a bus or taxi. It relays the results to a server, which acts as a database, along with information on the vehicle location and speed, as well as the temperature and humidity of the air at the measurement spot. Transmission of the data between the device and the server is accomplished with a radio modem operating in GSM/GPRS (Global System for Mobile Communication/General Packet Radio Service) systems.

II. EXPERIMENTAL SETUP

A. Description of the ARPOL monitoring unit

The ARPOL monitoring station has been developed and constructed in the laboratory of the Department of Radiocommunication Systems and Networks at Gdańsk University of Technology.[10,11] The set of commercially available gas concentration sensors has been selected by researchers from the Chemical Faculty of Gdańsk University of Technology and the ARMAAG Foundation.[10,11] The system has been constructed in accordance with the sensors requirements and their anticipated application.[12] It has been decided to use advanced semiconductor (thick-film) sensors made of nanostructures with grain-size distribution from 30 to 50 nm. After preliminary investigations, the following sensors were chosen: TGS2442 for CO, TGS4161 for CO_2, TGS823 for benzene, TGS2106 for NO_2, and TGS2201 for NO_x (all manufactured by Figaro Engineering Inc., Osaka, Japan). Some of them are designed to measure gases in ppm (parts per million, 10^{-6}) concentrations, while the concentration of NO_x, CO, or C_6H_6 in typical air conditions is in the range of ppb (parts per billion, 10^{-9}). However, comparison of the measurement results collected for several months proved that after proper calibration and compensation of air temperature and humidity, the sensors were stable and precise enough to determine the sources and regions of the highest pollution caused by road traffic.

All the gas concentration sensors are heated by internal heaters that act as substrates for the sensing structure. The

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substrate temperature cannot be controlled as no temperature sensor is built into the substrate of the gas-sensing element. The substrate temperature change caused by change of temperature of air flowing around the sensor can be corrected with an additional semiconductor sensor and appropriate calibration equations. Proper heating of the sensors takes up to several tens of minutes. Measurements taken during this time cannot be considered reliable. A cut in powering the sensors also makes the results unstable for up to several minutes. Therefore, uninterrupted heating of the sensors needs to be maintained throughout the measurement campaign. Special electronic circuits built into the sensors ensure high sensitivity and high accuracy of the measurements.

In the design of the ARPOL unit a microcontroller of the AtMega series (Atmel Corporation, San Jose, USA) with built-in analog-to-digital converters has been used. The microcontroller circuit has been connected to a ready-made GSM/GPRS modem board (Enfora, Richardson, USA) and a GPS signal receiver (Trimble Navigation Ltd., Sunnyvale, USA), as well as to a RS232 series interface (RS232 signal converter based on Maxim chip, Maxim Integrated Products Inc., Sunnyvale, USA) and additional supply circuits. The main board has also been provided with a connector for attaching more sensors, not included in the original design, transoptor circuits, and actuators, which facilitate application of control signals.

To ensure the highest resistance of the device to shock, it was decided that the whole electronic circuitry of the main part of ARPOL will be assembled on one printed board. As some parts of the device (power supply circuits in particular) may heat up during standard operation, it has been decided to place all the chemical sensors and the external temperature and air humidity sensors on one edge of the main board so that the microprocessor part with the power supply would be separated from the sensors with an appropriate dividing partition.

Thus the device has been enclosed in a housing that protects the system from precipitation, while simultaneously allowing access of atmospheric air to the gas concentration, temperature, and humidity sensors. The housing facilitates mounting the unit both in cars and at selected stationary points in town. The sensors have been enclosed in a plastic channel with an air in and out outlet and additionally provided with special "roofs" for protection from rain. In order to reduce the effect of exhaust gas of the engine, the unit possesses a forced sampling system opened toward the direction of driving. To ensure a smooth air flow, a blower with revolution control has been placed in the channel. The blower's failure or decline in its efficiency resulting in reduced air flow in the measurement channel is registered by a microcontroller as an alarm state. A view of the ARPOL unit mounted on the roof of an ARMAAG Foundation car is presented in Fig. 1, whereas Fig. 2 shows the block diagram of the unit.

