Classification of Air Quality Inside Car Cabin using Sensor System

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Keywords: Indoor Air Quality, Gas Sensor, Classification.

Abstract: Daily practice, but also research, show that poor indoor air quality (IAQ) is a serious problem in many vehicles. In this work we present an approach to the evaluation of air quality in car cabin. It consists in IAQ classification. We focussed on defining classes in a way which may be useful for improving air quality during a trip. In order to assure the provision of objective information, IAQ classes are specified with reference to measurable parameters of indoor air. The parameters: temperature, relative humidity, CO_2 concentration and VOC content indicator are considered jointly. Class assignment is realized on a software level, based on the measurement data provided by the sensor module located inside car cabin. The final announcement received by the driver refers to the class of indoor air. It informs about: thermal conditions, air humidity and air freshness. These components correspond to the capabilities of air handling system in the car and they were included in the message to provide hints for improving air quality. The information is delivered in real time. We believe, the implementation of the presented approach will contribute to the improvement of car microenvironment upon driving.

1 INTRODUCTION

It is estimated that over 1 billion passenger cars travel the streets and roads of the world today. In modern countries, people spend approximately 90 minutes in confined spaces of their cars, each day. During this time, many factors affect comfort, safety and health of drivers and passengers. Research has shown that particulate matter and harmful substances can be up to six times more concentrated inside a vehicle than outside.

Human experiences car microenvironment mainly via air quality, thermal conditions, noise level and vibration. Air quality is a term which describes the physical, chemical and biological state of indoor air at some place and time. Usually it is characterized by physical and chemical parameters such as temperature (T), relative humidity (RH), airflows and concentration of characteristic pollutants. Research and practice show that poor indoor air quality is a serious problem in many vehicles (Müller et al., 2011). For example, inside vehicle cabins concentrations of air pollutants such as: carbon monoxide (CO), hydrocarbons (HC), volatile organic compounds (VOC), and oxides of nitrogen (NO_x) are very often higher than safety limits set by Occupational Safety and Health Administration (OSHA) and World Health Organization (WHO). Especially in new car's interiors the levels of airborne chemicals are significantly higher than recommended for indoor environments today (Fedoruk&Kerger, 2003). Another problem is a discomfort experienced due to offensive smells and inadequate temperature or humidity.

Currently, conditions inside car cabins may be improved by windows opening or the correct use of heat, ventilation and air conditioning (HVAC) system (manual or automated). There are also available portable air purifiers. The effectiveness of these methods is strongly dependent on the evaluation of indoor air quality by the drivers or passengers (Blashke et al., 2006). Traditionally it is based on stimuli which come from the environment and are perceived by human senses. This method is simple and cheap. Unfortunately, human sensation poses a number of problems when used as a source of information. Perception of physical and chemical conditions alters over time and varies among people. It is prone to bias, fatigue as well as the attention drift. For this reason, the most reliable evaluation of cabin microenvironment is based on measurements

Szczurek A. and Maciejewska M..
Classification of Air Quality Inside Car Cabin using Sensor System.
DOI: 10.5220/0005225802110219
In *Proceedings of the 4th International Conference on Sensor Networks* (SENSORNETS-2015), pages 211-219
ISBN: 978-989-758-086-4

of parameters describing indoor air quality. It should be noted that the concern for the vehicles interior air quality is focused on (Galatsi&Wlodarski, 2006):

- indoor temperature and relative humidity;
- air pollutants entering the vehicle via the ventilation system;
- lack of fresh airflow resulting in low O_2 and high CO_2 concentrations due to occupants breathing process;
- pollutant gases entering from the external environment via window openings, imperfect seals and other holes;
- toxic gases entering the vehicle cabin due to redirected exhaust fumes.

