Air Quality Into Cabin Environment of Different Passenger Cars: Effect of Car Usage, Fuel Type and Ventilation/Infiltration Conditions

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Research Article

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Abstract

Despite that commuters spend only 5.5% of their time in cabin vehicles, their exposure to harmful air pollutants, originated from the vehicle itself, and traffic emission is considered significant. In this study, two passenger cars with different type of fuels, were investigated in terms of air quality and thermal comfort of their cabin. Investigation was performed in the city of Kozani, Northern Greece. Moreover, air samples near the exhausts were taken, in order to compare concentration of compounds found indoors. 12 VOCs, and CO_2 were measured inside the cabin when the cars were stopped, when idle, and when they were cruising in medium and heavy traffic roads, under various ventilated conditions. Thermal comfort was investigated while driving the cars through the city traffic. Results showed that the air around the diesel exhaust is less affected by emissions from the engine compared to LPG fuel. This is reflected to the TVOC measured into the cabin. Results also revealed that the air quality of a diesel fuel moving car with open windows is only affected by the traffic emissions from neighboring vehicles, while for the car with LPG fuel, the self-pollution from its own exhaust might contribute together with the outdoor air.

1. Introduction

Human exposure to air pollution has become a major issue to scientific community and authorities, due to the fact that is strongly associated with human health problems and healthy life-years lost (e.g 2 million per year across EU-26, Boulanger et al. 2017). Indoor air, undoubtedly influenced by ambient air, gains interest during the last decades, as people generally spend more than 80% of their time indoors (Wang et al. 2007). A considerably amount of this time is spent inside vehicle cabins (~ 8% of the daily time), making this particular environment of special interest because of passengers' exposure to hazardous pollutants (Parry et al. 2007). As an example, concentration of Volatile Organic Compounds (VOCs) has been found in higher levels inside vehicle cabins compared to that of ambient air in the vicinity of the cabin (Weisel et al. 1992; Dor et al. 1995; Lawryk et al. 1995). On the other hand, short and long term exposure to several VOCs may cause mucosal irritation and considerably serious health problems such as neurological system damage, lung cancer and leukaemia (Araki et al. 2010; Hasan et al. 2013). Moreover, changes in pulmonary function and cardiac biomarkers were detected in adults when driving or working in private cars (Sarnat et al. 2014; Heinrich et al. 2005; Riediker et al. 2004).

Apart from exposure to potential indoor air pollution, car drivers and passengers are also exposed to thermal conditions; these conditions may be responsible for discomfort effects. It should be noted that thermal comfort in cars presents specific differences if compared to the case of buildings; these are mostly related to the effect of solar radiation, intensified by the complex and confined cabin shape. The presence of high-radiation surfaces inside the cabin, causes non-uniform and transient air-distribution through-out the operation of the air-conditioning system; psychological aspects can also be of concern, given the effort of the driver to cope with the requirements of the driving procedure (Zhou et al. 2019; Danca et al. 2016).

The air quality of vehicle cabin is potentially affected by the outside vehicle ambient air, the self-pollution from the vehicle’s own engine fumes, the vapour of the fuels used and the emissions from the interior materials of the cabin (Abi-Esber and El-Fadel 2013; Yue et al. 2017; Geiss et al. 2009). Many studies investigate the cabin air quality of a passenger car under static conditions (using chamber test or car parked), considering also car ageing (new versus old car, or new car over time passed), while underlying the presence of gassing pollutants from materials used for the manufacturing of the interior parts of the cabin. Given that the concentration of these pollutants decreases as time goes on, used cars present lower VOCs concentration compared to a new one (Yoshida and Matsunaga 2006; You et al. 2007; Kim et al. 2016; Xu et al. 2018; Deng and Chen 2008; Zhang et al. 2008; Brodzik et al 2014; Geiss et al. 2009). These studies also revealed that high concentrations of VOCs are observed while increasing interior temperatures. Kim et al. (2016) investigated the engine and ventilation condition effect in static automobile cabins, suggesting that the concentration trend of VOCs varied between engine off and idling engine on. Other studies investigate, among others, the air quality of vehicles’ cabin while commuting (Lawryk et al. 1995; Jo and Choi 1996; Jo and Park 1999; Som et al. 2007), indicating that VOC concentration is affected by the route characteristics (urban/suburban/tunnel route), the motor vehicle exhaust and evaporative emission of traffic conditions, the maintenance of the car engine, and the type of the vehicle used (bus versus passenger car). The results were extracted without considering the ventilation mode of the vehicles. Also, the pattern of individual VOC is shifted between static and driving condition (Fedoruk and Kerger 2003). In recent years, researchers studying the air quality of vehicles cabin, in the light of specific driving condition and various ventilation modes (Fedoruk and Kerger 2003; Duh 2015; Xu et al 2016); results demonstrate that ventilation conditions influence the VOC concentrations i.e. situation of a window half opened, rapidly reduced VOC levels. Finally, systematic investigation on the parameters that can affect cabin VOC levels under actual driving conditions is still scarce (Xu et al. 2016).