B. Description of the mobile monitoring system operation

A schematic description of the mobile monitoring system operation to test and analyze atmospheric air pollution along traffic arteries is presented in Fig. 3. This system consists of an ARPOL unit mounted on a vehicle and a server on which the database for collection and processing the measurement data has been established. The concentration values of the chemical compounds polluting the atmosphere are transmitted via radio, the mobile GSM/GPRS network and the Internet network to a server located at any place, e.g., at Gdańsk University of Technology (Gdańsk Polytechnic). There, the data are processed and verified as to their credibility. Subsequently, they are sorted according to the measurement date and, if needed, displayed on the monitor of an authorized user by a web browser.

FIG. 1. ARPOL unit mounted on the roof of a car.

To achieve simplicity of the monitoring system operation, configuration of the ARPOL unit and the server is kept to a minimum. This means that the system can be implemented on a wide range of servers.

The proposed monitoring unit can be described as maintenance-free. A properly configured and set up monitoring station can operate for several months without intervention. Information about the state of the device and possible errors in its functioning or problems with data collection is sent to a respective person in a text message.

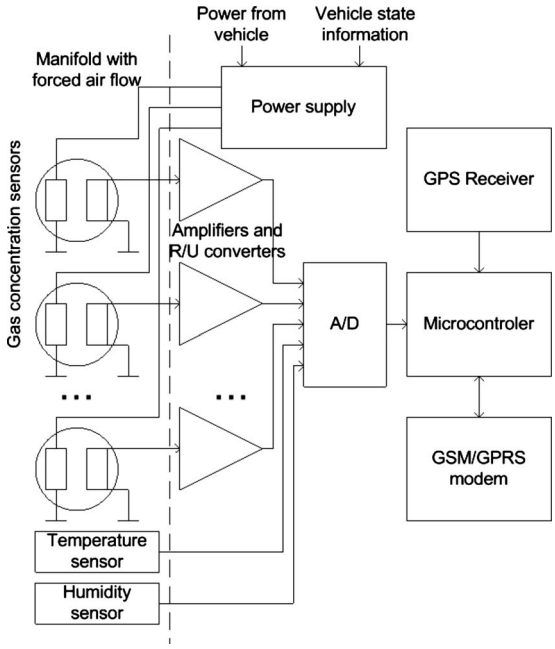

FIG. 2. Block diagram of mobile monitoring unit

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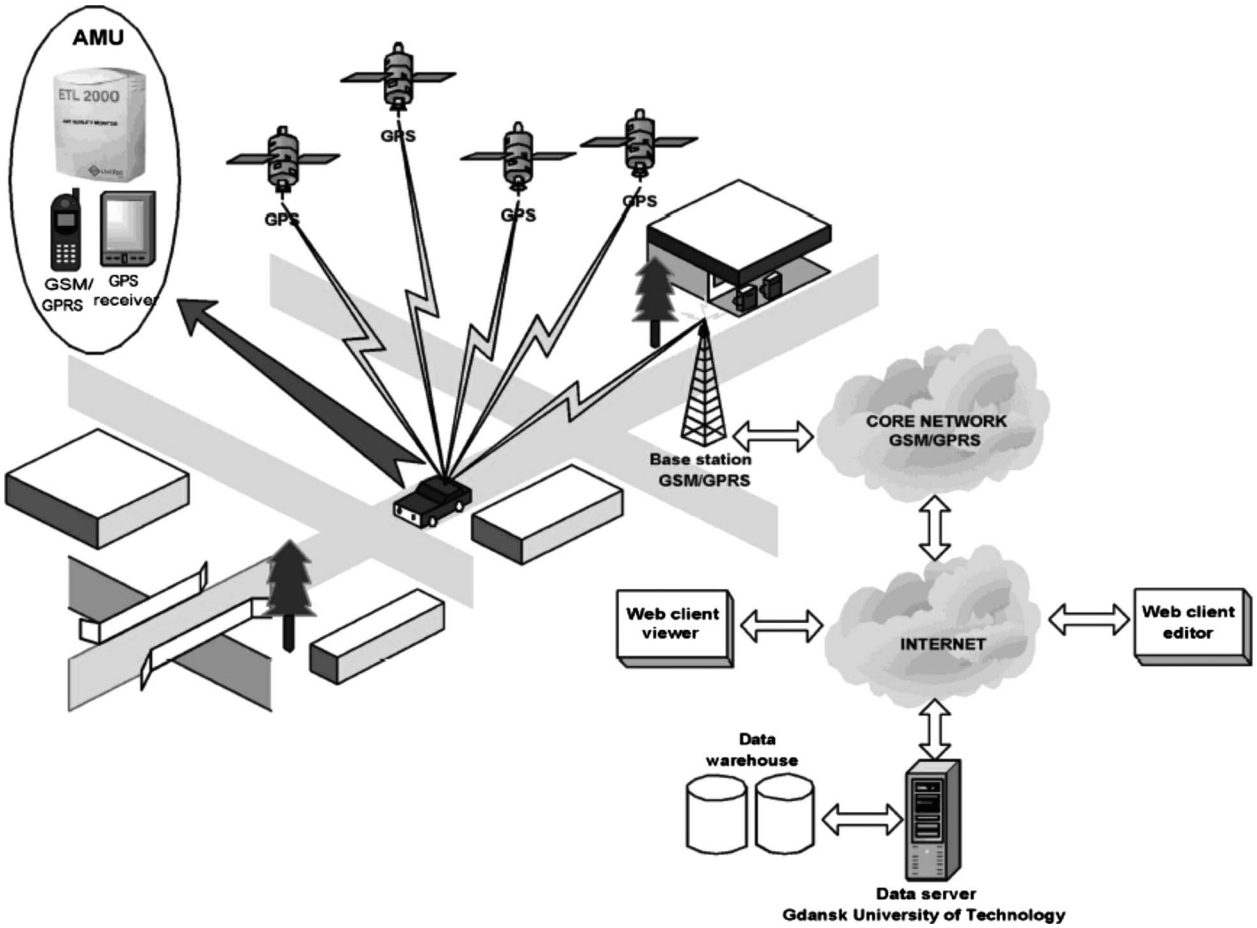

FIG. 3. Schematic diagram of the operation of the mobile monitoring system for testing and analyzing gaseous pollution of atmospheric air along traffic arteries (Ref. 12).

III. RESULTS AND DISCUSSION

