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Perception of Cabin Air Quality among Drivers and Passengers

Doru Constantin *, Crisanta-Alina Mazilescu, Mihai Nagi, Anca Draghici and Ana-Andreea Mihartescu

Teacher Training Department, Politehnica University Timisoara, Piata Victoriei nr 2, Timisoara 300003, Romania; alina.mazilescu@upt.ro (C.-A.M.); mihai.nagi@upt.ro (M.N.); anca.draghici@upt.ro (A.D.); andreea.mihartescu@upt.ro (A.-A.M.)

* Correspondence: doru.d.constantin@gmail.com or doru.constantin@upt.ro; Tel.: +40-723-227-617

Academic Editors: Daniel A. Vallero and Marc Rosen

Received: 28 May 2016; Accepted: 23 August 2016; Published: 29 August 2016

Abstract: Air analysis inside vehicles is a problem that can be interpreted from several perspectives. This research is oriented towards the perception of air quality within a car, regarding a situation of cars in stationary traffic. Carbon dioxide measurements were made using a Trotec Data Logger Air Quality CO_2 BZ30 machine inside different standing vehicles with up to five occupants, with and without circulating air. The perception of the air quality was measured on a Likert-type scale with seven levels on a sample group of 60 students. The results highlight, on the one hand, the conditions under which the CO_2 in the cabin air can reach concentrations which are, according to new data, considered to influence the cognitive capacity of occupants in the car, and on the other hand, they present a global assessment of the air quality in the vehicle when critical values of CO_2 have been reached. If the air exchange rates inside a car are low, this degrades the air quality in such a way that it affects the concentration and reactions necessary for safe driving without perceiving any discomfort that would put the drivers or the passengers on alert.

Keywords: cabin; air quality; carbon dioxide measurements; safe driving

1. Introduction

From the perspective of sustainable development in the automotive field, comfort is no longer solely derived from architecture, engineering, social sciences, or the humanities. Increasingly, the quality of the ambient environment is influencing the comfort of the vehicle occupants. Thus, the relationship between pollutant concentrations and comfort may also affect the safety of individuals and the public at large. Sustainable transportation policies are closely related to the potential contribution of this sector in order to decrease in CO_2 emissions [1–3]. Air quality and carbon dioxide emissions, especially in urban transportation and air transportation, is one of the major points of interest of researchers [4]. The concern of car manufacturers of air quality inside and outside the vehicle should combine and satisfy both the problematic aspects related to comfort and those related to traffic safety, without neglecting any aspects of reducing energy consumption. Watertight modern passenger vehicles greatly reduce heat loss and noise from the car and from outside of it, but prevent natural air renewal inside the vehicle. Also, the very good performances of the new engines reduce the loss of energy, but this energy was usable during the winter to heat the passenger compartment.

In this context of constraints regarding comfort, risk, cost and power consumption, we intend to conduct a study on the air quality in a vehicle, and more specifically, we want to study the perception of the air quality in terms of whether the concentration of carbon dioxide can reach values that can influence the attention and decision capacity of the driver. This influence has been the subject of debate for many researchers in recent years [5–13]. To this end we will review research that highlights the effects of carbon dioxide on health and cognitive performance that can be identified in the case of vehicle drivers.

Carbon dioxide is a component of the air, naturally emitted by living beings through breathing. Also called carbonic gas, CO_2 is one of the air pollutants. The presence of CO_2 in a given air sample is commonly expressed as parts per million (ppm). Studies show that the concentration of CO_2 in the air inside inhabited environments usually varies between 350 ppm and 2500 ppm [14–18], but can also reach values of 3000 ppm or 4000 ppm [19,20] depending on the number of people present and the ventilation of the air. At a global and European level there are regulations regarding the ventilation of inhabited environments without presenting scientific arguments regarding the setting of these explicit thresholds of CO_2 levels for residential and non-residential buildings [21]. The French rules indicate a level of 1000 ppm of CO_2 under the normal occupancy of non-residential buildings, with a tolerance margin for places where smoking is prohibited, where values up to 1300 ppm are allowed. In 2004 a value of 5000 ppm was regulated for occupational exposure.

The same limit is set in 19 other European countries, also establishing short-term exposures between 10,000 and 30,000 ppm [21,22].

Table 1 lists several values regulated or recommended for the CO_2 level in residences, classrooms and conference rooms.

Table 1. CO_2 standards and guidelines for indoor spaces.

	CO_2 Values Regulated or Recommended	
	in Residences	**in Classrooms**
Belgium [21]	500 ppm	500 ppm
Netherlands [21]	1000–1500 ppm	1200 ppm
Finland [21]	1200 ppm	1200 ppm
UK	-	1500 ppm
US [23] (ASHRAE)	1000 ppm	1000 ppm
US [24] (OSHA)	1000 ppm	1000 ppm

ASHRAE—American Society of Heating, Refrigeration and Air Conditioning Engineers; OSHA—Occupational Safety and Health Administration.