In this study, the air quality and thermal comfort of the cabin of two passenger cars, with different type of fuels, was investigated; cars were driven in the city of Kozani, Northern Greece. In addition, air samples near the exhausts were taken, in order to compare concentration of compounds of the surrounding environment with that found indoors. 12 VOCs, and CO_2 were measured inside the cabin when the cars were stopped, when idle, and when they were cruising in medium and heavy traffic roads, under various ventilated conditions. Thermal comfort was investigated while driving the cars through the city traffic. The analysis concentrated on the factors affecting cabin pollution, including, among others, the type of fuel, ventilation conditions and driving conditions. This study contributes to the building of concrete knowledge on maintaining sufficient vehicle air quality for the driver and the rest of the passengers.

2. Materials And Methods

2.1 Vehicle and measurements procedure

Two cars were investigated for cabin air quality; one manufactured in 2012, 1200cc (car A), and the other one in 2002, 1800cc (car B), presenting 132,450 km and 185,364 km of kilometrage, until the time of measurements, respectively. The study refers, regarding chemical compounds, to concentration analysis of VOCs and CO_2, as well as to thermal comfort analysis, for the cabin of the two vehicles. Car A uses diesel fuel, while car B is operated with both gasoline and LPG (Liquefied Petroleum Gas). The interior trims were mostly fabric ones for car A and mostly leather ones for car B. Before the measurements, all the additional accessories were removed (air fresheners, music cds, pillow etc). Measurements were conducted on 20th of April 2018, inside the cabin of the two cars, while they were parked outside the Environmental Technology Laboratory facilities, University of Western Macedonia, at an urban background site of the city of Kozani. Sampling took place when the engine was off and when the engine operated at idle mode; the fan of the vehicle cabin was not in operation, while the front windows were closed or half opened for both cases, thus resulting to four measurement scenarios (back windows remained closed for all cases presented in this work). Ambient conditions were also simultaneously recorded, for comparison purposes. In addition, two sets of measurements were conducted near the exhaust of the cars, using two kinds of fuels (diesel and LPG, Fig. 1). After these measurements, sampling of cabin's air took place, when both cars were driving in a route at the city centre of Kozani. The measurements were conducted regarding car A (diesel fuel) on 8th of May 2018, at 14:10 time, for a route with the windows closed, while the same route was repeated at 14:40 time with the windows open. For the two routes, the fan and AC (air condition) were closed. The route and the time of commuting were selected with regard to the occurrence of the heaviest possible traffic, while chosen roads included the presence of traffic lights, roundabouts, etc. Given that Kozani is a city of 40,000 habitants, with narrow roads and not too much traffic (only at rush hours), the above selections demonstrated a situation that can be characterized typical for a citizen driving at the particular city. At the same time, measurements for ambient air at a static point took place, namely outside the town hall building at the city centre. The above procedure was repeated at 9th of May 2018 for car B (LPG fuel). The sampling plan and the corresponding measurements are illustrated in Table 1.

Table 1
Details of the sampling procedure for different study conditions and the corresponding measurements.

Vehicle	Near exhaust (engine on-idle) (20/4/18)	In cabin, -windows closed, -engine off -Fan off (20/4/18)	In cabin, -windows closed, -engine on (idle) -fan off (20/4/18)	In cabin, -windows *opened*, -engine on (idle) -fan off (20/4/18)	In cabin, -windows closed, -driving -fan off	In cabin, -windows *opened*, -driving -fan off
Car **A** (diesel)	VOCs	VOCs	VOCs	VOCs	VOCs, CO_2, thermal comfort (8/5/18)	VOCs, CO_2, thermal comfort (8/5/18)
Car **B** (LPG)	VOCs	VOCs	VOCs	VOCs	VOCs, CO_2, thermal comfort (9/5/18)	VOCs, CO_2, thermal comfort (9/5/18)
Outside car air		VOCs	VOCs	VOCs	CO_2, external T, %RH	CO_2, external T, %RH

