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Prediction of Vehicle Cabin Air Quality

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Abstract:

The quality of microclimate within the vehicle cabin substantially influences the driver and crew work performance and operational efficiency. One of the main factors of the microclimate quality is the carbon dioxide content in the vehicle cabin air, where the decisive source of increasing the CO_2 concentration is the human breathing. The mathematical model for the unsteady state prediction of the CO_2 content in the vehicle is closely described in the article. The model is validated for two examples of the CO_2 concentration prediction: for varied number of persons in a vehicle and for various rates of vehicle ventilation. The method was verified by an experiment, where the measurement of the CO_2 content was performed in a passenger vehicle for the combination of low and high rates of ventilation.

Keywords:

Cabin air quality, vehicle microclimate, carbon dioxide, predictive model.

1. Introduction

Traffic safety is a one of crucial problems of nowadays society. The number of means of transport has been increasing constantly which has a negative effect upon the number of road accidents.

According to the World Health Organization, vehicle crashes are the leading cause of death after the stroke and the acquired immune deficiency syndrome (AIDS) [1]. Annually, at least 1.2 million people are killed in road accidents and as many as 50 million people are injured. Up to now, it is estimated that there have been more than 30 million of the car crash victims [2].

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Basic factors that affect road safety cover the following: the human factor (drivers, pedestrians, other road users), the safety design of vehicles (active, passive, and rescue components), environment (road, weather), and the legislative system [3]. It appears that the entirely technical failures of vehicles and transport systems have been relatively rare due to a permanent increase in the level of reliability and safety of vehicle components and systems. Many studies show convincingly that more than 90 % of all traffic accidents are caused by human error. This means especially the decline of the driver's attention on driving, the influence of alcohol and drugs, the aggressive driving behaviours, high-speed driving, and other influences [4]. An increase in the driver's concentration would be a substantial step forward in the field of road safety.

Therefore, the permanent attention is given to the research of problems dealing with the driver's concentration and reflexes as the keeping of attention is possible only for a limited time. Usually it is approximately one hour of intensive activity and then the mind will transfer from the state of full concentration to the state of relaxation, then it will become sleepy, consequently follows the state of napping, which can sometimes fall into micro-sleep. It can take varying lengths of time, from fractions of seconds to several minutes or longer. In the state of relaxation and sleepiness, the driver is able to perform the required work only partially, but in the state of napping or micro-sleep it is not possible at all. The micro-sleep is followed by awakening, which may be very sudden and may cause a panic or fright reaction, and in which individuals may make hasty and often very wrong decisions [5, 6].

Therefore, the research work of scientists is focused on the development of technical systems (e.g. measuring vehicle speed, steering angle, etc.) but also on the psycho-physiological systems (monitoring of movements of the eyeball and blinking, face tracking, measuring the blood alcohol content, etc.), by which the driver is excited, controlled, and slowed down.

A brief overview of methods and measured parameters for systems monitoring driver's attention is given in Tab. 1 [6, 7].

Tab. 1 Methods and measured parameters for systems monitoring driver's attention

Methods of observation	**Measured parameter of driver's attention**
Technical	Vehicle trajectory (lateral drift warning systems)
	Vehicle velocity
	Steering wheel turning
	Reaction time
	Quality of required tasks fulfilment
Psycho-physiological	Eye ball motion and blinking
	Electroencephalography signals analysis
	Face observation
	Muscular activity
	Blood pressure, heart beat frequency
	Skin resistance
	Breathing frequency
	Blood alcohol content

It follows from the information stated above that car manufacturers pay considerable attention to the driver's attention issue.

Driver's working environment, or its final condition in a vehicle cabin in terms of affecting the human being, has also significant effect on the driver's performance. The place where the human stays is called a microclimate. The suitable vehicle environment contributes to the comfortable option for personnel transport and it significantly decreases the driver's tiredness, thereby increases the total vehicle safety.

The quality of vehicle microclimate is influenced by [8-12]:

- Physical factors: the air temperature and humidity (the temperature-humidity complex), the air flow, the cooling value of air, the solar irradiation, the lighting, the barometric pressure, and the noise.
- Chemical factors: the chemical composition of air, especially with regard to the concentration of toxic gases (ammonia, carbon oxides, hydrogen sulphide, etc.)
- Biological factors: dust and microorganisms contained in the inspired air.