In what concerns the CO_2 standards for vehicles, we only found the standards of the Taiwan Environmental Protection Administration established at 1000 ppm for 8 h-CO_2 for buses and the air quality guideline of the Hong Kong Environmental Protection Department (1 h-CO_2: 2500 ppm for Level 1 for buses) (see Table 2) [5].

Level 1 represents good air quality at which there is no health concern identified.

Level 2 represents the air quality at which there is no health concern identified.

Table 2. Numerical values of carbon dioxide for the two-level air quality guidelines established for ferries [25] and buses [26].

Parameters	**Air Quality Guidelines**	
	Level 1	**Level 2**
Carbon dioxide	2500 ppm (4500 mg/m^3)	3500 ppm (6300 mg/m^3)

Williams presents several clarifications from the National Institute of Occupational Safety and Health (NIOSH), indicating the potential effects, limitation and exposure limits in the case of a very high work rate and while at rest (see Table 3) [10].

Table 3. Potential effects, limitations and exposure limits in the case of a very high work rate and at rest [10].

	At Rest (65 W·m^2)		Very, Very High Work Rate (400 W·m^2)	
ppm CO_2	**Potential Effects and/or Limitations**	**Exposure Limit (Time)**	**Potential Effects and/or Limitations**	**Exposure Limit (Time)**
25,000	Increase in ventilation	unknown	Increase in ventilation	2 h
30,000	Increase in ventilation No restrictions within the exposure limit	15 h	Increase in ventilation	30 min
50,000	Increase in ventilation No restrictions within the exposure limit	8 h	Increase in ventilation Collapse/unconsciousness	5 min
70,000	Increase in ventilation Severe limitations on activity	<30 min	Collapse/unconsciousness	n/a
100,000	Increased heart rate Collapse/unconsciousness	<2.0 min	Collapse/unconsciousness	n/a

Carbon dioxide (CO_2) was selected as a proxy indicator of air quality because its concentration within an indoor environment indicates the effectiveness of the ventilation system and the adequacy of the ventilation [25].

There are important physical and physiological responses to CO_2 exposure throughout the body. CO_2 is a potent stimulus of cerebral vasodilation and blood flow [10,27]. Early symptoms include a sense of "air hunger" or dyspnea and increased respiration and headaches. A higher CO_2 concentration produces heart palpitations, confusion, severe dyspnea, vomiting, disorientation and hypertension [10,28]. CO_2 is also considered a potent stimulus of pulmonary minute ventilation [27]. Due to a low pH in the blood (which means a high level of acid), the respiratory center in the brain stimulates the respiratory muscles that increase ventilation [8]. CO_2 can also alter the intracellular pH, thus having effects on the metabolism [10].

Existing studies have tried to establish a link between carbon dioxide concentration and its effects on both health and performances and also on the perception of the state of comfort [13].

1.1. CO_2 Effects on Health

The studies conducted in order to identify the effects of carbon dioxide on health have revealed symptoms related to unhealthy building syndrome (sick building syndrome) [29], respiratory symptoms [16] related to asthma [19] and other effects such as respiratory and otorhinolaryngology infections, rash [30] or general symptoms such as fatigue and headache [17].

Cardiovascular effects have also been highlighted. For example, at a concentration higher than 5% (50,000 ppm), effects such as the increase of blood pressure and heart rate [31], the occurrence of extra systoles during effort [32] or the increase of blood supply to the kidneys and brain have been identified [33]. Also, at levels higher than 50,000 ppm, the effects on the central nervous system were highlighted, such as headache symptoms, dizziness and physical arousal [34], and even visual disturbances [32] at concentrations above 100,000 ppm. Starting from 1% (or 10,000 ppm), an exposure of 30 min may lead to early respiratory acidosis effects [33]; inhalation of air with concentrations higher than 50,000 ppm for one hour leads to lung inflammation [19,35], and exposure to levels above 200,000 ppm can cause coma and/or death [32].

1.2. CO_2 Effects on Cognitive Performances and Productivity

Regarding the effects of carbon dioxide on cognitive performances and productivity, recent studies conducted in offices and schools show that increased ventilation above the normal recommendations indicates an increase of productivity by 5%–10% [36]. The recommended fresh air supply rate for school classrooms in the UK is 3 L per second per pupil (L/s.p) with the capacity to supply 8 L/s.p. [37].

Although there are few studies conducted on vehicles regarding carbon dioxide [5–7], the laboratory studies and those conducted in schools or in spacecrafts highlight alterations of the attention capacities and decision-making and academic performances [8,9,11–13,27].

Chiu, Chen and Chang showed in a recent study (2015) that high-capacity tour bus cabins with the air conditioning system operating in the recirculation mode severely lack in air exchange rate, which may negatively impact transportation safety. They found that both the driver zones and the passenger zones of the tour buses reached more than 3000 ppm of carbon dioxide concentration, and maximum daily average concentrations of 2510.6 and 2646.9 ppm [5].