Nowadays, there is no system or aftermarket product designed to control thermal and chemical conditions in vehicles in a comprehensive manner. There are available sensors to measure temperature and relative humidity. Regarding more advanced proposals, currently there exist only two commercial air quality monitoring (AQM) solutions for cars. The most common are AQM systems controlling HVAC ventilation flaps. The air quality sensors are typically, located near the fresh air inlet, and not inside car cabin. Their function is limited to reducing the amount of pollution entering the vehicle cabin through the HVAC system when the vehicle enters a highly polluted area. Less common are aftermarket toxic gas alarms for vehicle cabin applications. Cars evolution as well as research and development dedicated to comfort improvement are responsible for the fact that around 10 % of the produced cars are currently equipped with Air Quality Sensors (AQS). Road test done by car manufacturers, involving in/out car cabin analysers, revealed more than 80 % reduction of pollution peaks caused by the air entering the cabin (http, 2013).

The interior of a vehicle may be regarded as a specific microenvironment. Many different factors, either individually or in combination, influence car interior. Hence, the quality of this gas should be characterized by several parameters. Currently, it is not a problem to measure/monitor physical and chemical properties of air inside the vehicle cabin, in real time. The problem is the simultaneous and quick analysis of multivariate measurement data which would extract a comprehensive information about indoor air quality. This operation may be complicated. It requires some knowledge and cannot be performed by the drivers during a trip. Their involvement might elevate the likelihood of collision or other road fatalities. For that reason, we propose an approach which is based on the idea of a collective classification of air quality using a sensor measurement system.

Generally speaking, classification is a systematic arrangement in categories (classes) according to the established criteria. In our work, we propose the collective categorization of air quality inside car cabin. In other words the properties of this gas are recognized i.e. assigned to a class, which is characterized descriptively. In this way, there is provided a concise information and the driver can make decisions how to improve air quality very quickly and safely.

The aim of this work is to propose a method of air quality classification. On this basis, we want to show that classification of indoor air may be used to improve car microenvironment. We assume that the classification procedure should be an element of a sensor measurement system. Due to fact that these devices are relatively cheap the proposed method may be widely applied.

2 ASSUMPTIONS

In this work we made several assumptions concerning:

- target user of the sensor system for indoor air quality classification ;
- subject of the evaluation;
- basis for IAQ classification;
- principle of IAQ classification;
- form of the final result.

The sensor system for air quality classification inside car cabin is addressed to drivers as well as passengers. Currently, they are most obvious target users of this type of measurement equipment. However, we assume that the idea of air quality classification may be utilized in automatic systems for heating, ventilation and air conditioning as well.

The subject of evaluation is the quality of air in a selected location inside the cabin of a vehicle. More specifically, it may be the surrounding of the driver or the passenger. We chose the perspective of local IAQ classification in order to be able to account for the comfort of the driver and passengers individually. People differently influence the quality of air around them. It is due to: various level of personal hygiene, health condition, metabolism rate, sweating intensity, etc. On the other hand, the sensitivity of various people to changes in air quality is also different. It may depend on age and sex, but not exclusively. As a consequence, satisfaction of

Table 1: Ranges of measured parameters utilized for determining IAQ class in car interior.

Indoor air parameter	Range 1	Range 2	Range 3
Temperature [C]	t ≤ 24	24 < t ≤ 27	t > 27
Relative humidity [%]	t ≤ 30	30 < RH ≤ 50	RH > 50
CO_2 concentration [ppm]	$[CO_2] \leq 600$	$600 < [CO_2] \leq 1000$	$[CO_2] > 1000$
IAQ sensor response $R_{VOC}=(R-R_0)/R_0$ [-]	$R_{VOC} \leq 0.33$	$0.33 < R_{VOC} \leq 1.22$	$R_{VOC} > 1.22$

Table 2: Terms used for describing three major aspects of IAQ in car interior.

IAQ coordinates	Term 1	Term 2	Term 3
Thermal comfort	too cold	appropriate	too warm
Air humidity	dry	appropriate	too humid
Air freshness	fresh air	bad air	very bad air

everybody in the car may be difficult to achieve. Therefore in our concept, indoor air quality is evaluated locally. But, one may choose various locations to focus on them.