A. Functional tests of proper ARPOL operation in real conditions

After developing the ARPOL unit, tests of equivalence of the used measurement method with the results of reference analyzers from an automatic monitoring station were carried out. The station is part of the network belonging to the Agency of Regional Monitoring of the Atmosphere in the municipality of Gdańsk. All the monitoring units built in the laboratories of Gdańsk University of Technology were installed in fixed monitoring stations. For several weeks, data obtained from the units were compared with precise gas concentrations measured using reference methods.

As a result, equations and values of coefficients to convert values of the electrical signals from the sensors to concentration of the measured gases in the air were derived. For example, the concentration of NO_x can be calculated from resistance of one of the tested TGS2201 sensors using the equation:

$$NO_x[\mu g/m^3] = -1.3 \cdot \text{temp}[^\circ C] - 0.25 \cdot \text{hum}[\%] - 1.76 \times 10^{-5} \cdot R_{TGS2201}[\Omega] + 78.8 \quad (1)$$

and to calculate the concentration of C_6H_6 the following equation is required:

$$C_6H_6[\mu g/m^3] = 10^{-2.8\cdot\log_{10}(R_{TGS823}[\Omega])-0.63\cdot\log_{10}(\text{temp}[^\circ C])-0.23\cdot\log_{10}(\text{hum}[\%])+15.3}. \quad (2)$$

In general, these equations are nonlinear and, additionally, the value of ppb concentrations makes the discrepancy between the characteristics of different sensors significant. This means that each mobile monitoring unit must pass a separate measurement calibration procedure in a special calibration chamber with precisely calculated concentrations of selected gases. The equipment calibration cost is the largest part of the total cost of the whole mobile monitoring system. Almost

