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1	Experimental analysis and quantification of air infiltration into a
2	passenger car cabin
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17	Abstract
18	Nowadays, air quality in closed environments is of major interest, particularly in very small
19	volumes such as car cabins. In typical driving conditions, ambient air enters by infiltration as
20	the vehicle speed increases. In order to satisfy more ambitious requirements on air quality and
21	energy savings, it is necessary to evaluate the infiltration risk. At first, an experimental
22	method is created to identify the infiltration path in the cabin of a moving car. On a modern
23	electric vehicle, the privileged path is observed at the front of the cabin near the feet of the
24	front passengers. A second experimental campaign is performed to quantify the infiltration
25	flow rate. Results show that the flow rate is not negligible as it can reach several dozen
26	kilograms per hour. The ventilation settings (blower speed and recirculation ratio) can be
27	managed to reduce or even completely remove infiltration in some cases.
28	
29	
30	Keywords
31	Infiltration, Leakage, Ventilation, Air quality, Tracer gas
32	
33	

34	Nomenclature						
35	Q	Volumetric flow rate (m <sup>3</sup> /h)					
36	t	Time (s)					
37	V	Cabin volume (m <sup>3</sup> )					
38	C(t)	Mass fraction concentration					
39							
40	Subscripts						
41	amb	Ambient (outside environment)					
42	CO <sub>2</sub>	Carbon dioxide					
43							
44	Acronyms						
45	GPS	Global Positioning System					
46	GRG	Generalised Reduced Gradient					
47	HVAC	Heating, ventilation and air-conditioning					
48	NEDC	New European Driving Cycle					
49	WLTC	Worldwide Harmonised Light Vehicle Test Cycle					
50							

### 52 **1. Introduction**

53 Heating, ventilation and air-conditioning (HVAC) system plays a major role in the thermal 54 comfort (Lesage et al., 2019b) and air quality of car cabins (Mathai et al., 2020; Migaud et al., 55 2018). It also has a safety aspect regarding the windshield defogging. In modern vehicles, the 56 HVAC system is managed either manually by the passengers or automatically by the on-57 board control system. Depending on the outside conditions (temperature, humidity, pollution) 58 the amount of air driven by the blower can be adjusted, as well as the portion of recirculated 59 air compared to fresh air. In addition to this controlled airflow, there can be another uncontrolled airflow from the outside into the cabin: infiltration. The terminology related to 60 61 airflows considered in the article is shown in Figure 1.



Figure 1 Overview of the air circulation in and out of a passenger car

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66 The "infiltration" term refers to the air entering the cabin by other means than the blower 67 operation. This word has a similar meaning than the words "intrusion" or "penetration". 68 Depending of its intensity, infiltration can have a wide impact on the cabin system. Indeed 69 one can build a perfect filtration system in the ventilation circuit, it remains pointless if the air 70 enters the cabin by other means. This issue is also important concerning the energy aspect. 71 The thermal balance can be influenced as more outside air enters the cabin. The infiltration 72 phenomenon must not be neglected as it can introduce a significant amount of air, particularly 73 at high vehicle speeds. The objectives of this study is to understand the infiltration process 74 and quantify the flow rate driven. Eventually the work presented in this paper can help to 75 offer solutions: either change the vehicle manufacturing process to achieve an airtight car 76 body, or apply a strategy to the ventilation system to limit the infiltration flow rate. The 77 benefits could be important either on the air quality or on the energy consumption.

78

At first, this article presents the state of the art found in the literature regarding infiltration. Then experiments are realised on a modern electric vehicle in order to identify the air paths as it exits or enters the cabin. The localisation of infiltration on this vehicle leads to reconsider the models found in the literature. An experimental campaign is realised on two modern vehicles to evaluate the infiltration flow rate in driving conditions.

84 85

### 86 **2. Literature review**

The literature research shows that infiltration is not a widespread phenomenon in the automotive field. Most findings concerning the infiltration of air in a closed volume is for building applications. Old or recent studies investigate the characterisation of airflow through cracks, with a pressure approach (Baker et al., 1987; Lv et al., 2018). Equations are created to 91 link the pressure drop and the flow rate. The most common use a power law, but the authors 92 advocate for a quadratic equation as a better and more general equation to describe crack 93 flow. These equations are verified with experiments for different crack geometries and a large 94 range of Reynolds number. The characterisation of infiltration in buildings can also be 95 evaluated with means of gas tracer methodology (Heidt and Werner, 1986). The monitoring 96 of a gas concentration is used to calculate the air exchange rate within a room. Both the 97 pressure approach and the gas tracer methodology could be applied to vehicles.

98

99 One of the few studies with a vehicle application is the work of Xu et al. (2010). It 100 investigates the penetration of particles through different crack geometries in the car body. 101 The authors point out the high influence of this infiltration over the cabin air quality. 102 However, the investigation is not made with a moving car but in static conditions. Another 103 study explores the influence of the vehicle velocity on the ventilation system (Fišer and 104 Pokorný, 2014). The authors built a thermal model to predict the cabin heat load. They point 105 out that the vehicle velocity has high influence on the model accuracy, particularly at high 106 speed. A possible cause could be a dependency between the amount of air exchange rate and 107 vehicle speed. The authors do not investigate the infiltration issue.