2.2 Field sampling and analysis

Air samples for VOC analysis were taken using low volume personal pumps (SKC) and pre-conditioned glass tubes filled with Tenax TA (Chrompack) at flow ratios of about 80 mL/min for 30 minutes. Moreover, duplicate samples were taken and blank tubes were analyzed for quality assurance/quality control purposes. Samples were analyzed using a thermal desorption unit (Gerstel TDS2) coupled to a gas chromatograph (Agilent 6890N), equipped with a mass spectroscopy detector. Tenax tubes were thermally desorbed using Gerstel thermodesorption system TDS2 with autosampler TDSA, in splitless mode, using the following programme: initial temperature: 40 ^{o}C, raised to 250 ^{o}C at 30 ^{o}C/min, held at 2.5 min and raised up to the final temperature of 280 ^{o}C, which was the transfer temperature to the CIS (Cryocooling injection system). The desorbed compounds were trapped at the CIS at -120 ^{o}C and then underwent rapid heating to 280 ^{o}C to enter the gas chromatography capillary column. The initial oven temperature was kept at 35 ^{o}C for 5 min and then increased at 80 ^{o}C with a rate of 8 ^{o}C/min and kept there for 6 min. After that the temperature increased up to 100 ^{o}C with a rate of 20 ^{o}C/min and kept there for 3 min. The total run time was 30.63 min. Cabin and ambient thermal comfort parameters, namely temperature and relative humidity, as well as CO_2 concentration, were measured with Hobo MX1102; sampling time of 1 minute was implemented. According to technical specifications data provided by the manufacturer, the accuracy of the temperature sensors is ± 0.21 ^{o}C, that of relative humidity sensor ± 2%, while that of the CO_2 sensor ± 5% or ± 50 ppm.

3. Results And Discussion

3.1 VOC concentrations under static conditions

VOC compounds measured near the exhaust are illustrated in Table 2; results demonstrate that the air in this position is less influenced by the emission of the engine exhaust, compared to the case of LPG fuel. It is worth noting that, as one may see in Fig. 1, these measurements do not represent the emission of the two cars, but only the air around the exhaust. The measurements were taken with very calm windy conditions in order not to dilute the air. Also, the time of sampling was 3 min, at a flow rate of 80 mL/min, in order not to overload the sampling tubes. In Table 2, the air concentration of VOC near the exhaust of vehicle B when it is operated with Unleaded Petrol (ULP), is also illustrated. The most abundant compound near diesel exhaust was benzene, while for the LPG and ULP was toluene. These findings agreed with previous studies, except than in the case of ULP where toluene was the second abundant compound (Ayoko et al. 2014; Hu et al. 2017). In Figs. 2 and 3, the cabin VOC concentration, for the two cars A and B, is illustrated respectively. Concerning the interior trims of the two cars, car A with most of fabric surface showed less VOC concentration for all the measured compounds, than car B with most leather interior surface (ΣVOC_{meas} of 15.69 and 154.17 μg/m^3 respectively). Even though the car B is older than car A, it seems that the interior material is responsible for the higher VOCs concentration obtained. Toluene was the most abundant compound found in the two cars, with a concentration of 56.10 μg/m^3 (for car B, with leather interior), which was 14 times higher than the level in the vehicle A (fabric interior). Similar results were also found at previous studies (Xu et al. 2016; Yoshida et al. 2006).

Table 2
VOCs air concentration near car exhaust using different type of fuel (in μg/m^3)

Compounds	Diesel	LPG	ULP
Benzene	12.45	210.62	869.20
Toluene	2.85	658.56	2467.85
Octane	0.45	12.45	54.34
Ethylbenzene	1.31	199.26	807.65
p-m-xylene	1.94	548.31	2272.50
a-pinene	ND	ND	ND
o-xylene	0.89	239.57	978.35
1,2,4-Trimethylbenzene	0.73	238.40	956.50
Napthalene	0.08	18.42	92.87
d-limonene	ND	ND	ND
Styrene	0.11	20.06	75.05
1,2,3-Trimethylbenzene	0.83	280.79	1074.76
$\Sigma VOCs_{meas}$	21.64	2426.44	9649.07
ND: Not Detected			

For car A, comparing the cabin VOC with engine idle, under conditions of closed windows and fan off against windows open and fan off, it can be concluded that when the window is closed, the level of VOCs is increased, suggesting that the engine emissions do influence the cabin air. The same situation was observed for car B, as well. When the windows of the car A were opened, it seems that the vehicle cabin air VOCs concentration remains more or less at the same level compared with that of outdoor air. On the other hand, for car B (LPG fuel), the cabin VOCs concentration is elevated when the windows are open, compared to the outdoor air (ΣVOC_{meas} of 34.25 and 10.86 μg/m^3 respectively), thus suggesting that the exhaust emissions influence more the interior than in the case of the diesel. This could also be attributed to the fact that air near LPG exhaust presents significantly higher VOCs concentration, compared to the case of diesel (Table 2). Moreover, from Fig. 2, it can be concluded that, for the diesel case, the engine emissions play an important role instead of the cabin materials emissions, as the ΣVOC_{meas} is almost double for windows closed and engine on in idle mode, compared to measurements with windows closed and engine off.

The above findings demonstrate differences between the air quality of the vehicle's cabin with regard to the type of fuel of the cars adopted in this work. In addition, the ventilation mode with windows open positively affects the VOCs’ concentration, forcing their reduction, in contrast to the case of windows closed. These are concluded when the car is stopped and the engine is on idle mode.