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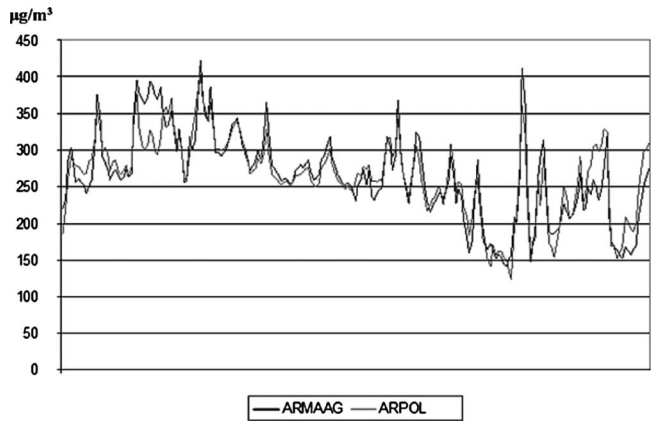

FIG. 4. Comparison of carbon monoxide concentration ($\mu g/m^3$) after introducing a corrective equation.

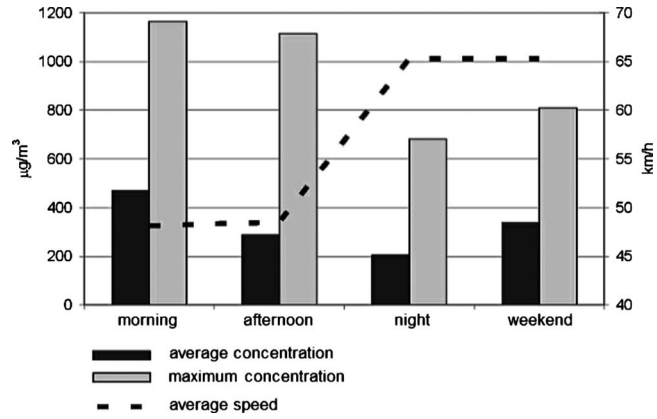

FIG. 5. Concentration of carbon monoxide depending on the time of day and week, as well as on the vehicle speed along a selected section of the bypass of Gdynia, Sopot, and Gdańsk.

all the electronic components and sensors are inexpensive and the electronic circuit assembly procedure is rather simple.

A model comparison of carbon monoxide concentration after correction from an ARPOL measurement series and a reference analyzer from the network of the ARMAAG Foundation is shown in Fig. 4.

The measurements from the ARMAAG Foundation network conform to PN EN IEC/ISO17025:2005 standards. The monitoring stations collect data basing on standard transmission protocols and the data are stored in Round Robin Database repositorium. The candidate method for automatic measurements is based on reference methodologies. The equivalence tests were performed before each measurement campaign.

B. Collection of measurement data along selected traffic arteries

The research on ambient concentration of substances emitted by vehicles traveling along selected roads has been performed using the ARPOL monitoring station, mounted on the roof of a Cinquecento van belonging to the ARMAAG Foundation. The measurement campaign consisted of

- measuring carbon monoxide, nitrogen oxide, nitrogen dioxide, benzene, and carbon dioxide concentrations;
- locating the van by means of GPS;
- measuring the vehicle speed; and
- measuring external air temperature and humidity.

The measurements were taken on a selected section of the bypass of Gdynia, Sopot, and Gdańsk, and on a section of the motorway A1 between Gdańsk and Tczew. The tests revealed that the unit was not affected by the car exhaust fumes. Model values of carbon monoxide concentrations depending on the time of day and week, as well as on the vehicle speed on the selected section of the bypass are shown in Fig. 5.