The most important parameters of vehicle microclimate are air temperature and humidity. The systems of ventilation, heating and air-conditioning help to provide thermal comfort in a vehicle.

It is understood that air quality inside a car means getting rid/elimination of harmful substances produced by passengers. Pollutants like e.g. CO_2, air humidity from breathing, smoke from cigarettes, various smells, etc. are considered as exactly those harmful substances.

It turns out that rather little attention is paid to the fact that a lot of drivers spend quite a long time in the enclosed space of vehicle cabin. Enclosed (airtight) spaces have many advantages, e.g. they are resistant to the noise incursion from the outside, etc. The main disadvantage is the impossibility of automatic air exchange, which causes the cabin air quality worsening [7].

Keeping the air cleanness in a vehicle interior is often neglected even in the most modern cars and is limited only to the monitoring of carbon monoxide which gets into the vehicle from the outside [10].

The approximate percentage composition of clean dry air by volume is given in the pie chart in Fig. 1 and the corresponding composition of exhaled air (air that is breathed out) is shown in Fig. 2 [13, 14].

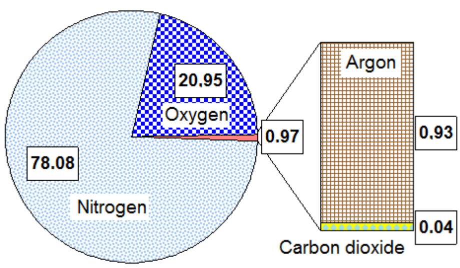

Fig. 1 Approximate composition of clean dry air

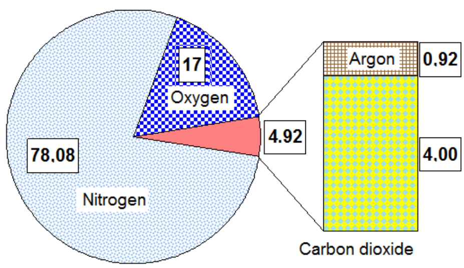

Fig. 2 Approximate composition of exhaled air

It is apparent from the graphs above that the composition of exhaled air is very different from the composition of inhaled air. Due to respiration, a portion of inhaled oxygen is converted to carbon dioxide. The inhaled fresh air contains approximately

0.04 % of carbon dioxide by volume, which is approx 400 ppm (parts per million) of CO_2. However, the exhaled air of an adult contains approx 4 % of CO_2 on average, which is approx 40 000 ppm of CO_2 (ca. 100 times higher concentration than in the fresh air).

When breathing in the open air, the 4% concentration of CO_2 is likely to be insignificant. However, a different situation might occur in the closed (almost airtight) space. Driver environment is a typical example where a small space and insufficient ventilation might be the main cause of the increase in CO_2 concentration. A driver's sleepiness, lethargy, and tiredness might increase when a CO_2 level is higher. Driver attention decline might be finally the main cause of a traffic accident. The microclimate quality in a vehicle and the mathematical modelling of prediction the CO_2 concentration in vehicles are supposed to be the main subject of the article.

2. Predictive Model for the Carbon Dioxide Content

The unsteady state process of the change of the CO_2 content is determined by the change of number of CO_2 moles inside the system given by the molar balance of the control volume expressed in the rate form as summation of all the inlets, sources, and exits [15]

$$\left(\frac{\mathrm{d}n}{\mathrm{d}\tau}\right)_{CO_2} = \sum_j \left(\frac{\mathrm{d}n_j}{\mathrm{d}\tau}\right)_{CO_2} . \tag{1}$$

According to Avogadro's Law stating that the equal volumes of ideal gases, at the same temperature and pressure, contain the same number of molecules and Amalgam's Law of partial volumes [11], the number of moles can be substituted by the product of the CO_2 molar fraction x and the volume V of gas mixture (air). Applying this principle on a vehicle open system the scheme of which is shown in Fig. 3, we can obtain

$$\frac{\mathrm{d}(Vx)}{\mathrm{d}\tau} = \frac{\mathrm{d}V_{\mathrm{in}}}{\mathrm{d}\tau} x_{\mathrm{air}} + \frac{\mathrm{d}V_{\mathrm{breath}}}{\mathrm{d}\tau} x_{\mathrm{breath}} - \frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}\tau} x \,, \tag{2}$$

where the inlet flow rate is positive and the exit flow rate is negative.

