IOSUD - Polytechnic University Timisoara
Doctoral School of Engineering Studies

Studies and research on comfort parameters improvement in transport systems

PhD thesis - Summary
to obtain the scientific title of doctor (PhD) at
Polytechnic University of Timisoara
in the field of Ph.D. Program MECHANICAL ENGINEERING
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Given that climate change is increasingly affecting people's lives, comfort and its appreciation in motor vehicles must be seen in a new context where it is necessary to take into account the reduction of global air pollution and air pollution within a vehicle, while reducing the energy consumption needed to ensure this comfort.

The topic of the thesis is related to the problems of air quality inside a vehicle and its ventilation, studied from the perspective of comfort-discomfort, the perception of safety while driving a vehicle and energy efficiency.

In this respect, the aim of the thesis is to **contribute to the problems of air comfort and quality in vehicles**, as the **reduction of the energy consumption** corresponding to comfort is a challenge for the car manufacturers and a necessity especially felt by the electric vehicle owners.

The research is conducted on an exploratory approach to CO2- related air quality analysis and perceived vehicle comfort, aiming to contribute both to enhancing road safety knowledge and identifying a solution to reduce energy consumption in a vehicle, while ensuring conditions of comfort and air quality

The thesis is structured in accordance with the **research objectives**:

Objective 1: Conduct a theoretical synthesis of the comfort / discomfort in a vehicle from the perspective of ventilation and air quality, highlighting the effects that CO2 concentration may have while driving a vehicle;

Objective 2: Identifying comfort / discomfort elements in a vehicle and obtain a hierarchy of them;

Objective 3: Air quality assessment and determine the amount of CO2 accumulated in the passenger compartment of a stationary vehicle with one or more occupants, highlighting the time at which air quality deteriorates in such a way as to endanger the safe driving of a vehicle.

Objective 4: Determination of fresh air intake required to maintain air quality in accordance with existing rules for one or more occupants of the vehicle.

Objective 5: Identify a way to manage energy consumption in a vehicle by dosing outside air intake to provide an acceptable air quality that is considered safe for driving a

vehicle.

The first part of the thesis provides the theoretical and conceptual basis necessary for the implementation of the applied research from the second part of the thesis. The content of the thesis is presented in two parts and seven chapters.

The theoretical framework of the research presented in the first part addresses in three chapters the aspects related to the interdisciplinary nature of the studied subject: comfort and air quality in motor vehicles.

Chapter 1 "Comfort" includes definitions and general assessments of comfort / discomfort, dimensions and meanings, typologies based on comfort dimensions, as well as its multidisciplinary approaches from the perspective of architecture, engineering sciences and socio-human sciences. Particular attention is paid to the comfort research in transport vehicles: trains, airplanes and cars. Regarding the comfort in cars, it is also presented a synthesis of the current state of research in the Romanian academic publications

In **chapter 2** called Physical Ambiance Comfort are presented the physical phenomena that influence the perception and visual, acoustic and aeraulic comfort of the human operators in various professional backgrounds. The comfort of light is influenced by both the quantity, distribution and quality of light, as well as the visual capabilities of the human operator. Optimizing visual comfort and driver safety is one of the goals of today's automakers. The same importance is given to the study of sounds (noises) in vehicles to ensure on one hand acoustic comfort, but especially to increase driver safety. Examples of noise levels resulting from various activities are exemplified, as well as some legal regulations on ambient noise. Aerodynamic and thermal comfort, as well as maintaining a good air quality level for the entire vehicle, are other aspects that are considered to meet the needs of vehicle occupants.

Chapter 3, "Comfort and Air Quality," presents recent results of research conducted in the Romanian and international academic space on indoor air quality, highlighting the effects that CO2 can have on both health and performance cognitive, and general perception of comfort.

The second part of the thesis, Studies and experimental determinations, composed of three chapters with experimental studies, a chapter with general conclusions and the author's contributions to the studied field, as well as suggestions regarding the improvement and the ongoing of research, the bibliographical references and the annexes of the thesis.

The second part of the thesis was based on multiple experiments made by the author on experimental CO2 measurements and minimum air flows required to provide a good quality air in a vehicle with 1-4 people. The choice of measuring devices, the various experimental protocols, the methods for processing the statistical data and the results associated with each experiment are detailed in chapters 4, 5 and 6.