C. Spatial visualization of measurement results

Air pollution measurements are carried out predominantly in a stationary way at selected points in towns representative of a larger region: some stations are background (located among buildings, slightly separated from larger traffic arteries) and some of them are situated close to larger traffic arteries. It is difficult to determine concentration values for the whole city area using data from only a few measuring stations. The designed system performing measurements in motion facilitates testing air pollutants concentrations at any spot along road arteries. The results are presented with the aid of the Geographic Information Systems (GIS) software.

Further analyses of the collected data were carried out using spatial interpolation, which is one of the most important calculation methods in geographic information systems. The data processing was performed using the method of inverse distances (inverse distance weighting). In this case, the value of the variable at the interpolation point is calculated as the weighted average from the values of the surrounding measurement points. This method, called a local method, employs the principle of spatial autocorrelation. It is assumed that the greatest effect upon the estimated value comes from the points located nearest the interpolation point. The method depicts local differentiation of the interpolated area. By calculating the weighted average, it is assumed that the weight value is inversely proportional to the distance between the interpolated point and the point of a given value. In effect, the smaller the influence of a given measurement point on the value of the interpolated point is, the farther the given measurement point is from the interpolated point.

Considering the method of spatial visualization of collected measurement results described above, model distributions of CO and benzene concentrations along the bypass of Gdańsk, Sopot, and Gdynia are presented in Figs. 6 and 7.

IV. CONCLUSIONS

A prototype of a mobile measuring unit called ARPOL, unique on the national scale, has been developed for testing atmospheric air pollution along traffic arteries. The equipment has been subjected to extensive functional and metrological analysis in real conditions. First and foremost, suitability of the employed sensors for pollution measurements in motion has been confirmed by performing indispensable

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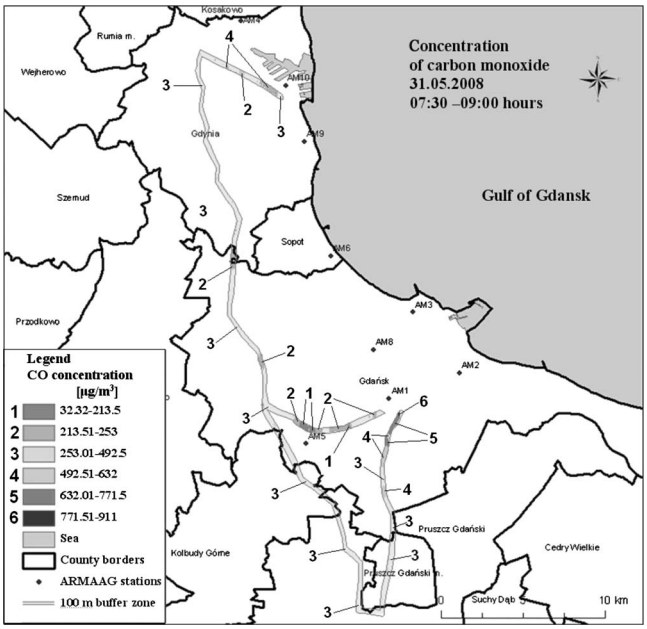

FIG. 6. Model emission concentration of carbon monoxide along the bypass of Gdańsk, Sopot, and Gdynia.

equivalence tests. Subsequently, a series of mobile measurements and a series of stationary measurements, each involving several 24 h cycles, have been carried out. The volume and structure of traffic have also been considered.

The developed device forms part of an expert system that undoubtedly contributes to the enhancement of ecological safety in a given area. It may be a cheap and useful tool