The classification of IAQ is based on measurements of selected indoor air parameters. We propose to monitor: temperature, relative humidity, CO_2 concentration and an indicator of VOCs content in air. These quantities contain complementary information, which may be combined, leading to a concise classification of indoor air quality. The first two parameters allow to determine thermal comfort in a given place inside car. Their usefulness is undisputable. Additionally, we propose to take into account the chemical aspect of air quality. For this purpose there are considered CO_2 concentration and the indication of VOCs content in air. In principle, the first quantity is associated with human (also animal) metabolism. Upon human presence, CO_2 is always emitted to car cabin air. Although it is known that carbon dioxide at high concentrations impairs human performance, our bodies do not have an efficient detection mechanism. Regarding VOCs, their main sources inside car are: cabin materials (ISO 12219-2, ISO 12219-3, ISO 12219-4), humans (also animals and luggage) and the ambient air. It is known that materials used in cars change their characteristics when they are exposed to UV light from the sun or due to high temperature. For this reason, the concentration of potentially toxic chemicals in car interior depends on its temperature and the duration of exposure to sunlight. However, based on our experiments, when the car is driven, the dominant contribution of VOCs inside automobile cabin comes from the road traffic emission. Interestingly, the gradual elevation of VOCs inside car usually remains unnoticed by passengers. This may result from the olfactory adaptation. On the other hand, a limited number of VOCs delivered to car cabin are able to induce the olfactory sensation.

The proposed principle of IAQ classification was meant to assure the transformation of multivariate measurement data into a comprehensive information. The basis for establishing IAQ classes in car are the predefined ranges of values of individual indoor air parameters. They are shown in Table 1. When choosing the limit values for temperature and humidity we were guided by thermal comfort requirements for space category A (ASHRAE Standard 55-2013). In this case the operative dry-bulb temperature is 25.5 °C. The ± 1.5 °C interval around this value is widely considered as the summertime temperature comfort range. The min-max humidity range for space category A was defined as 30 % to 50 % (ASHRAE Standard 55-2013). Based on (ACGIH. 1998; Bright et al., 1992) we accepted that in case of CO_2, comfort conditions are maintained when its concentration is smaller than 600 ppm. In general, higher concentrations are unwelcomed and the exceedance of 1000 ppm is disadvantageous. Respectively, we assumed that IAQ sensor response smaller than 0.33 indicates comfort conditions regarding VOCs content in air. Higher values of the response, in particular those exceeding 1.22, point at the increasingly unfavourable surrounding. The quoted limit values are associated with a particular sensor type and they are based on our measurement experience.

In our approach, IAQ class is defined by describing three aspects: thermal conditions, air humidity and air freshness inside car cabin. The terms used for characterization are given in Table 2.

An individual IAQ class is identified by the set of three terms. The first accounts for the thermal conditions – the evaluation is based on temperature, the second term addresses air humidity – the assignment is based on relative humidity and the third one characterizes air freshness – the rating is based on CO_2 concentration and VOCs content in car interior.

The choice of the particular set of terms to determine air quality class is dependent on values of air parameters measured inside the cabin of the automobile (Table 2). Considering thermal conditions, *term 1* is used if air temperature belongs to range 1, *term 2* is applied when air temperature belongs to range 2, and similar with *term 3*. The same rule is applied to determine air humidity component of IAQ class, based on the measurement of relative humidity in car cabin. Regarding air freshness, *term 1* is used when both CO_2 concentration and IAQ sensor response belong to range 1. *Term 2* is applied when any of these parameters is in range 2. *Term 3* is employed if either CO_2 concentration or IAQ sensor response belongs to range 3. Altogether, in our approach there were distinguished 27 air quality classes. They are presented in detail in Table 3. Additionally, their arrangement in the space of IAQ coordinates is displayed in Fig. 1.