3.2 VOCs concentration under driving conditions

VOCs’ concentration of cabin air of the two cars while they are driven around the city, in busy roads, are illustrated at Table 3. As discussed above, the two identical routes of car A were performed at 8th of May 2018, crossing the same roads; one route included the windows closed and fan off, while the other included windows half open and fan off. The two routes were done successively; the first started at 14:10 and the second started at 14:40; route times were chosen according to the presence of as much as possible traffic in the city roads. The same route, anticipating same procedures, was implemented for car B by the next day (9th of May 2018); at 13:45 with windows open, and at 14:16 with windows closed. From Table 3, it is obvious that, for car A (diesel fuel), when driving the route with windows open, the VOCs’ concentration level is almost 3 times higher than the one with the windows closed. This suggests that the traffic emissions highly affect the cabin air quality when the windows are open, in contrast to windows remaining closed. Also, as mentioned before, the emissions from car A exhaust and the emissions from the interior materials did not play an important role on cabin air quality. Comparing the two modes of car A (static and moving), different conclusions can be drawn for the use of ventilation: when the car is moving around the city, the windows should remain closed, while when the car is stopped, the windows must be opened. For car B (LPG fuel) the situation seems different: the levels of VOCs, comparing the route with the windows closed to the route with the windows open, are almost the same, suggesting that the ventilation mode does not play an important role. This could be related to the fact that the interior materials, as well as the exhaust emissions of the car B potentially affect the cabin air quality, as concluded for the case of static mode measurements. Also, the cabin air, for car B, is affected by the outside concentration when the windows are open.

Table 3
VOCs air concentration in vehicles cabin when they are moving (in μg/m^3)

	Car A (diesel)		**Car B (LPG)**	
Compound	windows **closed**	windows *open*	windows **closed**	windows *open*
Benzene	1.61	6.69	5.53	5.96
Toluene	4.96	17.39	20.32	19.23
Octane	1.19	1.59	1.08	1.31
Ethylbenzene	0.94	3.16	3.70	3.99
p-m-xylene	2.88	11.64	12.21	14.64
o-xylene	1.22	21.25	25.29	26.35
1,2,4-TMB	1.51	4.60	4.12	5.59
d-limonene	2.06	0.16	3.23	0.32
Naphthalene	0.34	0.40	0.62	0.51
Styrene	0.35	0.85	1.03	0.74
1,2,3-TMB	1.73	5.38	4.74	6.43
ΣVOC_{meas}	18.78	73.10	81.86	85.07

ND: Not Detected, TMB: Trimethylbenzene.

It is worth to mention here, that the only compound that is decreased when the windows are open, for car A, is d-limonene (Table 3) which is in higher concentration when windows are closed (2.06 to 0.16 μg/m^3 when windows are open). This can be attributed to the fact that d-limonene is not an exhaust emitter compound; the cabin concentration derived from the cabin materials emission or previous usage of aromatic air fresheners. This is a strong evidence that the cabin air quality is potentially affected by intrusion from neighbouring vehicles, when windows are open. The same can be the case for car B also, as the compound d-limonene concentration was 0.32 μg/m^3 for the case of open windows, in contrast to 3.23 μg/m^3 for the case of closed windows. Thus, it can be stated that the air quality of car B, when the windows remain open at driving mode, is highly affected by the traffic emissions and from self pollution by its exhaust.

Jo and Yu (2001), demonstrated that diesel fuelled vehicles are primarily impacted by the penetration of roadway air into the cabin, while for the gasoline fuelled vehicle, the exhaust emission is rich with the target VOCs, due to the presence of these components in the gasoline. The same conclusion can be conducted from the present study, according to Fig. 2 and Tables2 and 3. In addition, Som et al. (2007)

found that in vehicles with LPG fuel, the BTEX concentration is higher than the diesel one, as our study reveals.

3.3 Thermal comfort and CO_2 concentration

Thermal comfort parameters, namely temperature and relative humidity, as well as CO_2 concentration, were also measured throughout the above described experimental sequences for car A (diesel fuel). In the following figure (Fig. 4), one may see temperature and relative humidity, cabin (T_{in}, RH_{in}) and ambient quantities (T_{amb}, RH_{amb}), noting that Fig. 4a refers to the case of closed windows and 4b of open ones.

As one may see, the case of closed windows leads to a thermal environment characterized by significantly higher temperatures than the proposed ones for thermal comfort satisfaction by the relevant standards (ASHRAE, 2017; CEN, 2012; CEN, 2005). Relative humidity is within acceptable limits, even though, for that level of temperatures, the indicated values suggest increased presence of water vapour due to human breathing. For the case of open windows, ambient and cabin values are very close, as expected. The above findings are in agreement with the ones extracted through Fig. 5, demonstrating CO_2 concentration. Closed windows lead to very high values of CO_2 concentration, noting that the indicated value of 5000 ppm refers to the upper limit of the used instruments scale, thus actual values may exceed this value. The observed values lie far beyond the established acceptable levels of 1000–1100 ppm (CEN, 2007; ANSI/ASHRAE, 2001), noting that 5000 ppm is the limit for long-term exposure in workplaces, according to the Occupational Safety and Health Administration of the United States.