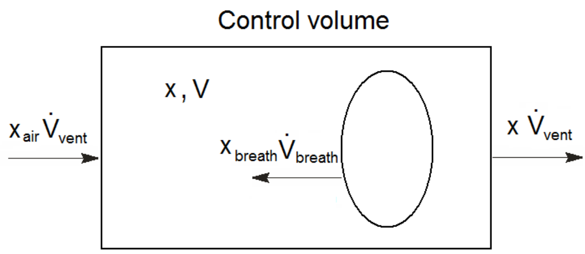

Fig. 3 Schematic of a vehicle open system

The terms appearing in the above equation are as follows:

- $\frac{\mathrm{d}V_{\mathrm{in}}}{\mathrm{d}\tau}$ and $\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}\tau}$ are the volumetric flow rates of incoming and outgoing air by ventilation

- $\frac{\mathrm{d}V_{\mathrm{breath}}}{\mathrm{d}\tau} = i\,k\,V_{\mathrm{t}}$ is the volumetric flow rate of breathed air as the product of the number of persons in a vehicle cabin i, the average breathing rate per time unit k, and the average tidal volume V_{t}
- $x_{\mathrm{air}}, x_{\mathrm{breath}}$, and x are the volumetric (molar) fractions of CO_2 in fresh air, in exhaled air, and in vehicle cabin air.

If the pressure within the vehicle cabin is constant, the volumetric flow rates of incoming and outgoing air by ventilation are the same

$$\frac{\mathrm{d}V_{\mathrm{in}}}{\mathrm{d}\tau} = \frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}\tau} = \dot{V}_{\mathrm{vent}} \tag{3}$$

and if the vehicle cabin air volume V is constant, the equation (2) can be rewritten as:

$$\frac{\mathrm{d}x}{\mathrm{d}\tau} V = \dot{V}_{\mathrm{vent}}(x_{\mathrm{air}} - x) + i\,k\,V_{\mathrm{t}}\, x_{\mathrm{breath}} \tag{4}$$

This differential equation can be solved by the separation of variables. That is

$$\int \frac{-\dot{V}_{\mathrm{vent}}}{V}\,\mathrm{d}\tau = \int \frac{1}{x - x_{\mathrm{air}} - \frac{i\,k\,V_{\mathrm{t}}\, x_{\mathrm{breath}}}{\dot{V}_{\mathrm{vent}}}}\,\mathrm{d}x \cdot \tag{5}$$

The integration of equation (5) for constant ventilation gives

$$-\frac{-\dot{V}_{\mathrm{vent}}}{V}\tau = \ln\left(x - x_{\mathrm{air}} - \frac{i\,k\,V_{\mathrm{t}}\, x_{\mathrm{breath}}}{\dot{V}_{\mathrm{vent}}} \right) - C\,, \tag{6}$$

where C is the constant of integration.

By rewriting the equation (6) into exponential form and by rearranging, we obtain

$$x = x_{\mathrm{air}} + \frac{i\,k\,V_{\mathrm{t}}\, x_{\mathrm{breath}}}{\dot{V}_{\mathrm{vent}}} - C\,\mathrm{e}^{\frac{-\dot{V}_{\mathrm{vent}}}{V}\tau}\,. \tag{7}$$

A single initial condition (the initial value of volumetric fraction x_0 of CO_2 in vehicle cabin air at time zero $\tau = 0$) can then be substituted to solve for the integration constant as

$$C = -x_0 + x_{\mathrm{air}} + \frac{i\,k\,V_{\mathrm{t}}\, x_{\mathrm{breath}}}{\dot{V}_{\mathrm{vent}}}\,. \tag{8}$$

By substituting the integration constant C into equation (7), we obtain the final form of the implicit equation for the instantaneous volumetric fraction x of CO_2 in vehicle cabin air as

$$x = x_{\mathrm{air}} + \frac{i\,k\,V_{\mathrm{t}}\, x_{\mathrm{breath}}}{\dot{V}_{\mathrm{vent}}} - \left(-x_0 + x_{\mathrm{air}} + \frac{i\,k\,V_{\mathrm{t}}\, x_{\mathrm{breath}}}{\dot{V}_{\mathrm{vent}}} \right) \mathrm{e}^{\frac{-\dot{V}_{\mathrm{vent}}}{V}\tau}\,. \tag{9}$$

By using the final equation (9), we can predict the time dependence of the carbon dioxide content in a vehicle cabin for various degrees of ventilation and for different vehicle’s configurations. The possibilities of the model are illustrated by the two following validation examples.

