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Experimental analysis and quantification of air infiltration into a passenger car cabin

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Abstract

Nowadays, air quality in closed environments is of major interest, particularly in very small volumes such as car cabins. In typical driving conditions, ambient air enters by infiltration as the vehicle speed increases. In order to satisfy more ambitious requirements on air quality and energy savings, it is necessary to evaluate the infiltration risk. At first, an experimental method is created to identify the infiltration path in the cabin of a moving car. On a modern electric vehicle, the privileged path is observed at the front of the cabin near the feet of the front passengers. A second experimental campaign is performed to quantify the infiltration flow rate. Results show that the flow rate is not negligible as it can reach several dozen kilograms per hour. The ventilation settings (blower speed and recirculation ratio) can be managed to reduce or even completely remove infiltration in some cases.

Keywords

Infiltration, Leakage, Ventilation, Air quality, Tracer gas

34 **Nomenclature**

35 Q Volumetric flow rate (m³/h)

36 t Time (s)

37 V Cabin volume (m³)

38 C(t) Mass fraction concentration

39

40 *Subscripts*

41 amb Ambient (outside environment)

42 CO₂ 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

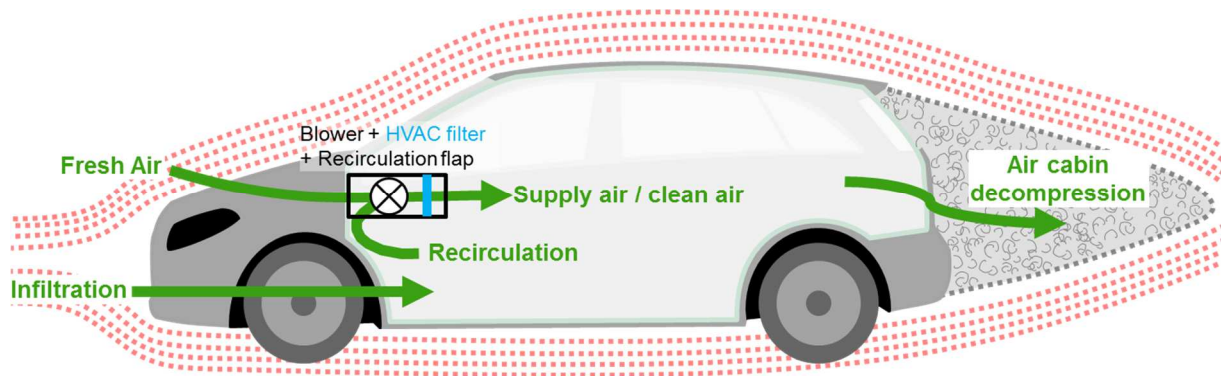
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52 **1. Introduction**

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
60 uncontrolled airflow from the outside into the cabin: infiltration. The terminology related to
61 airflows considered in the article is shown in Figure 1.

62



63
64 **Figure 1 Overview of the air circulation in and out of a passenger car**

65
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
79 At first, this article presents the state of the art found in the literature regarding infiltration.
80 Then experiments are realised on a modern electric vehicle in order to identify the air paths as
81 it exits or enters the cabin. The localisation of infiltration on this vehicle leads to reconsider
82 the models found in the literature. An experimental campaign is realised on two modern
83 vehicles to evaluate the infiltration flow rate in driving conditions.

84
85
86 **2. Literature review**

87 The literature research shows that infiltration is not a widespread phenomenon in the
88 automotive field. Most findings concerning the infiltration of air in a closed volume is for
89 building applications. Old or recent studies investigate the characterisation of airflow through
90 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.

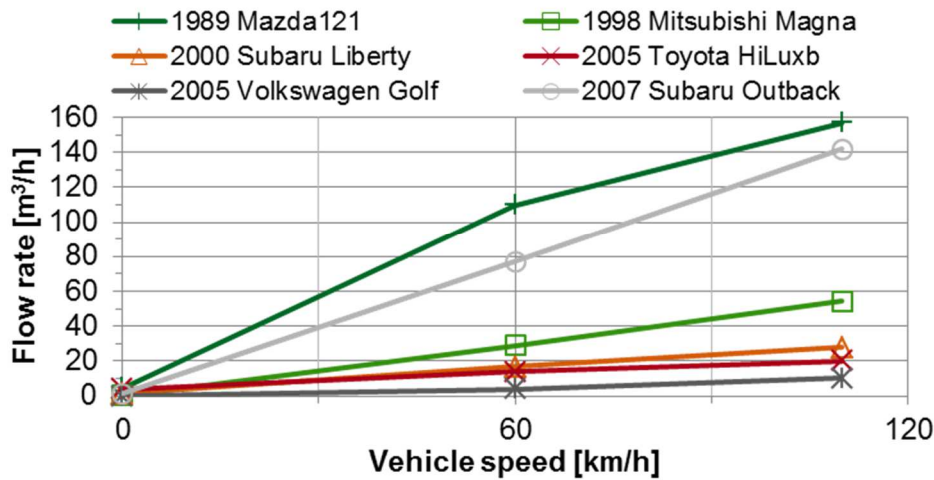
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109 Several studies suggest that the cabin pollution level is correlated to exhaust intrusion
110 elsewhere than through the blower (Chan et al., 1999; Fruin et al., 2011; Harik et al., 2017;
111 Hudda and Fruin, 2013). There is a debate whether this 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_6). 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 ($>$
123 120 000 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