The study conducted in **chapter 4** of this thesis was aimed to identify the factors considered as generators in the production of comfort / discomfort in motor vehicles, an investigation carried out in a representative sample of students of a technical university. Based on the perception of young drivers / passengers, the study highlighted the importance of air quality and air conditioning in both the hierarchy of comfort and discomfort.

In **chapter 5** we continued the research with a study regarding air quality in 3 vehicles (Dacia Logan, Hyundai i30 and Renault ZOE), in two situations (with and without air recirculation) with 1- 4 people in the car. For the assessment of air quality, CO2 concentration, have been measured in the above mentioned conditions, over a period of time, CO2 exposure from 350 ppm to 5000 ppm, the occupational exposure limit for CO2 for an 8-hour period. CO2 determinations were correlated, in an experiment with repeated measurements, with an air

quality assessment performed by 60 subjects participating in the experiment. Additionally, a different carbon dioxide measurement was made at 10,000 ppm in a Dacia Logan cabin in order to identify the time limit in which, in a vehicle with 5 people, CO2 could reach that concentration in which the occupants' health is endangered as a result of the first signs of respiratory acidosis (increase in CO2 in the blood).

In **Chapter 6**, the author sought to identify the minimum volume of fresh air intake required in the passenger compartment to ensure the maintenance of 3 levels of CO2 (5000 ppm, 2500 ppm, 1000 ppm). For this purpose, we carried out measurements of fresh air intake in a Dacia Logan 2010 model in 12 experimental situations (1-4 persons, 3 levels of CO2). Preceding this study, 16 airflow determinations of the same ventilation system of the same Dacia Logan were carried out according to the number of opened air-conditioners (A1-A4) and the speeds of the ventilation system (t1-t4).

The results obtained from these two studies and experimental determinations were compared to identify the difference between the air supplied by the ventilation system of Dacia Logan and the air considered necessary for a safe driving in a motor vehicle according to the number of occupants of that vehicle.

At the end of this chapter, we propose a solution to manage the energy consumption of a vehicle by measuring outside air intake, depending on the number of people in the vehicle and also on the concentration of CO2 in the breathing air, so as to ensure good air quality in the vehicle, air that does not affect the safety of people involved in road traffic.

The last chapter of the thesis, **chapter 7**, presents the general conclusions of the thesis, the personal contributions of the author, as well as suggestions for the continuing the research in the field of air comfort and air quality in vehicles.

The results obtained from the theoretical and experimental studies, reported on the objectives of the thesis, are presented in order to show the degree of their achievement.

In the first part of the thesis we aimed to study the bibliography of comfort and air quality in the interior spaces, approaching and synthesizing, in a multidisciplinary manner, current research on the comfort in the means of transport: on the train, on the plane and on the cars. The achievement of this first objective resulted in the structuring of a theoretical content, whose actuality is reflected both by the themes approached, the comfort and the quality of the air, as well as by the theories and bibliographical references used.

The theoretical presentation was made in three chapters, trying to capture from the interdisciplinary perspective the contribution of each aspect presented in understanding and completing the research made. The 150 bibliographic titles, highlight the degree of deepening of the researched subject and the up-to-date of the bibliography consulted.

Regarding the 2nd objective, the analysis and identification of comfort and discomfort elements in a vehicle, the results have led us to the creation of two lists (hierarchies) with elements generating comfort and discomfort, lists that can be useful to the car manufacturers. Also, part of the obtained results supports the existence of a single bipolar comfort-discomfort dimension, in which the presence of a comfort generating element leads to the reduction of the discomfort related to the absence of that element. The other part of the results comes to support the theory of the existence of two distinct dimensions , comfort and discomfort.

The results of multiple correspondence analysis have highlighted that discomfort-generating elements that differentiate passenger drivers are combined into a single dimension

(dimension 1), considered by the author to be a psychological dimension, responsible for the discomfort caused by a vehicle perceived as uncertainty and the malfunction of elements involved in driving. These results suggest the importance of a sense of safety in the appreciation of vehicle comfort, comfort being defined as a subjective state of pleasure and relaxation given to a certain extent by the confidence in the proper operation of the vehicle and in the safe driving of the vehicle. In this context, we propose a redefining of the concept of comfort in motor vehicles, by introducing in the scope of the meanings assigned to the comfort of a new dimension that is related to the safety in traffic. All these obtained results allow us to appreciate the successful accomplishment of the second objective of the thesis.