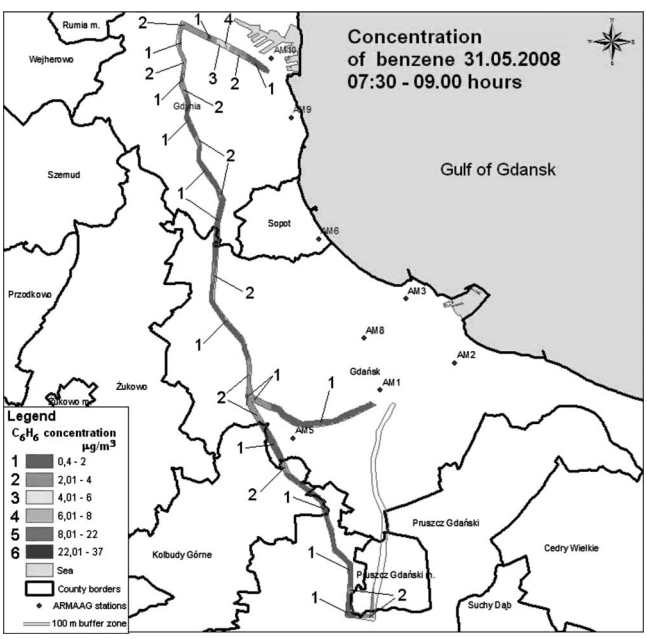

FIG. 7. Model emission concentration of benzene along the bypass of Gdańsk, Sopot, and Gdynia.

(considering low investment and exploitation costs) for assessing ecological effects of new efforts for limiting pollutants emissions rather than for assessment of air quality. It contributes to more careful environmental planning by extending the measurement basis with information from nonstationary sources.

According to existing law, member countries of the European Union are obliged to carry out measurements of atmospheric air cleanness and to introduce preventive measures against excessive pollution exceeding allowable threshold limits. To meet these obligations, the member countries are required to prepare inventories of zones and agglomerates where transgression of limiting norms occurs, and to prepare and introduce plans and programs how to adhere to the parameters required by law. Thus the mobile monitoring system described here can upgrade the existing system of measuring atmospheric air cleanness and facilitate taking appropriate decisions through analysis of various emission scenarios. In 2008, the prototype of the ARPOL unit won the award of the Marshal of Pomorskie Voivodeship in the category "Environmental protection and ecology" during the Fourth Fair of Industrial Engineering, Science, and Innovation in Gdansk.

ACKNOWLEDGMENTS

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[1] J. Namieśnik and W. Wardencki, Polish Journal of Environmental Studies **11**, 211 (2002).
[2] N. Bukowiecki, J. Dommen, A. S. H. Prevot, R. Richter, E. Weingartner, and U. Baltensperger, Atmos. Environ. **36**, 5569 (2002).
[3] L. Pirjola, H. Parviainen, T. Hussein, A. Valli, K. Hameri, P. Aaalto, A. Virtanen, J. Keskinen, T. A. Pakkanen, T. Makela, and R. E. Hillamo, Atmos. Environ. **38**, 3625 (2004).
[4] P. W. Seakins, D. L. Lansley, A. Hodgson, N. Huntley, and F. Pope, Atmos. Environ. **36**, 1247 (2002).
[5] F. Gouriou, J.-P. Morin, and M.-E. Weill, Atmos. Environ. **38**, 2831 (2004).
[6] D. Kittelson, J. Johnson, W. Watts, Q. Wei, M. Drayton, P. Paulsen, and N. Bukowiecki, SAE Technical Paper 2000-01-2212, 2000.
[7] H. Bogo, R. M. Negri, and E. San Roman, Atmos. Environ. **33**, 2587 (1999).
[8] M. Roosli, C. Braun-Fahrlander, N. Kunzli, L. Oglesby, G. Theis, M. Camenzind, P. Mathys, and J. Staehelin, J. Air Waste Manage. Assoc. **50**, 1115 (2000).
[9] B. Wehner, U. Uhrner, S. von Löwis, M. Zallinger, and A. Wiedensohler, Atmos. Environ. **43**, 1235 (2009).
[10] R. Katulski, J. Stefański, W. Wardencki, and J. Żurek, Proceedings of the IEEE Conference on Technologies for Homeland Security—Enhancing Transportation Security and Efficiency, 7–8 June 2006, Boston, USA, pp. 181–184.
[11] R. Katulski, J. Stefański, W. Wardencki, and J. Żurek, Proceedings of the Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy PITTCON'2007, 25 February–2 March, 2007, Chicago, USA.
[12] W. Wardencki, R. Katulski, J. Stefański, and J. Namieśnik, Crit. Rev. Anal. Chem. **38**, 259 (2008).

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