The study led by Allen and Spengler confirms the findings of Satish, who found the statistical influence of CO_2 on decision-making performance when the carbon dioxide level increases from 600 to 1000 and 2500 ppm, respectively [9,38].

At 2500 ppm, large and statistically significant reductions occurred across seven scales of decision-making performance [38]. The Allen and Spengler study also shows that cognitive scores were 61% higher on the Green building day and 101% higher on the two Green+ building days than on the Conventional building day ($p < 0.0001$) [9,38].

Kajtár, Herczeg and Láng conducted four experimental studies with the following CO_2 concentrations: 600, 1500, 3000, 4000 ppm. Their results revealed that the capacity to focus declines when the CO_2 concentration in the air increases up to 3000 ppm [12]. Two other experimental studies carried out by Kajtar, Herczeg, Lang, Hrustinszky and Banhidi showed that a CO_2 concentration over 3000 ppm makes the well-being and the focus of the subjects' decline [11].

Wargocki shows that performance (in addition and correction tests) significantly increases when carbon dioxide levels decrease [14]. The same author highlighted in 2007 the link between the speed of students solving tests and the increased ventilation of classrooms.

Twardella highlights both the significant correlations between the increase in ventilation and the decrease in the number of recorded errors, as well as non-significant correlations between the speed of executing tasks and focusing [39]. Two other experimental studies highlight the significant correlations between the increase in carbon dioxide levels and the decrease in performance (percent of identified errors) in a reading test [12] and a computer test [38].

There are also a few studies which do not always highlight the significant effects of CO_2's influence on cognitive skills [31].

A recent review by National Aeronautics and Space Administration NASA examined 76 studies and reported that it is difficult to draw firm conclusions about the impact of carbon dioxide on sleep, cognition and psychomotor performance, but it is necessary to understand and clarify the risk of adverse cognition and performance effects of carbon dioxide, especially in human spaceflights [13].

1.3. CO_2 Effects on the Perception of Comfort

The third aspect regarding the effects of carbon dioxide studied is its relationship with the perception of the state of comfort, especially with the perception of air quality. Wargocki finds that acceptability of air quality, its freshness and reduced odor perception increase significantly with the level of ventilation (and therefore with lower CO_2 levels), but these differences are perceived only when entering the room [14]. In the 2004 study, none of these variables is reported as significant. Other researchers obtained significant results between CO_2 reduction and the perception of air quality, specifically in connection with the freshness of the air, the perception of lower temperatures, increased perception of air movement and decreased perception of odors [14,40–43].

Recirculated air in the cabin can have benefits for the drivers who opt to put it into operation: it is considered the most effective option in terms of thermal management of the car and help to reduce fuel consumption [44]. The use of the air recirculation position leads to protection from different pollutants existing in the environment or helps reduce particles in the car [44]. The argument of effective thermal management is taken into account in the case of electric cars in order to increase the vehicle's autonomy movement.

The buses with air conditioning operating in the recirculation mode are severely lacking in terms of the air exchange rate and consequently elevate the risk of traffic accidents because bus drivers use the air conditioning system in the recirculation mode most of the time [5].

We chose to study the air quality in cars with and without using the air recirculation setting, because we supposed that the air recirculation setting can rapidly lead to significant increases in CO_2.

The hypothesis considered for the study, in a stationary car, is an atypical situation, but is frequently encountered in the following circumstances:

- when using the "drive-in" service where customers park their vehicles to enjoy an on-board service. As an example we can list drive-in restaurants, but also drive-in cinemas where people spend several hours in the car;
- in the daily traffic jams but also in occasional traffic jams, for example in cases of traffic accidents during blockages encountered when leaving or returning from vacations or when waiting at border crossing points, etc., when we are obliged to spend several hours in a stationary car.

The present research aims to study the air in vehicles from the perspective of carbon dioxide levels and the perception of air quality in cars in terms of the presence of different amounts of CO_2 in the breathing air.

2. Materials and Methods

2.1. Participants

All the participants in our study were students of a technical college, 19 students from the third year and 41 students from the fourth year. A total of 60 students, young drivers and passengers (34 men, 26 women; $M = 22.9$ years) participated in the assessment of the air quality during the measurement of CO_2 (first evaluation). Twenty out of the 60 subjects participated in another evaluation of the air before and after the measurement of CO_2. The perception of the air quality was measured on a Likert-type scale with seven levels (1—very poor; 7—very good quality of the air).

All participants signed an Informed Consent before participating in the research where they were informed about the purpose of the study, the procedure to be undergone, and the potential risks and benefits of their participation. Their participation was voluntary and they agreed to participate without remuneration.

2.2. Vehicle Instrumentation

Carbon dioxide measurements were made using a Trotec Data logger Air Quality CO_2 BZ30 machine with the following technical data: CO_2 sensor—NDIR (non-dispersive infrared); carbon dioxide measuring range: 0 to 9999 ppm CO_2; resolution (precision) CO_2: 1 ppm (±75 ppm or ±5% of measured value); measuring range: 2 s; readings memory: 50,000 measured values. A zero calibration was applied prior to every use.