3. Validation Examples for the Model

The first validation example determines the time dependence of the CO_2 content in the vehicle of volume $V = 6\ m^3$, which approximately corresponds to the armoured personnel carrier used by the Czech Army. The vehicle is considered to be hermetically sealed, i.e. the ventilation is zero. Since the equation (9) for the CO_2 fraction is not defined for $\dot{V}_{vent} = 0$ (divided by zero), it is necessary to introduce a very small value of the ventilation rate.

The other input data are as follows: the concentration of CO_2 in surrounded air is x_{air} = 370 ppm, the initial value of CO_2 concentration in vehicle cabin is x_0 = 370 ppm, the concentration of CO_2 in exhaled air is x_{breath} = 35000 ppm, the average breathing rate is k = 15 per minute, the average tidal volume is V_t = 0.45 litres. The calculation is performed for the varied number of persons in a vehicle cabin i = 1, 3 and 11, which corresponds firstly to a driver, secondly to a commander, gunner and driver and finally to the considered complete military vehicle crew. Results of the carbon dioxide content prediction are outlined in Fig. 4.

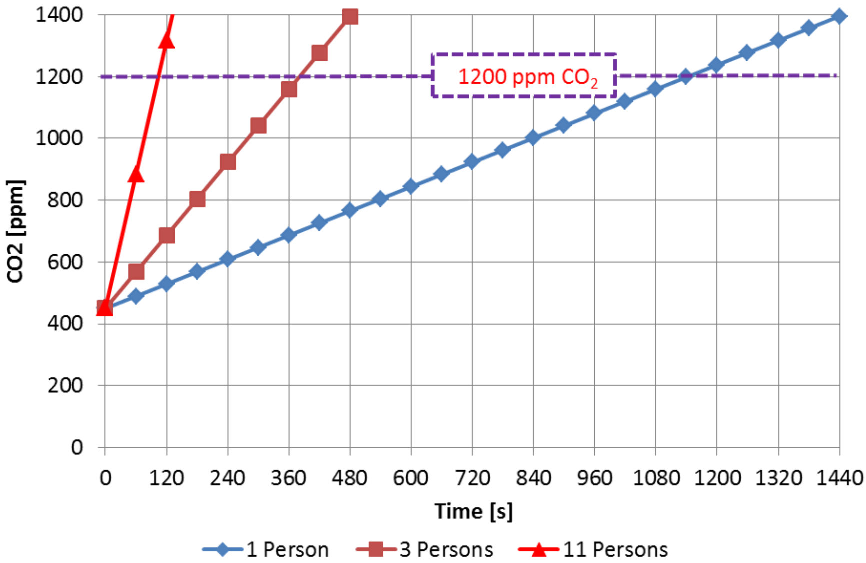

Fig. 4 Concentration of CO_2 in vehicle of volume 6 m^3 against time for 1, 3 and 11 persons in vehicle cabin

The presented model allows us to predict appropriate times to reach various limits of CO_2 exposure causing health dangers. Typical levels of the CO_2 concentration are outlined in Tab. 2 [8, 16, 17].

Tab. 2 Common levels of CO_2 concentration

CO_2 [ppm]	Situation
800 - 1000	Recommended indoor concentration
> 1200	Symptoms of fatigue and reduced ability to concentrate
5000	Maximum safe concentration, no health risks
35 000 - 50 000	Air exhaled. Symptoms of dizziness, confusion, headache

As it is clear from the diagram in Fig. 4 for the hermetically sealed system, the allowable limit of CO_2 exposure (1200 ppm CO_2) is reached: in about 19 minutes (1140 seconds) by breathing of one person (usually the driver of the vehicle), in about 6.5 minutes (380 seconds) by breathing of a crew of three (i.e. commander, gunner and driver), or in about 2 minutes (105 seconds) by breathing of crew of eleven (the entire crew of the vehicle).