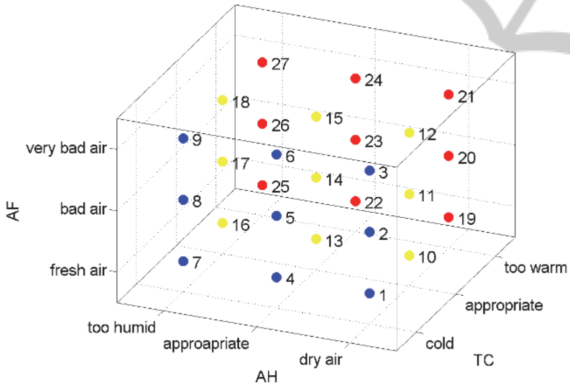

Figure 1: Arrangement of IAQ classes in the space of three coordinates: thermal comfort, air humidity and air freshness. Colours correspond to three levels of thermal comfort: cold, appropriate, too warm. Abbreviations: AF – air freshness, AH – air humidity, TC – thermal conditions.

IAQ class recognition is performed automatically by the dedicated software, based on the measurement data transmitted from the sensor module. Neither driver nor passengers are involved in the entire process. The user just receives the final result.

We proposed to announce IAQ class using the descriptive form. An example of information delivered to the user of the sensor system equipped with IAQ classification module is given in Fig. 2.

The form of descriptive communication of IAQ classes was chosen on purpose. It serves to provide the comprehensive information which is useful for maintaining proper air quality while driving.

Table 3: Description used to announce the air quality classes in car interior.

IAQ class	Thermal conditions	Air humidity	Air freshness
1	Cold	dry	fresh air
2	cold	dry	bad air
3	cold	dry	very bad air
4	cold	appropriate	fresh air
5	cold	appropriate	bad air
6	cold	appropriate	very bad air
7	cold	too humid	fresh air
8	cold	too humid	bad air
9	cold	too humid	very bad air
10	appropriate	dry	fresh air
11	appropriate	dry	bad air
12	appropriate	dry	very bad air
13	appropriate	appropriate	fresh air
14	appropriate	appropriate	bad air
15	appropriate	appropriate	very bad air
16	appropriate	too humid	fresh air
17	appropriate	too humid	bad air
18	appropriate	too humid	very bad air
19	too warm	dry	fresh air
20	too warm	dry	bad air
21	too warm	dry	very bad air
22	too warm	appropriate	fresh air
23	too warm	appropriate	bad air
24	too warm	appropriate	very bad air
25	too warm	too humid	fresh air
26	too warm	too humid	bad air
27	too warm	too humid	very bad air

Class of air quality

Thermal conditions:	**too warm**
Air humidity:	**appropriate**
Air freshness:	**bad air**

Figure 2: Example of IAQ class. The descriptive form used to announce the final result of classification.

Thermal conditions of car interior may be adjusted. The use of windows and the dedicated air handling system allows for heating and cooling. Air freshness is also under control. The regulation of intensity of ambient air delivery to car cabin has major contribution to this property of car interior. Although HVAC systems modify humidity, in cars they typically do not allow for its control. Nevertheless, we incorporated the information about humidity into IAQ class description. It may be very useful. For example, based on long-term observations that the air inside the car cabin tends to be permanently dry, one may decide to use a humidifier.

The information on IAQ class is provided in real time. The rate of update is limited exclusively by the time resolution of sensor measurements.

3 EXPERIMENTAL

The objective of the experiment was to record air parameters inside the cabin of a passenger car, during a trip.

Table 4: Measuring characteristics of devices based on various sensors, applied in measurements of air parameters inside car cabin.

Measured parameter	Measuring range	Accuracy	Resolution
Temperature	-20 – 60 °C	±0.2 °C ± 0.15 %MV	0.1 °C
Relative humidity	5 – 100 %RH	±2 % (10 – 90 %RH); ±2.5 % outside	0.1 %
CO_2 concentration	0 – 5000 ppm	±50 ppm + 3 %MV	1 ppm
IAQ sensor response	450 – 2000 ppm CO_2 equivalents	–	–

The following parameters were measured: temperature, relative humidity, carbon dioxide concentration and the indicator of total volatile organic compounds content in the air.