2.3. Design and Conduct of the Study

The air quality assessment was carried out under the following conditions:

- one, two, three and four people in the car;
- In three vehicles: Dacia Logan, Hyundai and Renault ZE;
- In two situations: with recirculation and without recirculation of the air.

A different measurement of carbon dioxide at 10,000 ppm was reached with five people in a Dacia Logan cabin.

Our study is based on an experimental design with two groups and repeated measurements, a pre-test T_i and a post-test T_f.

Participants in these measurements and evaluations received an evaluation form and were given the task to evaluate the air quality on a scale from 1 to 7 (1-very poor; 7-very good quality of the air). The air quality was assessed when entering the vehicle (initial T_i pre-test phase) and the participants remained in the vehicle until the air reached 5000 ppm CO_2. A final T_f post-test evaluation phase was conducted at 5000 ppm.

Half of the CO_2 measurements and of the air quality evaluations have been performed with the recirculation mode on and half with the recirculation mode off. The cars were stationary in all cases.

We continued the experiment with another level of the variable, in which 20 out of the 60 participants assessed the air quality two more times. The first evaluation was made when entering the vehicle (initial phase). After this initial evaluation, they left the vehicle and then re-entered it after the amount of carbon dioxide reached 5000 ppm. At this time they assessed the air quality a second time T_f (final phase). Ten out of these 20 participants assessed the air quality in cars with the recirculation mode activated and 10 in cars without recirculation.

All the cars were stationary and the results should only be interpreted under these conditions. We opted for a stationary machine in order to eliminate the influence of vehicle speed on the CO_2 concentration within the cabin.

3. Results

3.1. Measuring and Analyzing Carbon Dioxide in the Cockpit

Analyzing the air quality within the cockpit is one of the aims of this article. To this end we measured how long it took the air inside the passenger compartment to reach a level of carbon dioxide concentration characterized as the CO_2 limit in occupational exposure within a maximum of 8 h (5000–5000 parts per million).

Due to the health risks associated with carbon dioxide, the average exposure of a healthy employee during an eight-hour working shift should not exceed 5000 ppm [45].

We chose to study two relevant situations in which carbon dioxide levels easily reach values that can influence the cognitive capacity of the driver and, in extreme circumstances, can endanger the health of the passengers. We refer to the situation in which the vehicle is stationary without the air being recirculated and to a second situation in which the vehicle has the air recirculation option activated (the scenario of a car blocked in a tunnel or stuck in traffic).

Table 4 lists the average (M) and standard deviation (SD) for the measurements conducted for all three types of vehicles, with one, two, three and four persons in the cockpit. It was observed that for a single person it takes 24 min, whereas for four persons it takes 7 min, to reach a level of 3000 ppm CO_2, i.e., the concentration at which substantial adverse effects on cognitive performance can lead to transportation risk [38].

Table 4. The averages and standard deviations for the time span necessary for the air within the cockpit to reach certain values of CO_2 (stationary vehicle without the recirculation of air).

Stationary Vehicle without Recirculation the Air								
Level of CO_2 (ppm)	**Time in min/1 Person**		**Time in min/2 Persons**		**Time in min/3 Persons**		**Time in min/4 Persons**	
	M_{1pers}	**SD_{1pers}**	**M_{2pers}**	**SD_{2pers}**	**M_{3pers}**	**SD_{3pers}**	**M_{4pers}**	**SD_{4pers}**
1.000	T1 = 4.17	0.44	T1 = 3.22	0.58	T1 = 2.44	0.58	T1 = 1.5	0.17
2.000	T2 = 12.64	2.44	T2 = 8.92	0.5	T2 = 5.67	0.5	T2 = 4.05	0.35
3.000	T3 = 24.41	3.50	T3 = 17.08	0.76	T3 = 10.33	0.76	T3 = 7.5	0.73
4.000	T4 = 38.78	3.91	T4 = 26.72	1.29	T4 = 15.11	1.29	T4 = 9.89	0.19
5.000	T5 = 56	5.29	T5 = 38.19	1.23	T5 = 20.89	1.23	T5 = 13.05	1.29

Table 5 lists the time necessary for the cockpit air with five people inside to increase from a level of 350 ppm to 10,000 ppm, the limit at which the first signs of respiratory acidosis can occur. The measurement was made in a stationary Dacia Logan. The time needed to reach 10,000 ppm was 28 min.

Table 5. Time (in seconds or minutes) needed for the air breathed by five persons to reach 10,000 ppm.