The second example presents the ability of the model to predict the influence of the degree of vehicle ventilation on the CO_2 content. The sample input data are as follows: the vehicle of volume V = 6 m^3, the number of persons in a vehicle cabin is i = 11, the concentration of CO_2 in air is x_{air} = 370 ppm, the initial value of CO_2 concentration in vehicle is x_0 = 370 ppm, the concentration of CO_2 in exhaled air is x_{breath} = 35000 ppm, the average breathing rate is k = 15 per minute, the average tidal volume is V_t = 0.45 litre.

The calculation is performed for the varied rate of vehicle ventilation $\dot{V}_{vent}$ = 0.0001, 3, 10, and 57 litres per second. Results of the carbon dioxide content prediction are outlined in Fig. 5.

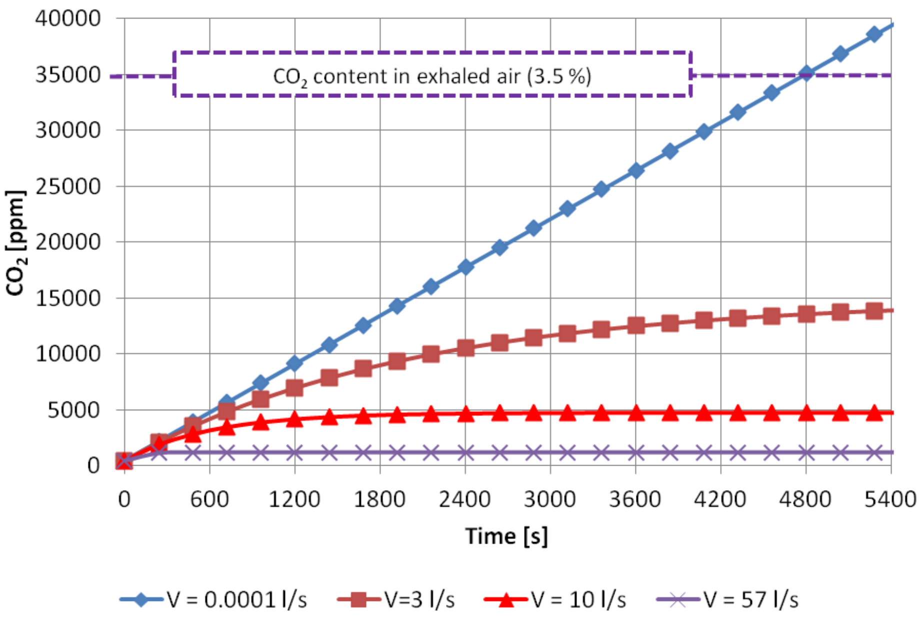

Fig. 5 Concentration of CO_2 in vehicle of volume 6 m^3 against time for various rates of vehicle ventilation

As it can be seen from the diagram above for the case of breathing of eleven persons, the limiting value of 3.5 % CO_2 in a hermetic vehicle is reached in 80 minutes.

If we want to ensure the maximum safe CO_2 concentration (5000 ppm CO_2), it is necessary to provide the ventilation flow rate 10 l/s. Further, for ensuring the allowable limit of CO_2 (1200 ppm CO_2), it would be necessary to provide the ventilation flow rate of 57 l/s.

4. Verification of the Model

The method of the carbon dioxide content prediction was verified by the measurement of CO_2 concentration in a passenger vehicle. The experiment facility and conditions of testing are closely described in [5].

The multi-functional measuring instrument Testo 435-3 was used to measure the CO_2 concentration in a tested vehicle. The used IAQ probe includes, besides the sensor for CO_2 concentration, sensors for measurement the air relative humidity, temperature and pressure. The measured data were collected every second and recorded by using of the Comfort Software Testo V 3.4.

The measuring conditions were as follows: the vehicle of volume V = 2.5 m^3, the number of persons in a vehicle i = 2, the concentration of CO_2 in air x_{air} = 540 ppm, the initial value of CO_2 concentration in vehicle x_0 = 540 ppm, the barometric temperature 28 °C, and the relative humidity 46 %.