Electric cars are a challenge for car manufacturers who are looking for technical solutions to increase their energy autonomy and on the other hand they try to ensure the comfort and quality of the air in the passenger compartment. From a desire to save energy, in order to increase the number of kilometers traveled, drivers of electric vehicles tend to resort to air recirculation much more often compared to the users of classic vehicles equipped with thermal motors. Their choice is fully motivated by the increased) in energy consumption used for air cooling (in the summer period) or for heating the air in winter. But if the air inside a vehicle is not sufficiently ventilated with fresh air, the presence of people in the vehicle (their breathing) leads to degradation of air quality in such a way as to affect the concentration and responses necessary to drive the vehicle safely.

Identifying of levels reached by CO2 concentrations due to the respiration of occupants of a vehicle, given the prolonged use of air recirculation, was one of the major objectives of this thesis (Figure 1). In this regard, conditions in which air quality can achieve values considered by specialists to jeopardize the concentration capability as well as the general cognitive skills of drivers have been identified and highlighted. The assessment of air quality in terms of CO2 accumulation was achieved in 3 stationary experimental vehicles (Dacia Logan, Hyundai i30 and Renault ZE) in 2 situations (with recirculation and without recirculation of air) and with 1- 4 people in the car.

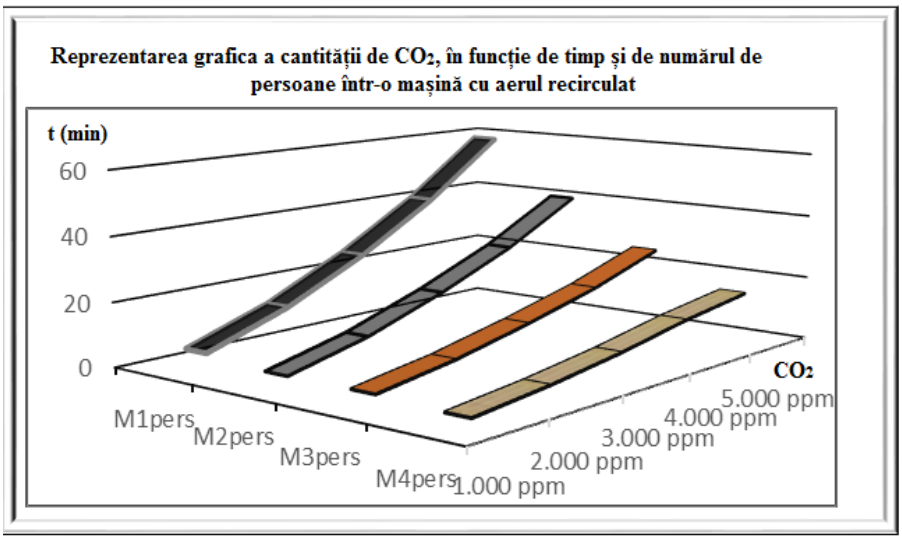

Figure 1: Variation of CO2 (in ppm), (recirculated air)

In addition, a different CO2 measurement at 10000 ppm with 5 people in a Dacia Logan

stationary cabin (Figure 2) was performed. The measurements made, show that in about 12 minutes the CO2 level reached the occupational exposure limit (5000 ppm). In about 28 minutes, the amount of CO2 reached 10000 ppm, the level at which the first signs of respiratory acidosis (DFG, 2002) appeared.