Level of CO_2	Time of Measurement	Δt (min) between 2 Levels of CO_2	Δt (s) 2 Levels of CO_2	T (s) Cumulative	T (min + s) Cumulative
350 ppm	09:46:49	00.00	00	00	0 min
1000 ppm	09:49:23	2 min 34 s	154	154	2 min 34 s
2000 ppm	09:51:29	2 min 06 s	126	280	4 min 40 s
3000 ppm	09:53:55	2 min 26 s	146	426	7 min 06 s
4000 ppm	09:56:21	2 min 26 s	146	572	9 min 32 s
5000 ppm	09:58:41	2 min 20 s	140	712	11 min 52 s
6000 ppm	10:01:37	2 min 58 s	178	890	14 min 50 s
7000 ppm	10:04:17	2 min 40 s	160	1050	17 min 30 s
8000 ppm	10:07:25	3 min 08 s	188	1238	20 min 38 s
9000 ppm	10:11:02	3 min 37 s	217	1455	24 min 15 s
10,000 ppm	10:14:52	3 min 50 s	230	1685	28 min 05 s

min = minute; s = seconds.

We include Figure 1 to show the time during which the carbon dioxide increased from 350 to 10,000 ppm (for five persons in a Dacia Logan).

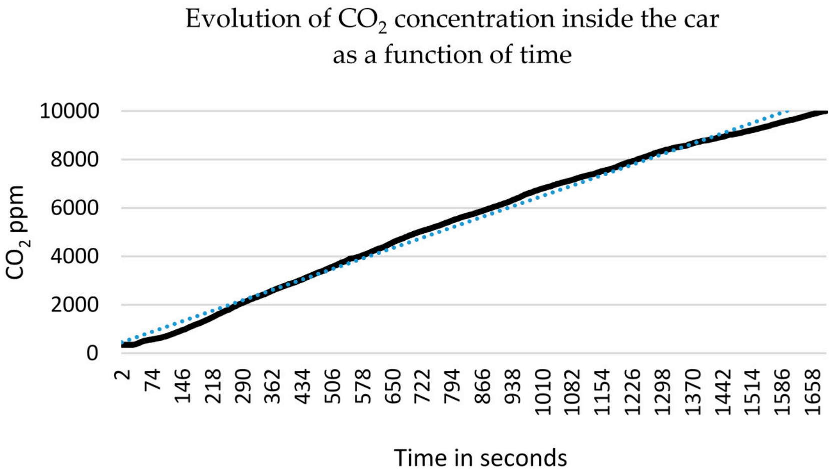

Figure 1. The graph curve of carbon dioxide in time.

The CO_2 curve indicates the amount of carbon dioxide and its evolution over time in a stationary vehicle with the recirculated air mode on, with five passengers. The measurements show that in about 12 min, the carbon dioxide level reached the limit for occupational exposure (5000 ppm). In about 28 min, the amount of carbon dioxide reached the level at which the first signs of respiratory acidosis appear (10,000 ppm). This plot suggests that CO_2 does not approach a steady-state concentration, not even at 10,000 ppm. This could be dangerous, calling for an alert, e.g., an alarm system triggered at this concentration.

Table 6 indicates the maximum, minimum and average scores for the three characteristics measured in a stationary Dacia Logan with five people in the cockpit. The sampling frequency was of 2 s, yielding 1581 measurements.

Another situation was the study of the air quality in the cockpit with the air being recirculated. There are usually economic reasons for which some people wish to recycle the air inside the cockpit.

However, increasing carbon dioxide levels can endanger the attention of the driver and even the lives of the passengers.

Table 6. Minimum, maximum and average CO_2, temperature and air humidity during the time in which the carbon dioxide level has risen from 350 to 10,000 ppm.

	Maximum	**Minimum**	**Average**
Carbon dioxide	10,000 ppm	350 ppm	5174.5 ppm
Temperature	29.20 °C	24.20 °C	26.8 °C
Humidity	45.50	30.30	37.9

Table 7 lists the time during which the air breathed by the occupants of the vehicles reached certain values of carbon dioxide, in the case of a stationary vehicle with recycled air. Recirculation was carried out at a flow rate of 105.64 m^3/h with ventilation activated at level 2 out of 4.

Table 7. The time during which the air breathed by the occupants of the vehicles reached certain values of carbon dioxide in the case of a stationary vehicle with recycled air.

Stationary Vehicle with Recycled Air								
Level of CO_2	**Time in min/1 Person**		**Time in min/2 Persons**		**Time in min/3 Persons**		**Time in min/4 Persons**	
(ppm)	M_{1pers}	As_{1pers}	M_{2pers}	As_{2pers}	M_{3pers}	As_{3pers}	M_{4pers}	As_{4pers}
1.000	T1 = 4.58	0.38	T1 = 2.75	0.50	T1 = 2.81	0.50	T1 = 1.83	0.17
2.000	T2 = 13.59	2.15	T2 = 8.86	0.33	T2 = 6.67	0.33	T2 = 4.39	0.54
3.000	T3 = 25.67	3.34	T3 = 17.53	1.25	T3 = 11.97	1.25	T3 = 7.83	1.04
4.000	T4 = 40.44	3.81	T4 = 27.69	2.96	T4 = 18.06	2.96	T4 = 12.19	3.81
5.000	T5 = 58.58	6.14	T5 = 40.53	4.73	T5 = 25.92	4.73	T5 = 15.53	2.61

The flow rate was measured using a TA 300 wire anemometer. The TA 300 Trotec had an accuracy of ±5% of +1 measurement unit and a 0.01 resolution. The values measured in the circulation mode are compatible and fit into the instrument's accuracy class.