108

109 Several studies suggest that the cabin pollution level is correlated to exhaust intrusion 110 elsewhere than through the blower (Chan et al., 1999; Fruin et al., 2011; Harik et al., 2017; 111 Hudda and Fruin, 2013). There is a debate whether this penetration occurs at the front of the 112 cabin through the firewall (Abi-Esber and El-Fadel, 2013; Chan and Chung, 2003) or near the 113 trunk (Behrentz et al., 2004; Zagury, 2000). This is important to know if the infiltration air is 114 polluted by the vehicle itself (self-pollution through the trunk) or by the upfront vehicle 115 (infiltration at the front). It should be noted that these studies focus on the pollution level 116 within the cabin rather than the infiltration effect itself or any attempt to quantify it.

117

118 A detailed methodology to measure infiltration flow rate is found in the work by Knibbs et al. 119 (2007). This is an experimental investigation of the air flow rates with different ventilation 120 settings and vehicle velocity. The authors used a tracer gas methodology with sulphur 121 hexafluoride (SF<sub>6</sub>). The study is made with cars of different types: small hatchback, sedan, 122 pick-up truck and large hatchback. Two cars are from 1989 and 1998 with high mileage (> 120 000 km) while two cars are both from 2005 and in relatively new condition (< 8 000 km). 124 Tests are performed at 0, 60 and 110 km/h with four ventilation settings. The test results indicate that the flow rate increases with vehicle speed, particularly for older vehicles. From lowest to highest vehicle speed, the air flow rate can be increased by up to  $150 \text{ m}^3/\text{h}$  for the 1989's car, and around 30 m<sup>3</sup>/h for the 2005's cars. The experiment is repeated with two additional vehicles (Knibbs et al., 2009). Authors explain that the blower operation is likely to reduce the infiltration flow rate. Infiltration appears in recirculation mode as well as in fresh air mode. This infiltration has a negative impact on the particle level within the cabin.





133 Figure 2 Evidence of infiltration in 6 vehicles from Knibbs et al. (2009, 2007)

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135 Similar methodology has been used in several older studies using CO or SF<sub>6</sub> as the tracer gas 136 in passenger cars (Conceição et al., 1997; Fletcher and Saunders, 1994; Ott et al., 1994; 137 Petersen and Sabersky, 1975) and school buses (Behrentz et al., 2004; Ireson et al., 2004; 138 Marshall and Behrentz, 2005). All studies confirm an increase of the air exchange rate with 139 vehicle speed. Fletcher and Saunders (1994) find that the wind speed and direction have a low 140 influence on infiltration compared to the influence of vehicle speed. Overall, the vehicle 141 samples are limited, as well as the maximum speed and the ventilation settings. A couple of 142 studies use CO<sub>2</sub> (Park et al., 1998), N<sub>2</sub>O (Clifford et al., 1997) or alcohol (Engelmann et al., 143 1992; Ott et al., 2008) as a tracer gas but only in stationary conditions.

144

The most complete and detailed work on infiltration is performed by Lee et al (Lee, 2013; Lee et al., 2015a, 2015b; Quiros et al., 2013; Zhu and Lee, n.d.). The global approach relies on the pressure competition in and out of the cabin. According to the authors, the infiltration flow rate can be calculated knowing two differential pressures (cabin and aerodynamic).



151 Figure 3 Cabin pressurisation and infiltration model adapted from Lee studies

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153 Experimental tests with a broad range of vehicles (sedan, hatchback, SUV, minivan) led to 154 repeatable outcomes. Tests are performed with a moving vehicle (up to 120 km/h). A model is 155 created from the test results. On the one side, the aerodynamic pressure can be calculated 156 knowing the vehicle speed. On the other side, the cabin pressurisation depends on the flow 157 rate of fresh air entering the cabin (itself depending on blower speed and recirculation ratio). 158 Several correlation coefficients are used to adjust the model for each tested vehicle. The idea 159 is that infiltration is triggered by the competition between the aerodynamic and cabin 160 pressures: infiltration happens when the aerodynamic pressure is higher than the cabin 161 pressure. According to the article the infiltration is located at the rear back of the cabin for all 162 the studied vehicles.

163

164 In order to assess what could be the potential impact of infiltration on the cabin air quality in 165 real driving conditions a computed scenario is performed. This one is developed with the 166 vehicle X parameters (see part 3). The vehicle is in fresh air mode (recirculation OFF), and 167 Lee's infiltration model based on its average vehicle is used. The calculation is performed on 168 a normalised road cycle. The WLTC is a mixed cycle, with urban, suburban and highway 169 parts, that replaced the NEDC as the most common procedure in Europe. This cycle covers 170 most driving conditions in terms of vehicle speed. The infiltration results are presented on 171 Figure 4.



174Figure 4 Results of infiltration flow rate with Lee's model on normalised driving cycle (WLTC) with175various blower settings

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On the road cycle, the infiltration occurs most of the time but at a reduced flow rate. With a blower setting at 10 m<sup>3</sup>/h, the infiltration volume over the whole cycle (1800s) is 15 m<sup>3</sup>. This is a very high amount compared to the air volume driven by the blower (5 m<sup>3</sup>). As the blower flow rate increases, the infiltration decreases. At medium blower position (150 m<sup>3</sup>/h) the infiltration does not appear before the final part of the cycle (highway). This setting is good for urban and suburban trips. With the blower at its maximum speed (300 m<sup>3</sup>/h) there is no infiltration in the highway part either.