There were applied instruments based on various sensors: thermistor NTC 10Ω for temperature, capacitive sensor for relative humidity, non-dispersive infrared sensor for CO_2 and semiconductor gas sensor as IAQ sensor. The characteristics of these devices are presented in Table 4.

Because of the fact that indoor air parameters exhibit spatial dependence sensor devices were located in different places inside car cabin. There were examined spaces: in front of the driver's seat, ahead of the front seat passenger and ahead of the back seat passengers. During a trip measurements were carried out simultaneously in two selected locations.

The tests were performed in the summer. The car was driven in real traffic on the way from town A to B and back. One way single trip lasted for about 1h 20 min. The car was occupied by the driver and three passengers. They were asked to adjust air quality in car cabin according to their needs.

4 MEASUREMENT RESULTS

In Fig. 3 and Fig. 4 we show the data collected during air monitoring inside a traveling car. There are displayed time series of temperature, relative humidity, CO_2 concentration and IAQ sensor response recorded in different locations inside car cabin. In Fig. 3 we compare conditions in the immediate vicinity of driver's head and the back seat passenger's head. The surrounding of the front seat passenger and back seat passenger are characterized in Fig. 4. Data displayed in Fig. 3 and Fig. 4 were collected during different trips, but on the same rout.

Based on Fig. 3 and Fig. 4 indoor air parameters monitored in car cabin exhibited: temporal variation, spatial variation and parameter-specific behaviour. As shown in Fig. 3 and Fig. 4, all quantities exhibited considerable changes in time. Their values varied in a wide range, including extreme ones. The changes in time domain could be described as rapid. Spatial dependence of indoor air parameters in car cabin was also well pronounced. Usually, the values recorded in different locations were just shifted with respect to each other (Fig. 3d, Fig. 4d), but in some cases, distinct tendencies were observed. In particular, we noted that thermal conditions close to the driver's seat were very different compared with passenger's seat, see Fig. 3a,b. The comparison of simultaneously recorded distinct parameters of indoor air revealed that they behaved differently. There could be noticed some degree of correlation between temperature and humidity as well as between CO_2 concentration and VOC content indicator. Nevertheless, each of these quantities provided a great amount of distinct information on the conditions in car cabin.

Upon driving the air quality in car interior is under joint influence of many factors. The main ones are: car itself (interior materials, HVAC operation), human passengers, road traffic, passed land (its character) and meteorological conditions. The influence of individual factors is reflected in particular parameters of indoor air. Hence, the behaviour of individual parameters is distinct. The individual factors themselves exhibit temporal and spatial variations. Due to this property, they cause temporal changes of indoor air parameters as well as induce differences between distinct locations inside the vehicle cabin.