Table 7 and Figure 2 show that the CO_2 concentration in the cabin increased from 1000 to 5000 ppm according to the time span and the number of persons in the car, with the air being recirculated. In the case of a single person, 58 min are needed for the air to reach 5000 ppm, while for four people, 15 min are needed to reach the same concentration of carbon dioxide.

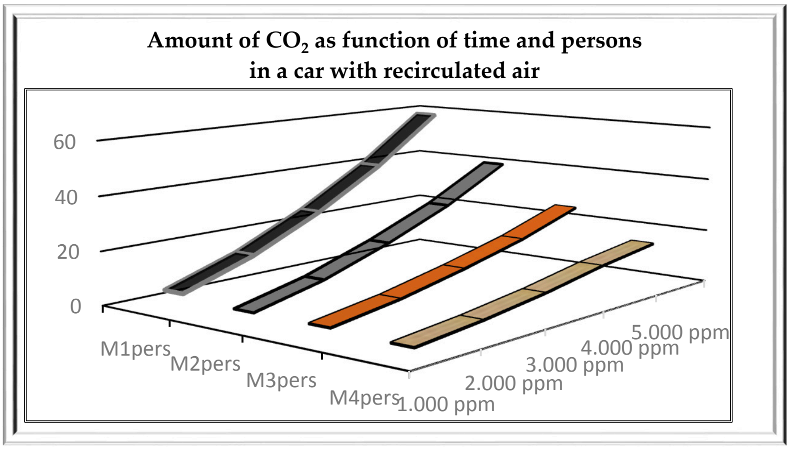

Figure 2. Amount of CO_2 according to time span and number of people in a car with recirculated air.

3.2. Analysis of the Air Quality Perception

The air quality analysis was based on the perception of the participants toward the study and consisted of a global assessment of the air quality at two different times: at the beginning of the carbon dioxide measurements (T_i), and at the end of the measurements (T_f) at 5000 ppm. The perception of the air quality was measured on a Likert-type scale with seven levels: 1, very poor; 7, very good quality of the air.

Our air quality study is based on an experimental design with two groups and repeated measurements, a T_i pre-test and a T_f post-test. The independent variable has two levels of variation (with recirculation and without recirculation) measured in the initial T_i pre-test phase and in the final T_f post-test phase. Since the data obtained on a Likert scale is ordinal data, we used nonparametric analysis tests.

3.2.1. Comparisons between the Two Groups of Participants (with and without Recirculated Air)

The comparative analysis conducted using the Mann-Whitney test shows that the scores obtained in the Ti pre-test phase with the group of participants who stayed in the car with the air being recirculated do not differ significantly from the scores obtained in the Ti pre-test phase of the evaluation conducted with the group of participants who stayed in the car without the air being recirculated (U = 450; N1 = 30; N2 = 30; p = 1). This result is obvious because both groups had the same relatively low (350 ppm) CO_2 concentrations, so they would be expected to have similar scores.

Participant post-test scores showed a divergence between the participants in vehicles with recirculated air versus those in vehicles without air recirculation, as indicated by the statistically significant difference in the Mann-Whitney test results (U = 194, N1 = 30; N2 = 30; p = 0.001).

The results of both comparisons are shown in Table 8.

Table 8. Results of the Mann-Whitney test.

Criterion		N	Mean Rank	Sum of Ranks	Test Statistics			
					Mann-Whitney U	**Wilcoxon W**	**Z**	**Asymp. Sig. (2-Tailed)**
Ti initial (pre-test)	R (−)	30	30.50	915.00	450.000	915.000	0.000	1.000
	R (+)	30	30.50	915.00				
Tf final (post-test)	R (−)	30	21.98	659.50	194.500	659.500	−4.070	0.000
	R (+)	30	39.02	1170.5				

R (+): with recirculation; R (−): without recirculation.

3.2.2. Comparisons of the Two Groups between the T_i Pre-Test and T_f Post-Test

The comparisons between the T_i pre-test and the T_f post-test phases have been made separately for each group, but also for both groups.

The comparative analysis, performed using the Wilcoxon Test (N = 60, z = 6.73, p = 0.000), shows that there is a significant difference in the air quality assessment between the T_i pre-test and the T_f post-test phases, for all participants.

In the case of the group with the recirculated air, the results of the Wilcoxon Test show that in the T_f post-test phase, the air with a concentration of 5000 ppm was considered to have a poorer quality than the air in the T_i pre-test phase, with 350 ppm CO_2 (N = 30, z = 4.84, p = 0.000).