Open windows reveal slightly higher cabin values, with regard to the ambient ones, potentially due to the effect of traffic emission on the cabin environment.

4. Conclusions

The cabin air quality of two passenger cars, with different types of fuel used, was investigated in correlation with driving mode and ventilation conditions. The results show that the type of the interior material used, affects the VOC concentration level; leather surface seems to influence more the air quality instead of fabric ones. For both cars investigated, exhaust emission influences the cabin air concentration, in terms of VOCs, when the windows of the car are closed. Moreover, the type of the fuel used seems to play an important role when the engine is on, the car is stopped and the windows are open, because of the different levels of cabin air VOCs’ concentration in contrast to outdoor air concentration.

The ventilation mode appears to be an important issue for cabin air VOCs’ concentration when the car is stopped and the engine is on, as open windows reduce the cabin VOCs’ level, compared to closed ones. The air quality of car A, when the windows are opened at driving mode, is only affected by the traffic emissions from neighboring vehicles, while, for car B, the self pollution from its own exhaust might contribute, together with the outdoor air.

Finally, in terms of thermal comfort, closed windows lead to unacceptable cabin temperature, while the relative humidity, even though within acceptable limits, demonstrates higher water vapour quantity than ambient one, due to the lack of fresh air. CO_2 concentration verifies the above, leading to considerably higher values than the acceptable levels by the relevant standards. Open windows reveal similar to ambient conditions for the cabin, regarding both thermal and CO_2 concentration quantities, noting the slight effect of traffic on cabin CO_2 concentration.

Declarations

Authors Contributions

E.T.* directed the research participate at sampling and analysis and wrote the manuscript with input from all authors, T. C. and G. S. participate to sampling and analysis G.P. contributed to the indoor climate measurement and their analysis, J.B. contributed to the resources, writing—review and editing.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Consent given by all contributing authors.

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Competing Interests

The authors declare that they have no competing interests.

Availability of data and materials

Not applicable

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Figures

Figure 1

a) Vehicle measurement and b) map of route travelled during measurement campaigns in Kozani city, Greece (blue line)