184

185 It appears that the infiltration can have a very high impact on the air circulating in the vehicle. 186 In recirculation mode or at a low blower setting the infiltration air prevails in the cabin. A 187 solution to reduce or even delete the infiltration is to increase the amount of fresh air driven 188 by the blower. According to Lee's model, this allows creating an overpressure in the cabin 189 that acts as a shield against infiltration. Lee's studies do not include experiments on modern 190 or electric vehicles. Hence, this model must be checked and/or adapted. In that purpose 191 several experiments are performed, described in the following sections.

192

193

### **3. Experimental identification of leakage and infiltration paths**

The experiments are performed with a full electric vehicle from 2018 with a total mileage of 3800 km. It is referred to as "vehicle X". All tests are performed at ordinary ambient temperature (19-25°C) and relative humidity (40-60%).

199 At first, the idea is to acquire knowledge on the exchange of air between the cabin and its 200 surrounding environment. In that regard, it is important to identify the leakage path(s), from 201 the cabin to the outside, and the infiltration path(s), from the outside to the cabin. The outside 202 air driven by the blower into the cabin is not included in the "infiltration" term, but rather as a 203 "fresh-air inlet" (as depicted on Figure 1). Indeed the fresh-air inlet flows through the HVAC 204 system comprising the filters and heat exchangers, while the infiltration is an unwanted and 205 uncontrolled airflow allegedly introducing pollutants, particles and disturbing the thermal 206 balance of the cabin.

207

208 Tests are performed in static condition (0 km/h). The vehicle is placed in a room which 209 ventilation system can be deactivated by the operator. Hence, the tests are not influenced by 210 any uncontrolled external airflow (e.g. wind). For information, the vehicle cabin volume is 211  $2.5 \text{ m}^3$  (specification from manufacturer), and the raw volume of the room (i.e. empty) is 212 approximately 90 m<sup>3</sup>. As depicted in Figure 5, the vehicle is mounted with a fake window 213 adaptation in order to inject air into the cabin (leakage tests) or to suck air (infiltration tests). 214 The shape and dimensions of the fake window is the same as the top part of the original 215 window. The material selected is transparent polycarbonate, so that the hole can be drilled 216 easily while maintaining good visibility. The fake window is placed on top of the original 217 window, with airtight sealing tape at the junction. It is assumed that the sealing properties of 218 the window are not altered. The blower ventilation path is blocked: ventilation grids are 219 sealed with tape (as shown in Figure 5) and the HVAC system is placed in recirculation 220 mode. This ensures no backward airflow in the blower circuit (this path is known). Otherwise, 221 the vehicle is in its original configuration with all doors and windows closed.



- Figure 5 Test setup to identify leakage and infiltration paths of vehicle X.
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- 226
- 227

### 228 **3.1 Leakage paths**

229 For the leakage tests, a fog machine is used to generate smoke in the vehicle. Once the cabin 230 is filled with smoke, clean air is injected through the fake window. Different methods and 231 tools are used to identify the leakage paths (i.e. smoke) at the outside of the vehicle. The 232 leakage points are found mostly by observation, with the help of a flashlight and a laser to 233 better identify the minor leakage points. Besides, the smoke creates a huge increase of the 234 particle concentration. Then a fine particle sensor (a TSI 8525 P-Trak) is navigated all around 235 the car body to corroborate the observation method. This device counts the particles with 236 diameter from 20 nm to 1 µm. The concentration in the ambient air is in the range of 5 000-237 10 000 particles per cubic centimetre, while it is up to 30 000-50 000 near smoke streams. 238 Two types of leakage paths are identified:

- 239
- Main leakages, easily identifiable even at low flow rate of injected air
- 240 2<sup>nd</sup> order leakages that only occur for high inlet air flow rate (high cabin pressurisation)
- 242

The main leakages are located at the bottom of the rear trunk door, under the battery box below the vehicle, and above the rear wheels. They are explained by two factors. On the one side, the car body assembly is made mainly by rivet, which does not guarantee airtightness. On the other side, there is the decompression traps located above the rear wheels. On the studied car, these decompression traps are passive flaps that connect the outside environment to the cabin. From the cabin inside one must remove the different garnish carpets in order to show the many holes in the car body that are connected to the decompression traps. Images extracted from different documentary video about manufacturing of modern electric vehicle illustrate the many holes in the car body that create a channel between the outside environment and the cabin (Figure 6). The vehicle is not designed to be airtight.