A significant difference was also found in the case of the group without air recirculation, between perceptions of the air with 350 ppm and perceptions of the air with 5000 ppm (N = 30, z = 4.76, p = 0.000), in this latter situation the air being considered of a lower quality as compared to the initial evaluation.

3.2.3. Comparisons of Three Groups in the T_f Post-Test Phase

We wanted to know whether there are differences between the two groups who participated in measuring the CO_2 level and the third group that only participated in the evaluation of the air re-entering in the passenger compartment after the air had reached 5000 ppm.

We have applied the Kruskal-Wallis test in order to identify the difference between the perceptions of the air quality in the T_f post-test phase between all three groups mentioned. The results (chi-square = 29.16; p = 0.001) indicate that there are significant differences between the participants' assessments of the air quality in the cabin.

The results obtained (average rank for the three groups) show that the best air quality was perceived by those who stayed in the cars with recirculated air (M1 = 56.73) and the poorest air quality was evaluated by those who stayed outside the cockpit during the increase in the amount of CO_2 (M3 = 23.83).

3.2.4. General Assessments of the Air Quality

Although there are significant differences regarding the perception of air quality at 350 ppm and at 5000 ppm, the overall air quality assessment is positive both for the group of 60 participants (G60) who stayed in the car until the CO_2 level increased to 5000 ppm, and for the 20 participants (G20) who left the car after the initial evaluation and then re-entered the car for the final evaluation at 5000 ppm.

As seen in Figure 3, a percentage of 81.67% of the G60 participants assessed the air at 5000 ppm as being of a good or quite good quality and 13.33% considered the air to be neither good nor bad.

Although the differences in the perception of air quality differ significantly between the two groups mentioned, G20 does not consider the air quality to be poor. Specifically, 30% of them believed that the air quality is poor or quite poor, while 35% considered that the air is neither good nor bad, and 35% believed the air quality to be good or quite good.

The ranking of the quality of the indoor air, according to the European norm EN 13779, shows that a difference between the indoor and the outdoor air greater than 1000 ppm CO_2 is considered a low air quality [21]. In regards to this ranking, our results show that the majority of the study participants assessed the air, which in reality was of a low quality, as being good quality air.

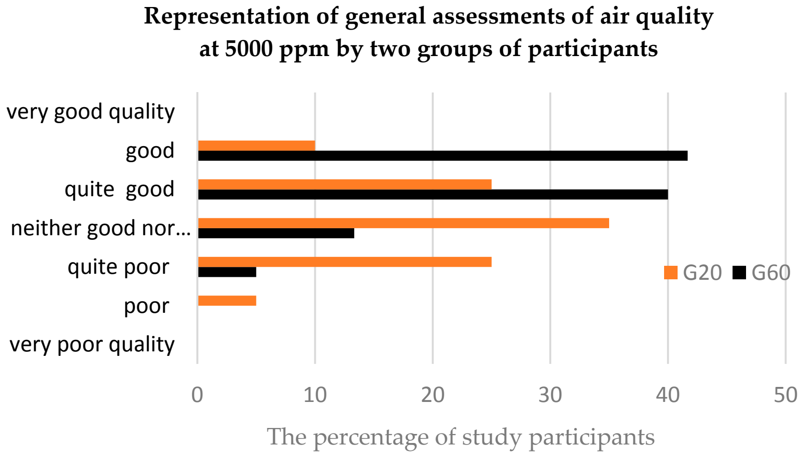

Figure 3. Representation of general assessments of air quality at 5000 ppm (T_f).

This situation in which stale air is perceived as good air must attract the attention of those responsible for traffic safety. They might require air quality regulation and control devices, because air whose characteristics as what regards the level of CO_2 is considered by many researchers to be air that can affect the cognitive abilities and the psychomotor reactions of the drivers.

4. Discussion

From the perspective of sustainable development, the energy efficiency of a vehicle is paramount for the preoccupations regarding comfort within the vehicles, but a concerted dialogue of specialists is required to study air, ambience and car interiors.

The aims of this article are to identify and highlight the conditions under which the air quality in vehicles can reach CO_2 concentrations which might influence the attention span and the cognitive abilities of drivers. The study also investigated how the perception of air quality changes with the CO_2 concentration.

The participants' perception of air quality varied considerably. Between the initial Ti and the final Tf phases of the evaluation, the carbon dioxide level in the air inside the vehicle increased from about

350 ppm to 5000 ppm. This difference in air quality was emphasized in the evaluations given by the participants. All of them ascertain that the quality of the air decreased after the CO_2 increased.

The participants who stayed in cars with the recirculation mode on perceived, at 5000 ppm, the quality of the air as being better compared to those who stayed in cars without the air being recirculated. This result can be explained by the fact that the existing ventilation, when the air recirculation is started, leads to an increase in the perception of the air quality.