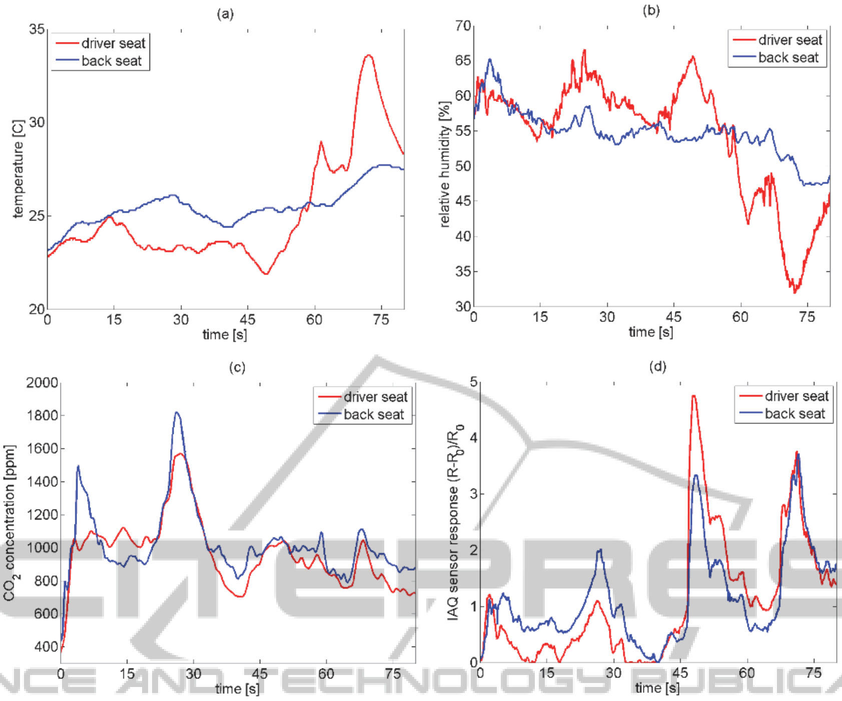

Figure 3: Results of indoor air parameters monitoring inside car cabin during a trip: a) temperature, b) relative humidity, c) CO_2 concentration, d) IAQ sensor response. Comparison between conditions in the immediate vicinity of driver's head and back seat passenger's head.

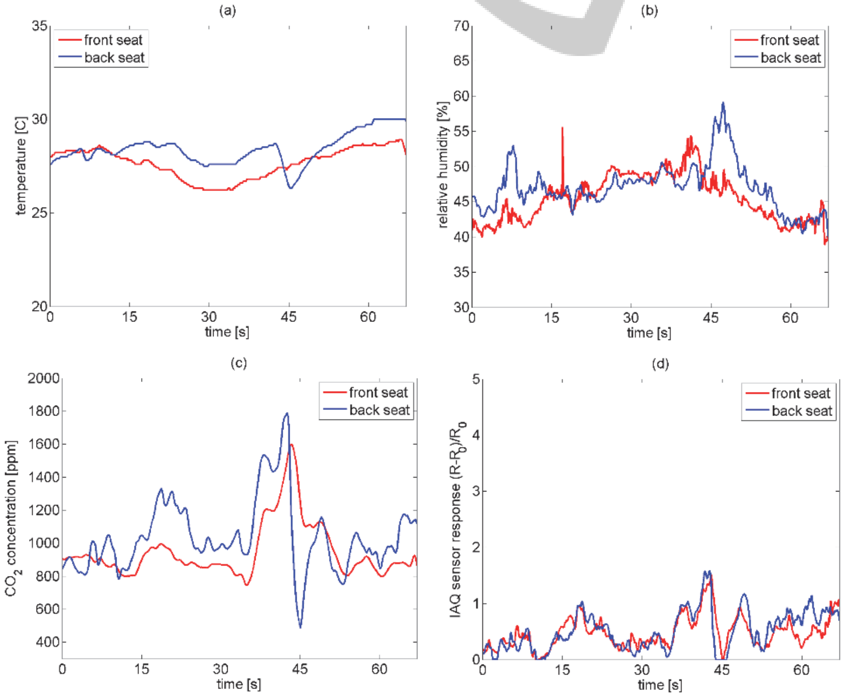

Figure 4: Results of indoor air parameters monitoring inside car cabin during a trip: a) temperature, b) relative humidity, c) CO_2 concentration, d) IAQ sensor response. Comparison between conditions in the immediate vicinity of front and back seat passengers' heads.

5 IAQ CLASSIFICATION

In our concept, sensor measurements of indoor air parameters are the basis for determination of IAQ classes. It is assumed that class assignment is performed in distinct time steps of the monitoring period. In Fig. 5 and Fig. 6 we present the results of IAQ classification, which was based on the data from monitoring car cabin air parameters displayed in Fig. 3 and Fig. 4, respectively.

The classification allows for a synthesis of data on various parameters of indoor air in order to provide a comprehensive announcement on its quality. At the same time there is preserved spatial and temporal resolution of information about IAQ corresponding to the instrumental monitoring frequency. These features of class approach become revealed when comparing indoor air monitoring data (Fig. 3 and Fig. 4) with the respective IAQ class recognition results (Fig. 5 and Fig. 6). As shown, the multivariate measurement data was transformed into a compact, univariate information, which has the same temporal and spatial resolution as the data itself.