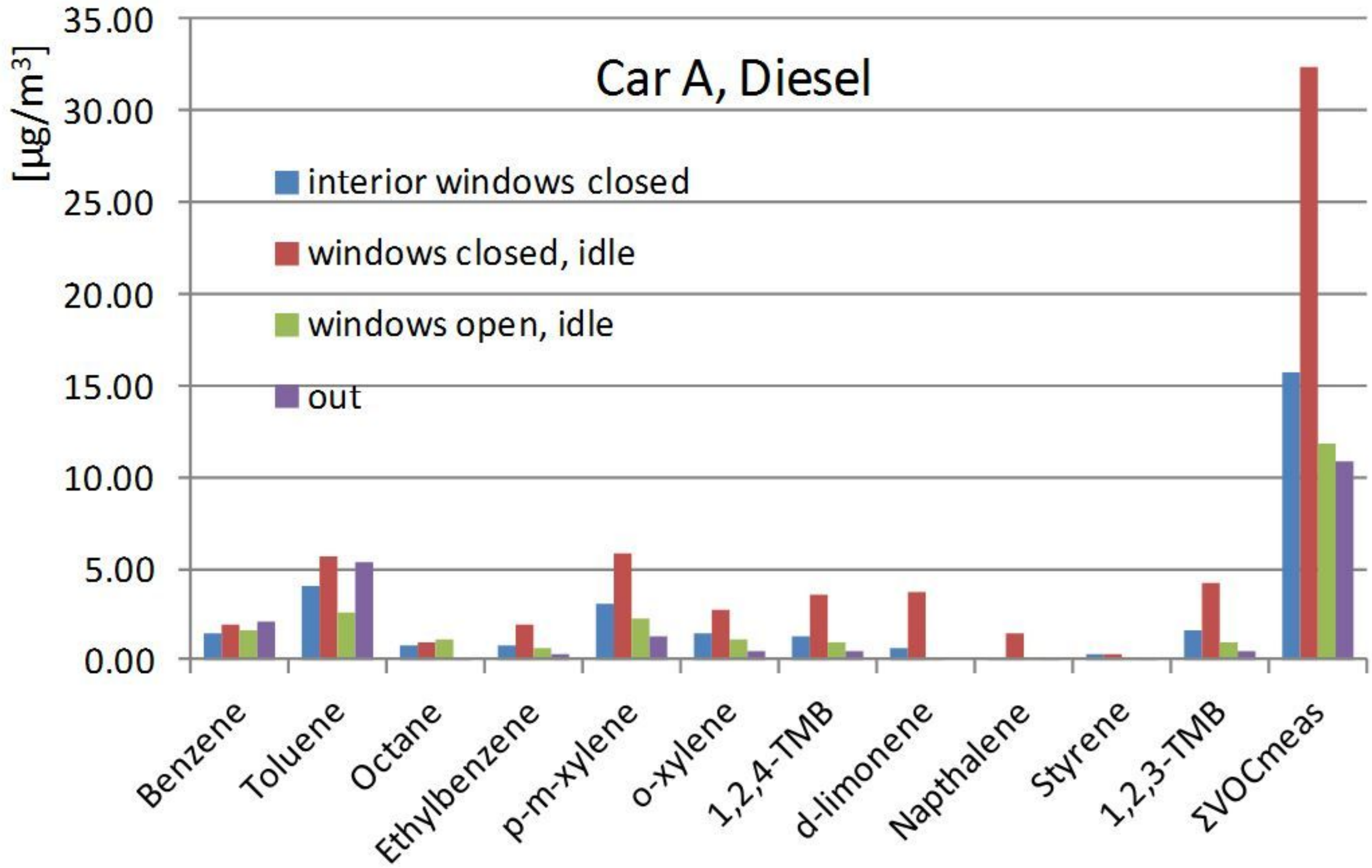


Figure 2

VOCs concentration (in µg/m3) for car A (diesel fuel) under static condition with