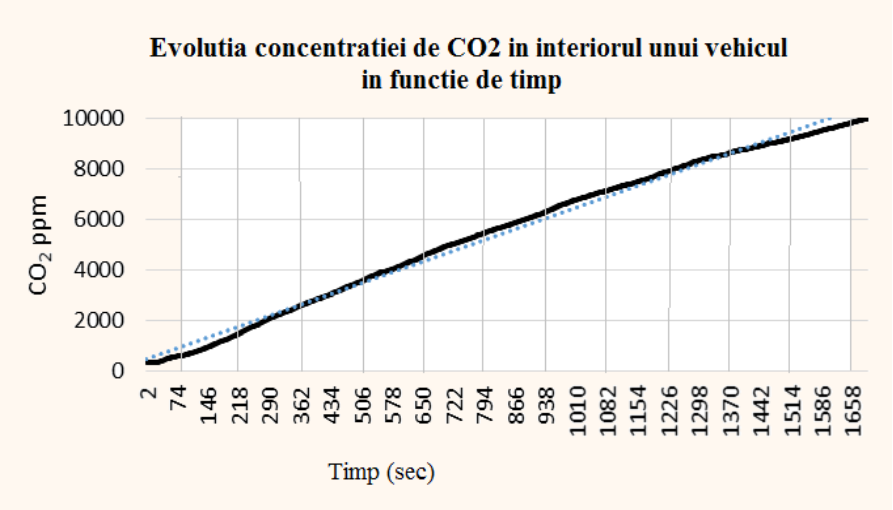

Figure 2: Concentration of CO2 in vehicle with 5 persons

The measurements recorded show that in about 12 minutes the CO2 level reached the occupational exposure limit (5000 ppm). In about 28 minutes, the amount of CO2 reached 10000 ppm, the level at which the first signs of respiratory acidosis (DFG, 2002) appeared. The experiments carried out had as objective, together with the measurement of CO2 concentrations, also the identifying the perception of the air quality with different concentrations of CO2.

The results confirm that the majority of the study participants assessed the bad quality of air in the vehicle as being of good quality when in reality the air quality was low in accordance with European Norm NF EN 13779. This situation where the vicious air is perceived as a good air it has to attract the attention of those responsible for traffic safety, because air with high concentration of CO2 is considered by many researchers to be an air that can affect the cognitive abilities and psychomotor responses of drivers (Satish et al., 2012).

The first part of the 6th chapter was devoted to preliminary experiments in which ventilated air flow measurements were made in a Dacia Logan vehicle. 16 airflow determinations were made, based on the number of open-air aerators A1-A4 and the speeds of the ventilation system t1-t4 (4 front air conditioners x 4 speed gears). The results obtained showed air flow rates ranging from 30 m3 / h (open aerator) and 70 m3 / h (all 4 open front ventilators) at ventilation stage 1, between 43 m3 / h -105 m3 / h (2^{nd} stage), 76 m3 / h -165 m3 / h (3^{rd} stage), and 101 m3 / h - 210 m3 / h (4^{th} stage).

A second type of preliminary measurement aimed at measuring the CO2 concentration in a Dacia Logan vehicle with 1-4 people depending on the steps of the ventilation system (Figure 3).

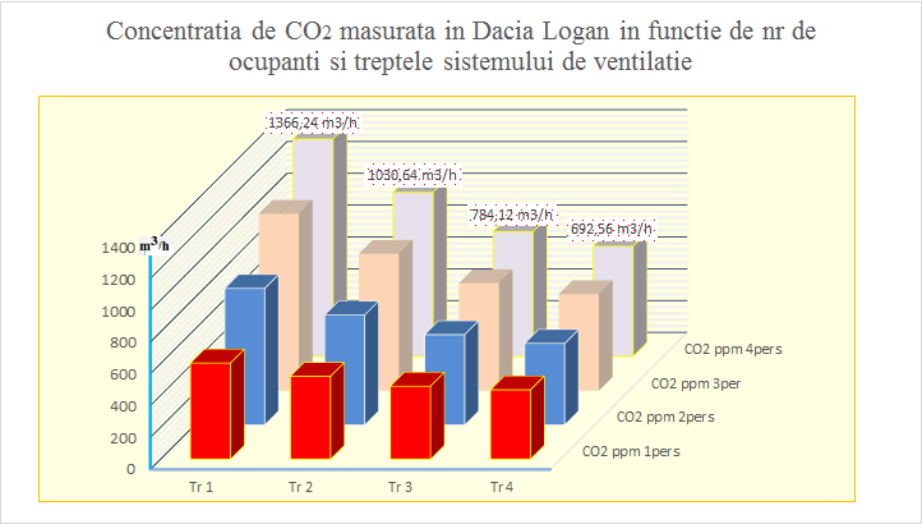

Figure 3: Variation of CO2 concentration by occupant and fan speed

The measurements made highlighted a clean, high-quality and low-CO2 air. For example, on the 4th ventilation stage the air in the car has almost the same concentration of CO2 as the outside air: 435 ppm with 1 person in the vehicle and 692 ppm with 4 people in the vehicle.