253



Figure 6 Decompression traps on various modern vehicles, and holes in the car body revealed during the manufacturing process (PlaneteGT TV, 2019; Motor.TV, 2017; manufacturing, 2013)

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The 2<sup>nd</sup> order leakages only happen for very high cabin pressure and are not easily identifiable 258 259 due to the low amount of smoke coming through these paths: near the side mirrors, at the top 260 of the four side doors on the corner, and at the bottom of the front windshield through the 261 HVAC inlet grid. The latter is probably a backward airflow coming through the ventilation 262 circuit although caution is taken to prevent such event. It is possible that the high cabin 263 pressurisation deforms the plastic parts of the HVAC box, which can create openings upstream the ventilation grids. The other 2<sup>nd</sup> order leakages are probably due to a deformation 264 265 of the rubber door seal with the high cabin pressure. The flow rate of injected air is 40% 266 higher than the maximum capability of the vehicle blower. Then the 2<sup>nd</sup> order leakages are 267 unlikely to occur on real driving conditions. However, these areas should be checked over the

- 268 lifetime of the vehicle, as wear or deformation could enlarge these leakage paths. A summary
- 269 of the leakage paths on the studied car is presented on Figure 7.
- 270



Figure 7 Leakage paths localisation: (a) bottom of the front windshield, (b) side mirrors, (c) top corner of the four side doors, (d) bottom of rear trunk door, (e) above rear wheels, (f) under battery box

- 274
- 275

### 276 **3.2 Infiltration paths**

277 The same setup as the leakage tests is used to identify the infiltration paths. Instead of 278 injecting air through the fake window, an industrial vacuum cleaner is used to suck the cabin 279 air at high flow rates. Different methods are used to identify the infiltration paths. At first, the 280 operator is placed at the outside of the vehicle. The operator walks the active smoke generator 281 all around the car while the cabin air is aspirated through the fake window. The objective is to 282 observe (by visual inspection) a smoke stream infiltrating the cabin. Although it is clear that 283 smoke enters the cabin by looking inside it through the windows, no clear stream is observed 284 at the outside of the vehicle. Several methods are tested without success: variation of the 285 operator-vehicle distance, variation of the smoke generation rate, and room lighting. 286 Particular attention is given to the alleged infiltration paths (near the trunk, rear wheels, 287 bottom of the vehicle, bottom of the front windshield) but no clear path is visible. A possible 288 explanation is that the infiltration does not occur in one location at a high flow rate but at 289 multiple locations at low flow rate.

290

In a second step, the operator is placed within the cabin. The room is filled with smoke and then the air is sucked in the vehicle. This methodology is more satisfactory than with the 293 outside operator, as the infiltration paths within the cabin are clearly noticeable. At the back 294 of the vehicle, infiltration happens widely in the trunk through holes in the car body. 295 Additional paths are witnessed at the bottom of rear seats on the door side, and through the 296 seatbelt connection. These paths at the back of the vehicle are all connected to the 297 decompression traps.

298

At the front of the vehicle, the infiltration paths are clearly visible below the dashboard, near driver and passenger feet. This infiltration stream is more important than at the back of the vehicle. Removing the carpet elements reveals several holes that could be connected to the outside, either below the car or at the front of it.

303

304 These tests are performed in static condition (0 km/h). In order to simulate the wind 305 resistance, a big fan is placed in front of the vehicle. This 45 kW fan is normally used in a 306 vehicle test bench facility. It does not act as a full aerodynamic facility (such as a wind 307 tunnel). Still, it can create airflow with a velocity up to 130 km/h over a large diameter (1m). 308 With the fan active, no infiltration is spotted in the trunk or near the rear seats. The only 309 infiltration path detected, either with light, laser or particle sensor, is the one at the front of the 310 cabin below the dashboard. An additional confirmation is obtained with a thermal camera. 311 The temperature in the cabin is increased to a value higher than 40°C. The room temperature 312 is kept at normal condition  $(23^{\circ}C)$ . The operator in the cabin examines the apparition of cold 313 clusters. As depicted on Figure 8 the cold areas on the driver side quickly appeared behind the 314 brake pedal and to the right of the accelerator pedal. These areas match the infiltration path 315 observed with the smoke procedure. In the trunk or near the back seats no cold cluster is 316 observed which leads to consider that in driving conditions there is no infiltration at the rear 317 of the vehicle.



319

320 Figure 8 Identification of infiltration path at the front cabin bottom in replicated driving condition

322 This finding is not in accordance with several articles of the literature review (Behrentz et al., 323 2004; Zagury, 2000), including the work from Lee et al (Lee, 2013; Lee et al., 2015a, 2015b) 324 which concludes that infiltration only occurs at the rear back of the vehicle in driving 325 conditions. However, in the literature no experiment is found about modern or electric 326 vehicles in new condition. There can be several important architecture and design differences 327 between a traditional thermal vehicle and a modern electric vehicle. Lee's work includes 328 many types of vehicle built between 2001 and 2013, with mileage from 1 900 to 261 000 329 kilometres. These factors might explain the difference in the infiltration location, since the 330 geometry and design of the vehicle are believed to be a major factor in the infiltration process. 331 In that regard the test procedure with the pressure approach cannot be applied to vehicle X. It 332 is decided to use the tracer gas approach.