Other input data of computation were chosen as follows: the concentration of CO_2 in exhaled air x_{breath} = 35000 ppm, the average breathing rate k = 15 per minute, and the average tidal volume V_t = 0.45 litre.

The measurement of CO_2 content was performed in two phases. The first one represents the stage with the low rate of ventilation 3 l/s, the duration of which is denoted as t_1 (see this time period in Fig. 6). The second phase of duration t_2 represents the stage with the high rate of ventilation 25 l/s. The time course of the measured concentration of CO_2 in a vehicle is indicated in Fig. 6 by the dashed line.

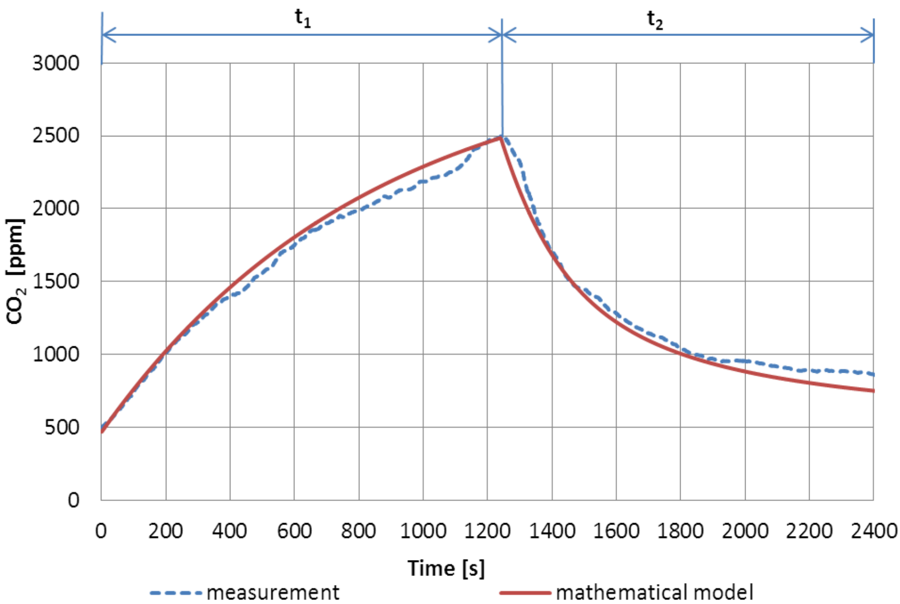

Fig. 6 Comparison of measured and calculated concentrations of CO_2 in vehicle against time for two stages of different rate of ventilation for two persons

The same conditions were applied as the input data for the mathematical model. Results of computation are presented in Fig. 6 by the solid line. Similarly as in experiment, the computation is divided into two phases. The first one of the duration t_1

has the initial value of CO_2 concentration 540 ppm and the rate of ventilation 3 l/s. The second phase of the duration t_2 has the initial CO_2 concentration of 2495 ppm and the rate of ventilation 25 l/s.

Fig. 6 shows a comparison of measured data of the CO_2 concentration with results of computation. There, it is seen that the results obtained from mathematical simulation agree quit well with the experimental observations.

5. Conclusion

The quality of microclimate within the closed space of vehicle cabin substantially influences the driver and crew work performance and operational efficiency. One of the main factors of the microclimate quality is the carbon dioxide content in the vehicle cabin air, where the decisive source of increasing the CO_2 concentration is the human breathing. The mathematical model for the unsteady state prediction of the CO_2 content in the vehicle was thoroughly described, validated, and verified.

The input data for the mathematical model enable to simulate influence of breathing rates (from the rate for quietness or very easy work, about 9 1/min, up to 60 1/min for a high workload), tidal volumes, and rates of a vehicle ventilation. Further, the various contents of CO_2 in the fresh air, in the exhaled air, and for the initial vehicle cabin air can be applied.

This model can be widely used as a tool for various predictions, quantifications, and analyses of the vehicle microclimate quality. The model proposed in this paper might be applied especially in following areas:

- To quantify design requirements for vehicle’s ventilation and filtration systems
- To prevent the health and traffic safety risks connected with the vehicle cabin microclimate quality.
- To simulate the operation possibilities in tactical conditions (filtration, hermetization) for various combat vehicle configurations and crew workloads.

The similar approach may be applied for the other components influencing the vehicle microclimate quality.

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