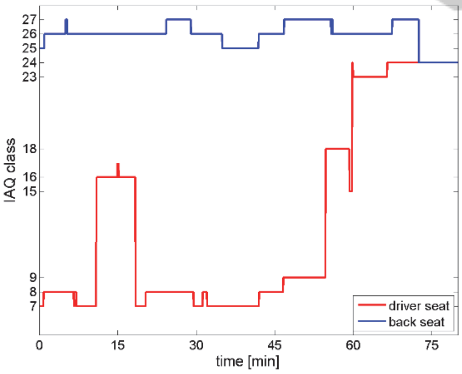

Figure 5: IAQ classes determined using data from monitoring car cabin air parameters in the space of a driver and back seat passenger (compare with Fig. 3).

Obviously, the characterization of IAQ in terms of classes is more coarse compared with using raw multivariate measurement data. But, due to this property class approach better serves the generalization. For example, using classes it is easier to group different locations inside car regarding IAQ similarity. Our results clearly demonstrate that conditions near the driver's seat were typically completely different than ahead of the back seat (see Fig. 5). On the other hand, the IAQ near the front seat and back seat belonged mostly to the same category. The generalization effect is also visible in time domain. As shown in Fig. 5 and Fig. 6, IAQ classes did not change as fast as the values of monitored indoor air parameters. Typically, in the periods of several minutes, conditions in a particular location inside car cabin were assigned to the same IAQ class (see Fig. 5 and Fig. 6), whereas indoor air parameters readily varied (see Fig. 3 and Fig. 4).

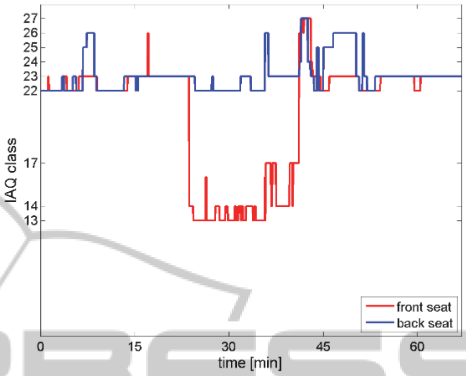

Figure 6: IAQ classes determined using data from car cabin air parameters monitoring in the space of front and back seat passenger (compare with Fig. 4).

The proposed classification approach gives rise to easy examination of how frequently particular IAQ conditions occur in various locations inside car cabin. The corresponding summaries of IAQ classes recognized during experiments considered in this work are shown in Fig. 7 and in Fig. 8. The class occurrence in the space of the driver and back seat passenger are shown in Fig. 7. The corresponding results for the spaces near the front and back seat passengers are displayed in Fig. 8.

6 CONCLUSIONS

Comfort, safety and health of drivers as well as passengers strongly depend on the quality of air inside vehicle cabins. Common experience shows that maintaining it at a high level may be a serious problem. In this work we proposed an approach to the evaluation of IAQ in car cabins. It consists in classification of air quality using a sensor system.

In order to be objective, IAQ classification is based on measurements of selected indoor air parameters, in a chosen location inside car cabin. The following parameters are considered: temperature, relative humidity, CO_2 concentration and VOCs content indicator. Together they form a multivariate representation of the physical and chemical conditions in a tested place of car interior.

Classification is meant to transform the measurement data into a comprehensive information