- 333334
- **4.** Evaluation of infiltration flow rate in driving condition with a tracer gas

# 336 **4.1 Experimental setup and methodology**

The aim of this test campaign is the characterisation of the infiltration flow rate in a moving vehicle. The idea is to evaluate the cabin air exchange rate by monitoring the carbon dioxide ( $CO_2$ ) concentration (mass fraction). The use of  $CO_2$  as a tracer gas to monitor air exchange rates within the vehicle cabin has already been done but in stationary condition (Park et al.,

- 1998) and with the uncertainty of the passenger breathing (Fruin et al., 2011). According tothe Figure 9, the test procedure is divided in three stages:
- I<sup>st</sup> step: increase the CO<sub>2</sub> level in the cabin (at least up to 1000 ppm), occupants
   breathe in the cabin in recirculation mode
- 2<sup>nd</sup> step: set the desired vehicle speed and ventilation settings for the test
- 346 3<sup>rd</sup> step: monitor the decay of CO<sub>2</sub> in the cabin while occupant(s) breathe(s) out of the
   347 cabin with a snorkelling tube
- 348



350 Figure 9 Methodology to evaluate infiltration using CO<sub>2</sub> as tracer gas

349

The methodology concept is based on the temporal decay of  $CO_2$  concentration. Tracer gas techniques for single zone to measure the air exchange rate are described in the literature (Laussmann and Helm, 2011; Sherman, 1990). It can be described with the mass conservation equation. The differential equation is solved by integration.

$$V \frac{dC_{CO_2}(t)}{dt} = C_{CO_2 \ amb} * Q - C_{CO_2}(t) * Q \tag{1}$$

$$C_{CO_2}(t) = C_{CO_2 \ amb} + \left(C_{CO_2 \ (t=0)} - C_{CO_2 \ amb}\right) \cdot exp(\frac{Q \cdot t}{-V})$$
(2)

The cabin CO<sub>2</sub> concentration depends on the cabin volume *V*, the exterior CO<sub>2</sub> concentration  $C_{CO_2 \ amb}$  and the inlet volumetric flow rate from outside *Q*. These equations are applied with several assumptions:

- a) Cabin is a perfectly homogeneous single-zone volume
- b) Exterior (atmospheric) CO<sub>2</sub> concentration is constant in space and time
- 361 c) CO<sub>2</sub> is chemically stable and inert (no reactions with other molecules)

- d)  $CO_2$  is not absorbed by any cabin material (roof, seats, doors...)
- 363 e) No in-cabin source (nor sink) of CO<sub>2</sub> (driver does not inhale nor exhale within the
  364 cabin)
- 365

Assumption a) is the consequence of having a single  $CO_2$  sensor but also to have data in order to develop a 0D model. This sensor is placed in the middle of the cabin between the four headrests. Within the cabin, the air is mixed by the air coming from the central ventilation grid, apart from for tests with blower off. The sensor is a Vaisala GMP343 with a response time (90%) of two seconds without the filter attached. Its accuracy in standard ambient conditions is +/- (5 ppm + 2% of reading).

372

For assumption b) no  $CO_2$  sensor is placed outside the cabin to directly validate this statement. The exterior concentration is measured at the beginning of each test. Besides the final cabin  $CO_2$  concentration converges toward the exterior concentration. The tests are time limited (a few minutes), thus space limited (a few kilometres). Because of these limitations, the final cabin stability is not reached for all tests. In cases that reached stability the initial and final  $CO_2$  concentrations are similar with a +/- 7 ppm margin. It suggests that the atmospheric concentration is stable in time (over a few minutes) and space (a few kilometres).

380

Assumptions c), d) and e) induce that  $CO_2$  concentration is only governed by air renewal. In other words, the cabin  $CO_2$  level is only influenced by the flow rate of air coming from the outside to the cabin. This flow rate is the sum of the infiltration flow rate and the fresh air blower flow rate (itself depending on the blower position and recirculation ratio).

$$Q = Q_{blower fresh air} + Q_{infiltrations}$$
(3)

385

386 All equipment and test procedures are made to minimise the influence of test conditions on 387 the infiltration phenomena. For instance, the installation of a flowmeter in the blower circuit 388 would create a large pressure drop that could alter the blower performances. In that regard, the 389 blower is characterised by a cabin differential pressure - flow rate calibration. It is a less 390 intrusive method in two stages. On the one hand, a link is made between cabin pressurisation 391 and flow rate injected by blowing air through the fake window. On the other hand, a link is 392 made between cabin pressurisation and the vehicle ventilation settings by blowing with the 393 blower at different positions. This methodology creates a link between the blower positions

and the flow rate of air injected. It allows knowing the fresh air blower flow rate for any
ventilation settings. The experiment is repeated with two vehicles of the same cabin size
range:

397

• Vehicle X (previously presented) from 2018, total mileage 3800 km

- Vehicle Y (gasoline engine) from 2016, total mileage 6000 km
- 399

398

400 Both models are relatively common in the automotive market amongst mid-size or compact 401 vehicles (cabin of 2.5 m<sup>3</sup>). Both cars are in their original configuration apart from the fake 402 window installation. A hole is made in the fake window for the snorkelling system. During 403 test recordings, the driver breathes in and out through a plastic tube. A nose clip is used to 404 ensure that the breathing is made exclusively with the outside environment, thus not 405 influencing the CO<sub>2</sub> level in the cabin. The CO<sub>2</sub> sensor and a temperature sensor are placed in 406 the middle of the cabin, at equal distance of the four headrests. The acquisition unit and laptop 407 are plugged on a battery. The GPS position is recorded to evaluate the vehicle speed with 408 accuracy. It should be noted that both cars are equipped with cruise control, which allows 409 keeping stable speed over time.