different ventilation scenarios and engine operation.

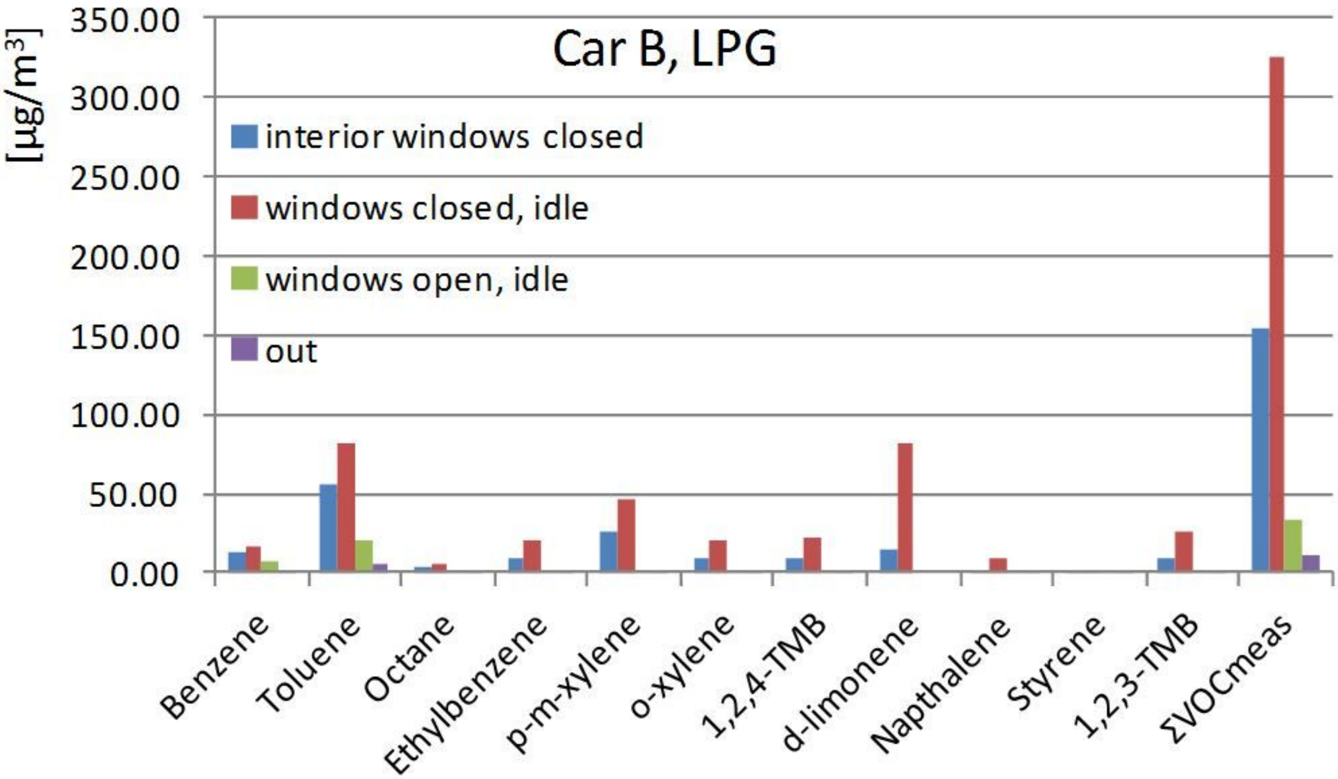
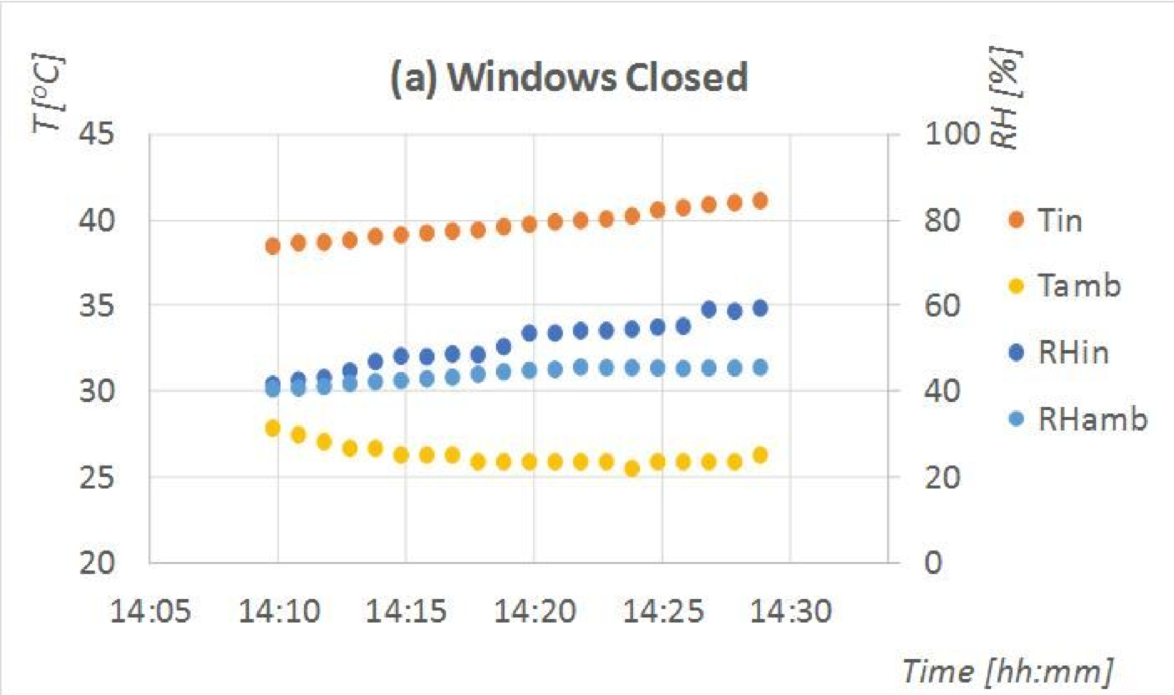