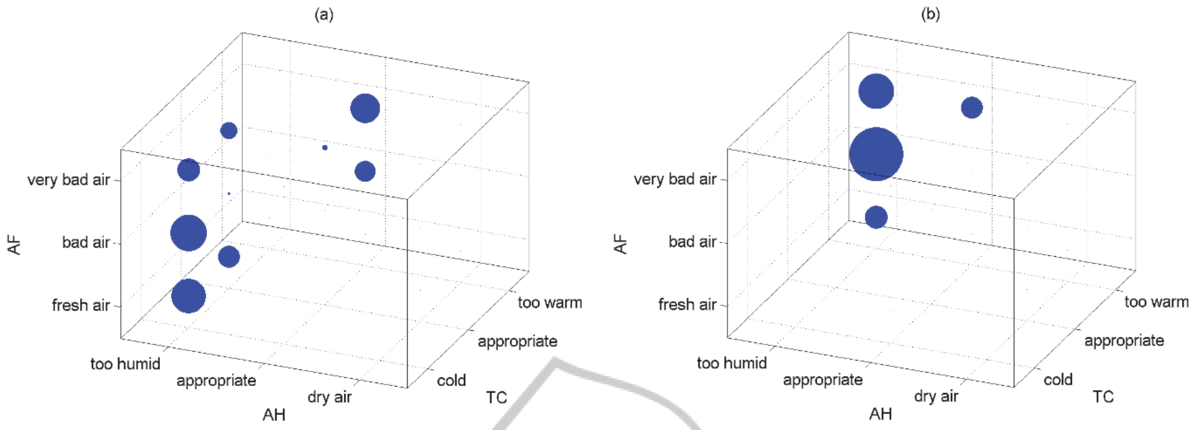

Figure 7: Comparison of the occurrence of distinct IAQ classes in two locations inside car cabin: (a) in the vicinity of driver's head, (b) in the vicinity of back seat passenger's head. Abbreviations: AF – air freshness, AH – air humidity, TC – thermal conditions.

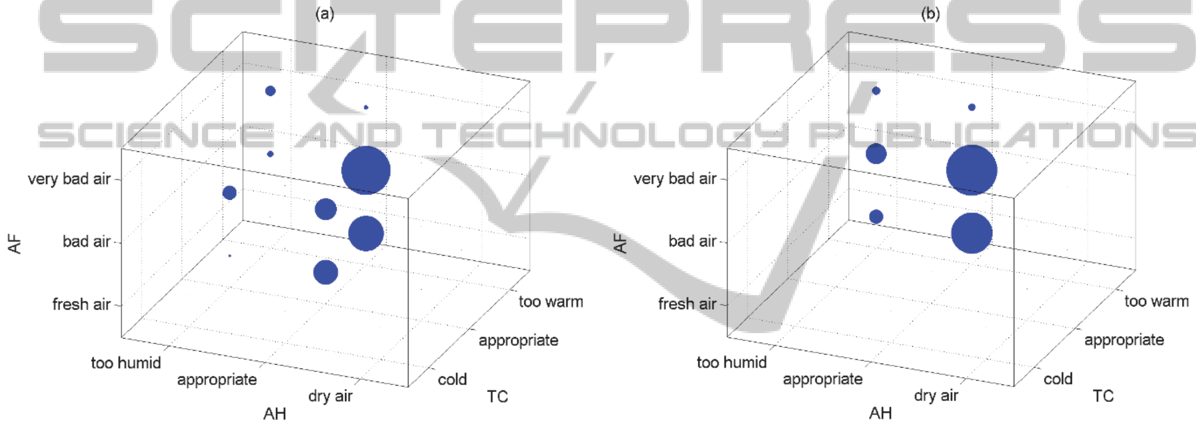

Figure 8: Comparison of the occurrence of distinct IAQ classes in two locations inside car cabin: (a) in the vicinity of front seat passenger's head, (b) in the vicinity of back seat passenger's head. Abbreviations: AF – air freshness, AH – air humidity, TC – thermal conditions.

about IAQ. It basically consist in assigning measured values to the predefined ranges and combining the obtained results. This process is performed by a software without human contribution. The sensor system user is provided with a final result in real-time.

The final announcement of IAQ class refers to: thermal conditions, air humidity and air freshness. This descriptive information provides hints for improving air quality, because its components correspond to the capabilities of air handling system in the car.

ACKNOWLEDGEMENTS

This contribution was supported by the project: "The variability of physical and chemical parameters in time as the source of comprehensive information about indoor air quality". The project is financially supported by the National Science Center, Poland, under the contract No. UMO-2012/07/B/ST8/03031.

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