The preliminary phase continued with a true exploratory phase to determine the minimum airflow required to enter in the passenger compartment in order to maintain CO2 concentrations of the analyzed air at 5000ppm, 2500ppm and 1000ppm CO2, acceptable or recommended for indoor various contexts (work / study / living) (Figure 4).

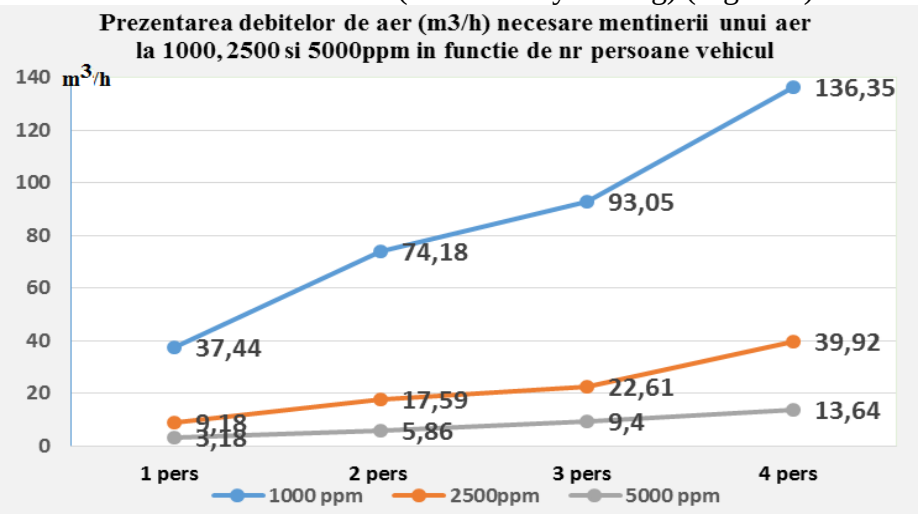

Figure 4: Airflows (m3 / h) introduced into the vehicle by number of people and CO2 concentration

The comparisons between the experimental airflow determinations from the previously described phases, underpin the implementation of a proposal for the management of the energy consumption of a vehicle by measuring the outside air intake, depending on the number of persons in the vehicle and, implicitly, the concentration CO2 from breathing air. Also in this context, the use of an air-to-air heat exchanger is proposed for the energy gains related to ventilated air.

In Figure 5 we present the airflow delivered by Dacia Logan (on stages 1-4 of ventilation) and the fresh air flow required to maintain air quality (2500 ppm CO2) for 4 occupants of a vehicle.

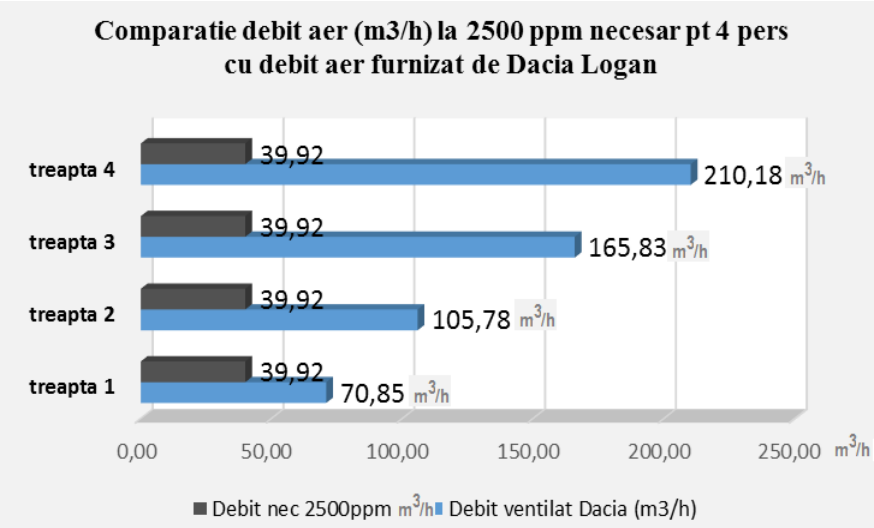

Figure 5: Graphical presentation of the differences between flows required to maintain air with 2500 ppm CO2