The participants who stayed outside the cockpit perceived the quality of the air (at 5000 ppm) as being lower compared to those who stayed in the cabin while the level of CO_2 increased. This result suggests that there is an accommodation with polluted air and it is perceived as being of a higher quality than it actually is.

Although differences were identified, the global assessment of the air quality is not negative, but rather the air quality evaluations conducted by the three groups of participants indicate that at 5000 ppm the air is not perceived as being of a low quality. The respondent underestimated the measured concentration.

Carbon dioxide measurements performed in a stationary vehicle show that reaching the limit of 5000 ppm ranges from 13 min (for four people) to 56 min (for one person). When this limit is exceeded, carbon dioxide can have negative effects on both the driver and the passengers because the research of Fisk and Satish highlights the deterioration of focus and of the decision-making abilities starting at values of 1000 ppm [46].

The cabin of a car is a relatively tightly closed space [44] in which the occupants can spend more or less time. If the inside air is recirculated, the air quality in the cockpit can drop rapidly and the air inside the passenger compartment becomes unhealthy [5].

Air recirculation is recommended in situations such as when one wishes to isolate the driver and the passenger compartment from the outside air which can sometimes be polluted by different air pollutants, such as the air inside tunnels or on dusty roads.

In real life, the recirculation button is used when people want to heat or cool the air from the passenger compartment faster, which due to the air passing through the air conditioning system is increasingly warmer/colder, instead of letting the warm (cool) air in from the outside. There are also environmental and economic reasons why some people wish to recirculate the inside air. In order to reduce fuel consumption used for cooling (during summer), people opt for recirculating the air, thus assuming certain inconveniences such as misting, without being aware of the possible effects of the increase in carbon dioxide**.** In an electric car in which the energy consumed in order to heat the air is more appreciated than in other cars because it depends on the travel distance, the temptation to save energy and keep the air warm (or cold) is quite big and may underlie some decisions (such as recirculating the air), and this sometimes entails effects on the driving of the car as well as on the health of its occupants.

The results of this study may be useful to any driver who has assumed an ecological conduct and aimed to reduce fuel consumption and CO_2 emissions by limiting the use of air conditioning. More recirculation means less energy, but it is important for drivers to be aware of the risks linked to an increased concentration of carbon dioxide. The fractional air recirculation method could be a simple innovative way of improving air quality, in order to maintain a level of CO_2 that does not affect the cognitive capacity of the driver and of the passengers, and of contributing to gaining energy.

In conclusion, the increase in the carbon dioxide level above certain limits can be achieved in the everyday traffic conditions and while parking over a short period of time (from 15 min to 1 h). If the air inside a car is not sufficiently ventilated with fresh air, it degrades the air quality in such a way that it affects the focus and reactions necessary for safe driving.

This situation may generate some risks for the occupants without them perceiving any discomfort that would put the drivers or the passengers on alert.

Driving is a very common, highly complex task that requires cognition during every routine task, but also when it comes to higher-level decision tasks [47]. Driving typically involves three classes of task processes: operational processes for stable driving, tactical processes that govern safe interactions with the environment and other vehicles, and strategic processes for higher-level reasoning and planning [48].

Even if, for the moment, CO_2 alone is not considered an indicator of the chemical pollution of indoor air, from the point of view of road safety, CO_2 measurement is very important for drivers, for whom psychological evaluation targets the cognitive capacities (attention, decision, etc.) which ensure safe driving. Consequently, we consider it useful to have a monitoring system for the CO_2 level in the public transportation system, as well as in personal cars, especially because the air with a high content of CO_2 is not perceived as stale air.

The CO_2 levels in our atmosphere are rapidly increasing. Climatologists and other scientists have warned for more than half a century that the accumulation of CO_2 and other greenhouse gases in the atmosphere is leading to global warming and other significant climatic, ecological, and societal changes. In 1900 the ambient atmosphere was below 300 ppm; now the average ambient concentration of CO_2 is about 350–400 ppm and the level predicted by the end of the 21st century is around 800–1000 ppm. This increase may have implications on all of society, especially in jobs with critical responsibilities such as surgeons, air traffic controllers or drivers [8]. Lowering CO_2 is important from a transportation safety standpoint. A global awareness of this issue may enable a change in practice on CO_2 emission activities.

Acknowledgments: The related findings were gained through our work in the national project: Researches based on Knowledge Management Approach Concerning Industry–University Collaboration in the Open Innovation Context (UNIinOI). This work was undertaken through the Partnerships in Priority Domains Programme-PN II, developed with the support of MEN-UEFISCDI, Project No. 337/2014 in Romania. Any findings, results, or conclusions expressed in this article belong to authors and do not necessarily reflect the views of the national authority UEFISCDI.

Author Contributions: The proposed study is part of research carried out by all the authors, within a synergic collaboration, with continuous reciprocal feedbacks during the literature studies, the writing of the text and the measurements made. All authors contributed in all phases of the work.

Conflicts of Interest: The authors declare no conflict of interest.

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