410

The tests are performed on open roads between the area of Nantes and Angers (France). The road selection and time of tests are selected to minimise wind influence and traffic conditions. However, random wind gust or passing cars can have an influence on the results. Static tests (0 km/h) are performed in a parking lot or within a ventilated room. Tests are performed at different vehicle speeds and ventilation settings (blower position and recirculation ratio):

- Blower speed: 3 positions (off, medium speed, full speed). On the dashboard, it
  corresponds respectively to positions 0, 4 and 8 for vehicle X, and positions 0, 3 and 6
  for vehicle Y.
- Recirculation mode: 2 positions (ON/OFF). Distinct pressurization tests in static
   conditions (0 km/h) have confirmed that for both vehicles the ON position
   corresponds to a true 100% recirculation mode. It is not fully confirmed that the OFF
   position corresponds to a true 0% recirculation, although it is most likely the case.
- Vehicle speed: static (0 km/h) plus several speeds from 50 to 130 km/h
- 424

425 Each test lasts a few minutes (2 to 10 minutes). For all tests the initial cabin  $CO_2$ 426 concentration varies from 1200 to 1900 ppm. A total of 39 tests are performed with vehicle Y 427 (including 8 repeatability tests), and 24 tests with vehicle X (with no repeatability tests). The428 few tests performed twice are very consistent.

429

430

## 431 **4.2 Test results and primary analysis**

432 The results with the two vehicles lead to the same conclusions. Two main categories of CO<sub>2</sub> 433 decay curves can be analysed. On the one hand, there are the recirculation OFF curves, with 434 clear exponential decrease of concentration over time. In such cases the stability can be 435 reached, with cabin concentration tending toward the exterior  $CO_2$  level. On the other hand, 436 there are the recirculation ON curves, with slow decrease of concentration. For these tests the 437 stability is not reached in the given limited time slot (5 minutes). In all cases the concentration 438 decreases over time. It suggests a flow of outside air coming into the cabin, either from the 439 blower action or from infiltration. For the recirculation ON cases, the blower does not drive 440 fresh air into the cabin, hence the CO<sub>2</sub> decrease is solely due to infiltration.

441

In order to illustrate the influence of vehicle speed on the results two examples are displayed in Figure 10. On the first chart, the ventilation settings are selected at medium blower position and recirculation mode. On the second chart, the blower is turned off, with recirculation flap in fresh air mode. These values are selected as an example. Similar analysis can be made with other ventilation settings.



448

449 Figure 10 Influence of vehicle speed on cabin CO<sub>2</sub> decay

451 For both ventilation settings, the initial cabin concentration is the same for all tests 452 (respectively 1440 and 1315 ppm). Six vehicle speeds are compared. A clear influence can be 453 observed, with a quicker decrease of concentration as the speed increases. In recirculation 454 mode at medium blower position, after 3 minutes the cabin CO<sub>2</sub> concentration decreases from 455 1440 ppm to 1330 ppm at 50 km/h, and down to 1215 ppm at 130 km/h. In fresh air mode 456 with the blower turned off (bottom chart), after 3 minutes the CO<sub>2</sub> level drops from 1315 ppm 457 to 910 ppm at 50 km/h, and down to 535 ppm at 130 km/h. At given ventilation setting the 458 slope is higher when the vehicle speed increases. These results suggest that the infiltration 459 flow rate increases with vehicle speed.

460

Similarly, the results can be displayed for a fixed vehicle speed and with varying ventilation settings. An example of the results at 105 km/h with vehicle Y is presented on Figure 11. The bottom curves represent the fresh air mode while the top curves are the recirculation mode. For each mode the blower position is set at 0 (blower off), 3 (medium position) and 6 (full 465 speed). In recirculation mode, the curve slopes are similar although not identical: the  $CO_2$ 466 decreases slightly more rapidly with upper blower positions. In fresh air mode, the influence 467 of blower position is more obvious, and in agreement with what can be expected: the cabin 468  $CO_2$  concentration decreases more rapidly when the blower drives more fresh air into the 469 cabin.







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471

474 An interesting takeout from this chart is that there is a clear difference between the two curves 475 with the blower off. If the recirculation flap is open (recirculation ON) the cabin CO<sub>2</sub> level 476 decreases slowly, in the same range as when the blower is active. If the recirculation flap is 477 closed (fresh air mode) the CO<sub>2</sub> decreases rapidly. It suggests that part of the infiltration path 478 must be through the HVAC system of the vehicle. This phenomenon is observed for vehicle Y 479 but not for vehicle X, as illustrated on Figure 12. For vehicle X the CO<sub>2</sub> curve slope with the 480 blower turned off is almost identical whether the recirculation mode is activated or not. For 481 this vehicle it suggests infiltration path must not be through the HVAC system, as opposed to 482 vehicle Y. This is verified for all vehicle speeds (> 0 km/h) on both vehicles. Beside the fact 483 that each vehicle has its own architectural design for the HVAC system, the difference could 484 be explained by the control strategy applied to the recirculation flap.