125 indicate that the flow rate increases with vehicle speed, particularly for older vehicles. From
 126 lowest to highest vehicle speed, the air flow rate can be increased by up to 150 m³/h for the
 127 1989's car, and around 30 m³/h for the 2005's cars. The experiment is repeated with two
 128 additional vehicles (Knibbs et al., 2009). Authors explain that the blower operation is likely to
 129 reduce the infiltration flow rate. Infiltration appears in recirculation mode as well as in fresh
 130 air mode. This infiltration has a negative impact on the particle level within the cabin.
 131

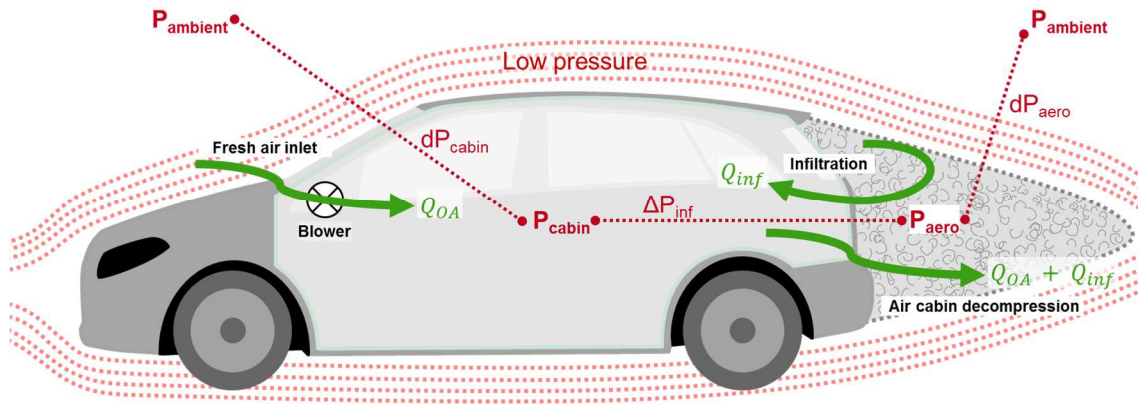


132
 133 **Figure 2 Evidence of infiltration in 6 vehicles from Knibbs et al. (2009, 2007)**

134
 135 Similar methodology has been used in several older studies using CO or SF₆ 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 CO₂ (Park et al., 1998), N₂O (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
 145 The most complete and detailed work on infiltration is performed by Lee et al (Lee, 2013; Lee
 146 et al., 2015a, 2015b; Quiros et al., 2013; Zhu and Lee, n.d.). The global approach relies on the
 147 pressure competition in and out of the cabin. According to the authors, the infiltration flow
 148 rate can be calculated knowing two differential pressures (cabin and aerodynamic).

149



150

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

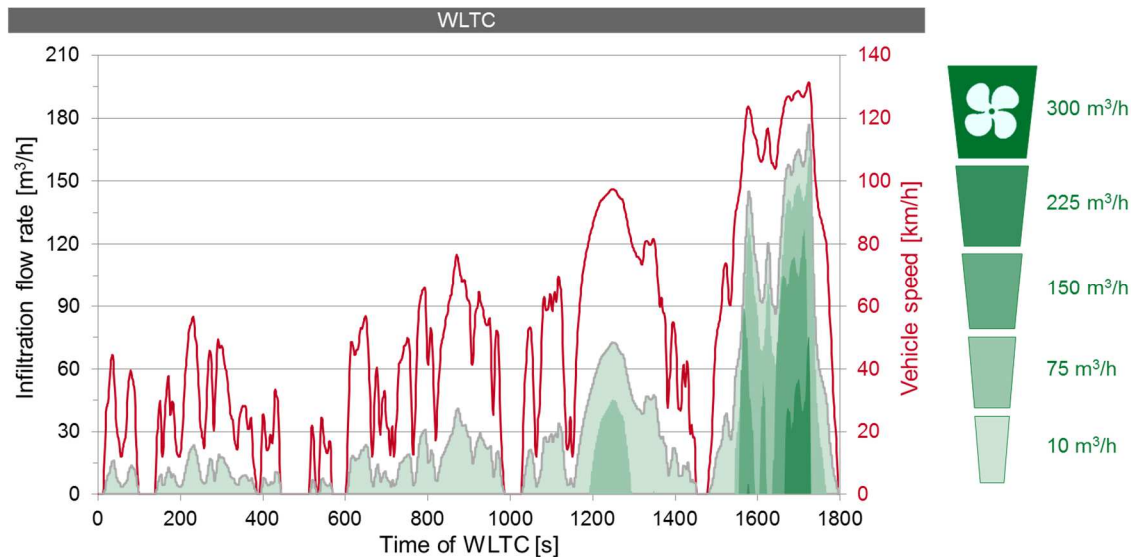
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153 Experimental tests with a broad range of vehicles (sedan, hatchback, SUV, minivan) led to
 154 repeatable outcomes. Tests are performed with a moving vehicle (up to 120 km/h). A model is
 155 created from the test results. On the one side, the 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.