The level of CO2 in the Earth's atmosphere is increasing rapidly. Climatologists and other scientists have warned for more than half a century that the accumulation of CO2 and other greenhouse gases in the atmosphere leads to global warming as well as to other significant environmental, ecological and social climatic changes. In 1900, the ambient atmosphere was below 300 ppm, now the average ambient CO2 concentration is about 350-400 ppm and the predicted level by the end of the 21st century is around 800-1000. This increase may have implications for the whole society, especially in jobs requiring responsibilities, such as drivers, air traffic controllers or surgeons (Bierwirth, 2016). Decreasing CO2 emissions is important from the point of view of transport safety. Awareness of these issues could allow changes in the practice of those activities that depend on maintaining low CO2 concentrations.

Personal contributions of the author of the thesis:

The PhD thesis "Studies and research on improvement of some comfort parameters in transport systems" is an interdisciplinary thesis based on an exploratory approach on the comfort and air quality in vehicles. The results of the thesis bring original contributions both with the theoretical and experimental plan, proposing solutions for increasing the comfort in vehicles, with the reduction of the energy consumption.

The research has led to the publication of 4 articles, one in an ISI (Clarivate Analytics) journal with impact factor FI = 1,789 (in 2016), two ISI Proceedings volumes and one in a BDI magazine. The impact of these publications can be highlighted through the 17 citations accumulated so far in both impact-impact journals and BDI journals or in doctoral dissertations from other European technical universities.

The research results highlight the following personal contributions:

- A broad theoretical synthesis of the recent research on air comfort and quality in cars, highlighting the effects of CO2 on health, productivity / cognitive performance and comfort perception. Through the studies presented, the thesis makes a direct contribution to reporting the implications of CO2 growth in road accidents.

- Redefining the concept of comfort in motor vehicles by introducing within its meaning a new dimension related to the safety of the occupants of a vehicle. Comfort can be defined by taking into account the subjective state of enjoyment and relaxation given by safe driving, as a

result of the confidence we have in the vehicle. The article (Constantin & all, 2014) in which this original theoretical contribution appears was quoted 4 times, in impact magazines (FI = 2,019; FI = 2,871) and in the volume of an international conference.

- Identification of comfort / discomfort elements from the perspective of young vehicle users and, consequently, identification of possible directions of intervention, on the one hand, in terms of eliminating discomfort and, on the other hand, in terms of increasing comfort. The article in which the results of this research were published (Constantin & all, 2014) is an indexed article ISI Proceedings, and has 12 citations in international publications.

- Experimental determination of CO2-level increase due to the breathing of occupants of a vehicle with no outside air supply (with and without air recirculation) and identification of the time when these CO2 levels can endanger the safe driving of a vehicle. The results of this research were published in the article "Perception of Cabin Air Quality among Drivers and Passengers" with impact factor FI = 1.789 (Constantin et al., 2016). Among the authors of the four citations received, we mention Professor Bierwirth, an emeritus professor at the Australian National University, as well as a research conducted for the Australian Government by the New South Wales Government Agency (Roads and Maritime Services) with a view to regulating the use of air recirculation in motor vehicles in the context of designing extensive road infrastructure including tunnels.

- Experimental determination of the volume of fresh air required to be introduced into the passenger compartment to provide three levels of air quality, ie: 5000 ppm - occupational exposure limit for CO2 during 8 hours of work; 2500 ppm - the limit at which first attention changes and decisional capabilities were identified (Satish et al., 2012); 1000 ppm - CO2 recommendation for residences, schools, offices).

- Conceiving, designing and practical implementation of an original air-control-adjustment system introduced into the passenger compartment of a vehicle.

- Identify the differences between the airflow delivered by Dacia Logan's ventilation system and the flow required to ensure good quality air that does not affect the cognitive capacities of the occupants of a vehicle.

- The concept of an energy management solution in a vehicle by fresh air intake, depending on the number of people in the vehicle and, implicitly, the concentration of CO2 in the breathing air.

These last contributions refer to the results of the research that is currently submitted for published.

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