486

487 Figure 12 Comparison of vehicles X and Y with blower off

489 Several tests are performed in static condition (0 km/h), either in a room or on a parking lot 490 area with minimum wind. The results show a temporal decay of  $CO_2$ . It induces that there is still an air renewal in the cabin although the lack of external flow rate removes the possibility 491 492 for infiltration. This must be a consequence of diffusion effect, the vehicle is not airtight. 493 Nevertheless, the CO<sub>2</sub> decay at 0 km/h is very slow compared to higher vehicle speeds. For 494 vehicle Y with the blower off, the recirculation curve has the same slope as the fresh air mode 495 curve, which is not the case when the vehicle is moving. It remains logical, because there is 496 no infiltration, only diffusion. For both vehicles the diffusion is accelerated with higher 497 blower flow rates. Indeed the airflow created by the blower allows achieving a better 498 homogeneity within the cabin, particularly near the decompression flaps which can be 499 considered as privileged places for diffusion.

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## 502 **4.3. Evaluation of infiltration flow rate**

503 Experiments with the gas tracer methodology show that, for a given ventilation setting, the 504 cabin air renewal rate depends on vehicle speed. This is due to infiltration phenomena. The 505 next objective is to create an infiltration model that could be used in a simulation code. The 506 first step is the evaluation of the infiltration flow rate in both vehicles (X and Y). The 507 methodology used is the curve fitting of the test results with equation (2). The parameters to 508 adjust the model are the ambient  $CO_2$  concentration, the cabin volume and the outside air flow 509 rate which is divided between the blower fresh air and the infiltration. The ambient CO<sub>2</sub> 510 concentration is measured at the beginning of each test and allegedly constant over time. In 511 fresh air mode, the blower flow rate is known for each position according to the cabin 512 differential pressure – flow rate calibration. It is assumed that this flow rate is independent of 513 the vehicle speed. In recirculation mode, this flow rate is null. The two remaining unknown 514 parameters to adjust the model are the cabin volume and the infiltration flow rate. The raw 515 cabin volume of each vehicle is known, but is reduced because of the equipment and 516 occupant(s). Then the cabin volume is used as a calibration parameter, within a reasonable 517 range below the raw volume. A constraint is added that the same volume must be selected for all tests. Indeed, there is the same equipment and constant number of occupants for all tests in 518 519 each vehicle (only the driver in vehicle X, two occupants in vehicle Y). Finally, the 520 infiltration flow rate is adjusted for each test. This last step is pictured on Figure 13 with two 521 examples of calibration for vehicle Y (recirculation ON or OFF). The idea is to minimise the 522 difference with the test result. In that purpose, a solver (with GRG nonlinear method) is used 523 to optimise the infiltration flow rate in order to minimise the error between the test result and 524 the fitting equation. Other examples of curve fittings are presented on Figure 14 and Figure 525 15.







529



531 Figure 14 Examples of curve fitting with vehicle Y tests at 120 km/h



533

534 Figure 15 Examples of curve fitting with vehicle X tests at 100 km/h

536 The overall curve fitting of test results with equation (2) is very acceptable. For vehicle Y the 537 average relative error is 1.7% (about 27 ppm) with a 2.1% standard deviation. This 538 calculation takes into account the measurement uncertainty from the CO<sub>2</sub> sensor. 18 of the 39 539 tests have an average relative error below 1%, and 10 tests have an error above 3%. The 8 540 tests performed twice with vehicle Y lead to similar infiltration flow rates with a 5% relative 541 error margin. The test methodology can be considered robust and repeatable. For vehicle X 542 the average relative error is 1.6% (about 16 ppm) with a 1.8% standard deviation. 9 of the 24 543 tests have a relative error below 1% and 5 tests are above 3%. No repeatable tests are 544 performed with vehicle X. Tests with this vehicle started with lower initial cabin CO<sub>2</sub> 545 concentration in average (1349 ppm) than with vehicle Y (1502 ppm).

546

All the resulting infiltration flow rates of both vehicles are presented on Table 1 and Table 2.
In recirculation mode, the infiltration is triggered by higher vehicle speeds and upper blower
position. In fresh air mode, infiltration only happens with the blower off and increases with

550 higher vehicle speeds. In fresh air mode with an active blower the results are displayed with 551 an asterisk "\*" in the table. At first, it seems that there is no infiltration (0 kg/h) for these configurations, such as illustrated on the second example of Figure 13. However, there are 552 553 several physical phenomena at stake (infiltration action, blower action, diffusion time in the 554 cabin...) combined with some unpredictability about the exact position of the recirculation 555 flap (not measured). Then an accurate identification of the infiltration flow rate appears 556 uncertain for these configurations. Further experiments could help refine the experimental 557 data set and thus improving the overall model accuracy. Yet the original vehicle 558 configurations are limited in the range of recirculation ratio and blower flow rate that can be 559 manually actuated on the dashboard. Such experiment would require a direct control on each 560 actuator, for example with a connection to the vehicle control system.