Figure 3

VOCs concentration (in µg/m3) for car B (LPG fuel) under static condition with different ventilation scenarios and engine operation.



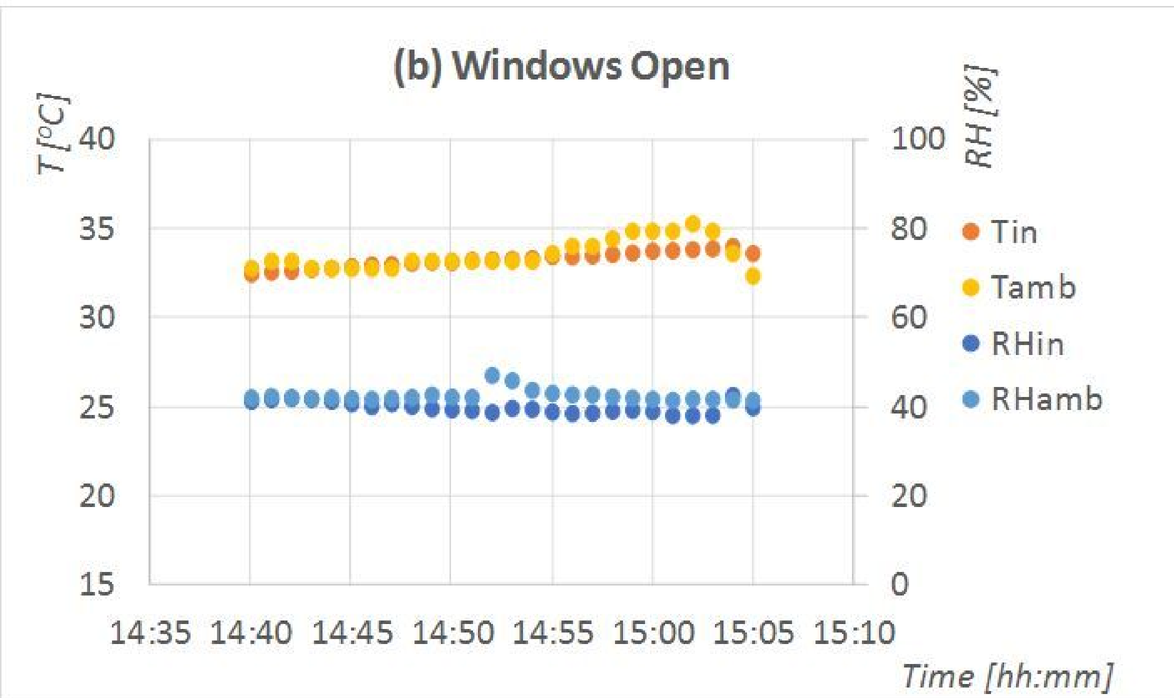


Figure 4

Cabin and ambient temperature for car A (diesel fuel): a. windows closed, b: windows open

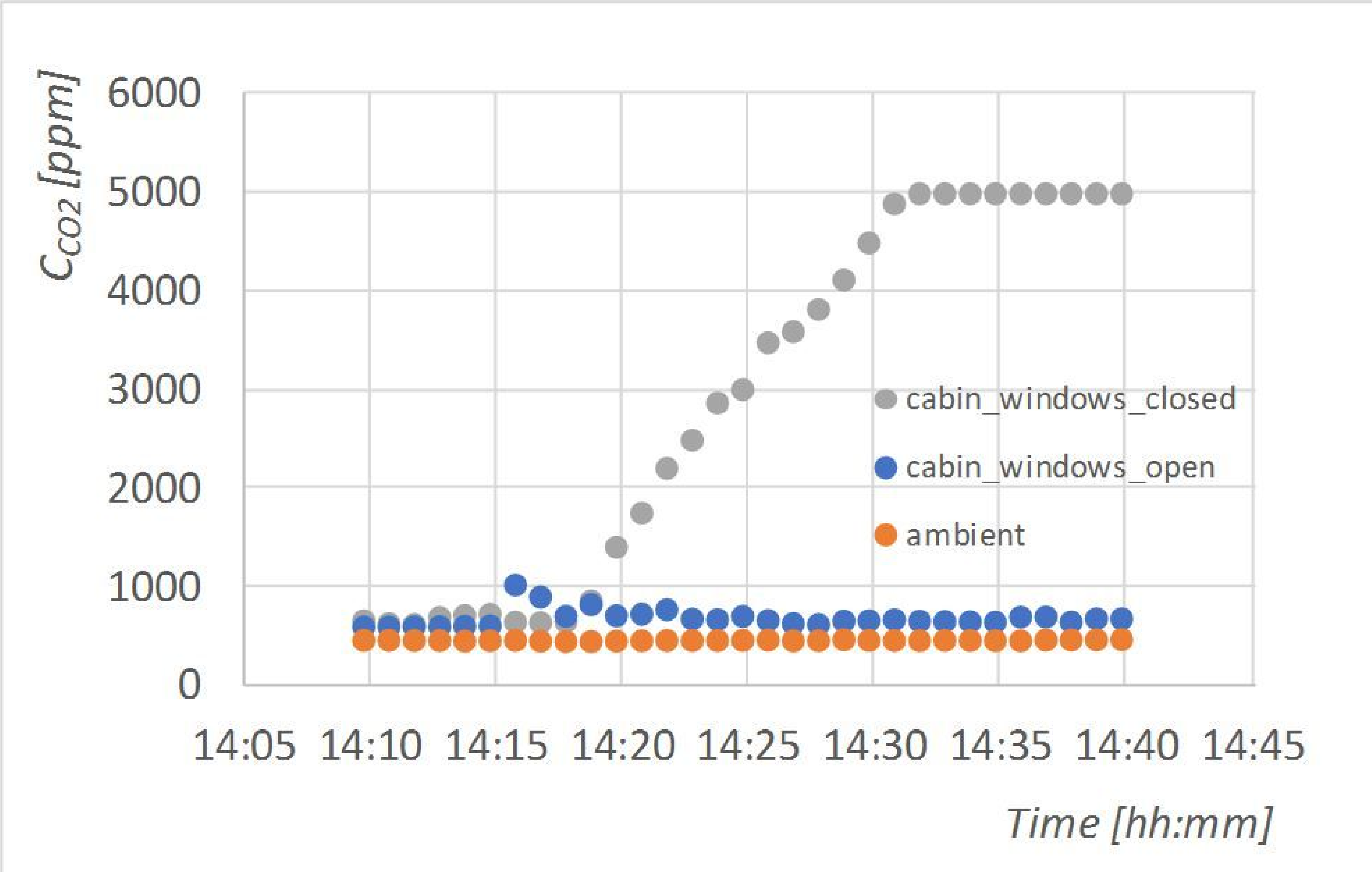


Figure 5

CO_2 concentration for car A (diesel fuel) under closed and open windows