561

Table 1 Estimation of infiltration mass flow rate on a gasoline vehicle for different ventilation settings and
 vehicle speeds

		Infiltr	ation mas	w rate vehicle Y [	kg/h]	
-	Recircula	tion ON			Recirculat	tion OFF
<b>GPS</b> speed	Blower position [0-6]			GPS speed	Blow	er positio
[km/h]	0	3	6 [km/h]	0	3	
0	3.5	4.0	6.0	0	2.5	-
46.7	-	6.0	-	46.7	35.0	-
66.5	-	9.5	-	66.5	48.0	-
87.0	11.0	13.5	15.0	87.0	60.0	-
101.4	10.0	12.8	16.0	101.4	68.7	*
116.3	13.0	12.8	18.5	116.3	100.5	*
126.1	17.0	16.0	19.0	126.1	117.5	*

#### 564

565Table 2 Estimation of infiltration mass flow rate on a modern electric vehicle for different ventilation566settings and vehicle speeds

		Infiltra	ation mas	rate vehicle X [	kg/h]		
Recirculation ON				]	Recirculat	tion OFF	
GPS speed	Blower position [0-8]			GPS speed	Blower position [0-8]		
[km/h]	0	4	8	[km/h]	0	4	8
0	1.0	6.5	10.5	0	2.0	*	×
73.2	8.5	24.0	26.0	73.2	8.0	*	*
96.9	22.5	27.0	29.0	96.9	16.0	*	*
116.8	27.0	32.0	38.0	116.8	24.0	*	8

568 The main difference between the two vehicles is when the blower is not active. The 569 infiltration flow rate of vehicle X is very similar in recirculation mode and fresh air mode. It 570 means that the infiltration path is likely to be the same in both modes. This path must not be 571 part of the HVAC circuit, thus the infiltration air is not filtered by the HVAC filter. 572 Infiltration introduces polluted air into the cabin. Vehicle Y leads to much higher infiltration 573 flow rates in fresh air mode than in recirculation mode (factor 7). As previously stated this 574 suggests that the infiltration path in fresh air mode goes largely through the HVAC pipes, 575 contrary to the electric vehicle X. Chances are that this air goes through the filters, acting as if 576 the blower is active. Infiltration introduces filtered air into the cabin. The difference between 577 the two vehicles for this specific ventilation setting is illustrated on Figure 16.





580 Figure 16 Infiltration path on vehicle X and Y in fresh air mode with blower OFF configuration

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579

In recirculation mode, it appears that there is a higher infiltration flow rate with vehicle X than with vehicle Y, particularly at high vehicle speed. For both vehicles and at a given vehicle speed the infiltration flow rate slightly increases with upper blower position. The explanation might be that the air is better mixed within the cabin with higher blower position. Similarly than for the diffusion effect at zero vehicle speed this could stimulate the air renewal near interior-exterior border locations such as the decompression traps.

588

589 Otherwise, in recirculation mode the vehicle speed has a high influence on the infiltration 590 flow rate. A trip on a highway (110 to 130 km/h) generates up to a dozen more kilograms per 591 hour infiltration flow rate than a trip on a local road (60 to 80 km/h). Besides, with vehicle X 592 it is deduced that the infiltration path does not go through the HVAC system. In other words, 593 the vehicle speed does not influence the recirculation flap behaviour. The airflow due to high 594 speed does not "push" the flap and does not create a leakage. Hence, it is likely that the infiltrated air does not flow through the filter elements. Infiltration introduces polluted air intothe cabin.

597

The overall analysis of the results depicts a competition between the infiltration flow rate and the fresh air flow rate driven by the blower. The fresh air driven by the blower behaves as a shield against infiltration. However, in some cases the infiltration flow rate can overcome the fresh air flow rate from the blower.

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#### 604 **5. Conclusions**

A tracer gas technique using  $CO_2$  is used to evaluate the air exchange rate of a cabin vehicle. The experiment performed on two vehicles shows that there is an additional flow rate inlet into the cabin with higher vehicle speed. The ventilation setting also has a broad impact. Beside the vehicle speed, the infiltration flow rate is triggered by recirculation mode and upper blower position. In fresh air mode with an active blower, the cabin is in a positive pressure mode that acts as a shield against infiltration. A number of enquiries are still active.

611

612 No other literature study is found to confirm the infiltration at the front of the cabin, or to 613 evaluate the infiltration of an electric vehicle. The architecture of an electric vehicle is much 614 different from a classic thermal engine vehicle (e.g. location of the engine, addition of a 615 battery pack). The infiltration process through the small gaps of the car body can be easily 616 impacted. Regarding gasoline engine vehicle (Y) no test is specifically performed in order to 617 locate the infiltration path. However driving this vehicle at high speed (with the ventilation 618 turned off) emphasises a clear feeling of airflow on the legs of the driver and the side 619 passenger. This infiltration airflow at the bottom front of the cabin is also perceived on other 620 personal vehicles in the same conditions. There is no evidence that it does not happen at the 621 rear back of the cabin as well.

622

Infiltration introduces non-filtered outside air directly into the cabin. Regarding the thermal aspect (temperature, humidity) or air quality aspect (pollutants, particles) this is something that should be avoided, or at least limited. It appears that at a given vehicle speed the best strategy to avoid infiltration is to increase the amount of fresh air driven by the blower. However, by doing so it also increases the amount of cold/hot air into the cabin, thus having a negative impact on the energy aspect. Besides, it also increases the load on the filtration 629 system. A trade-off must be found in order to optimise both air quality and energy savings. In

that purpose a new filtration system (Lesage et al., 2019a, 2019b) coupled with a smartcontrol of the ventilation settings could be integrated in a vehicle.

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