172



173

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

176

177 On the road cycle, the infiltration occurs most of the time but at a reduced flow rate. With a
 178 blower setting at 10 m³/h, the infiltration volume over the whole cycle (1800s) is 15 m³. This
 179 is a very high amount compared to the air volume driven by the blower (5 m³). As the blower
 180 flow rate increases, the infiltration decreases. At medium blower position (150 m³/h) the
 181 infiltration does not appear before the final part of the cycle (highway). This setting is good
 182 for urban and suburban trips. With the blower at its maximum speed (300 m³/h) there is no
 183 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

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

195 The experiments are performed with a full electric vehicle from 2018 with a total mileage of
 196 3800 km. It is referred to as "vehicle X". All tests are performed at ordinary ambient
 197 temperature (19-25°C) and relative humidity (40-60%).

198

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 m^3 (specification from manufacturer), and the raw volume of the room (i.e. empty) is
212 approximately 90 m^3 . 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.

222



223

224 **Figure 5 Test setup to identify leakage and infiltration paths of vehicle X.**

225

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 • 2nd order leakages that only occur for high inlet air flow rate (high cabin
 241 pressurisation)

242

243 The main leakages are located at the bottom of the rear trunk door, under the battery box
 244 below the vehicle, and above the rear wheels. They are explained by two factors. On the one
 245 side, the car body assembly is made mainly by rivet, which does not guarantee airtightness.
 246 On the other side, there is the decompression traps located above the rear wheels. On the
 247 studied car, these decompression traps are passive flaps that connect the outside environment

248 to the cabin. From the cabin inside one must remove the different garnish carpets in order to
249 show the many holes in the car body that are connected to the decompression traps. Images
250 extracted from different documentary video about manufacturing of modern electric vehicle
251 illustrate the many holes in the car body that create a channel between the outside
252 environment and the cabin (Figure 6). The vehicle is not designed to be airtight.
253

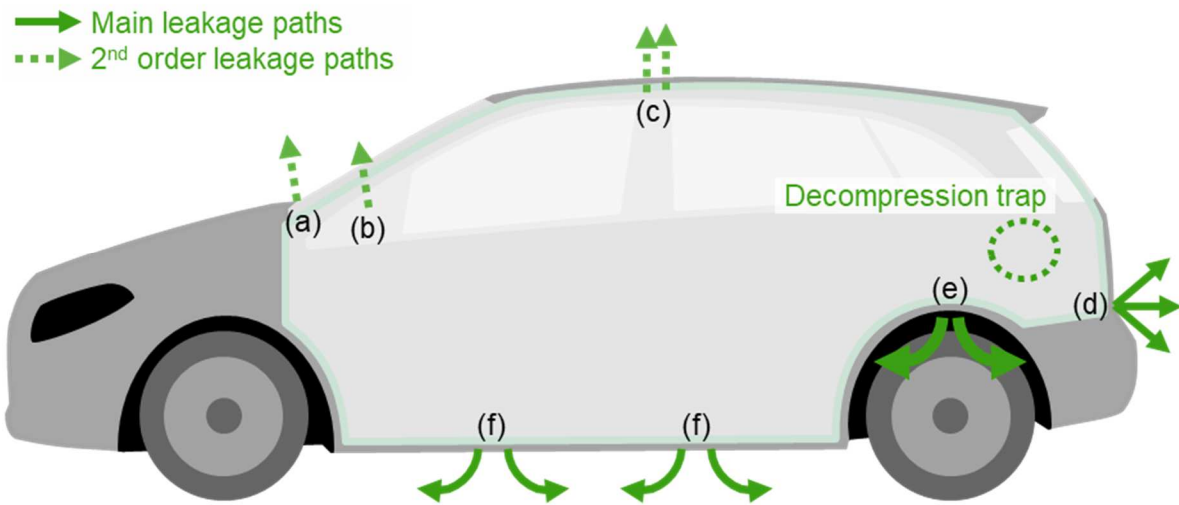


254
255 **Figure 6 Decompression traps on various modern vehicles, and holes in the car body revealed during the**
256 **manufacturing process (PlaneteGT TV, 2019; Motor.TV, 2017; manufacturing, 2013)**

257
258 The 2nd order leakages only happen for very high cabin pressure and are not easily identifiable
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
264 upstream the ventilation grids. The other 2nd order leakages are probably due to a deformation
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 2nd 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



271

272 **Figure 7 Leakage paths localisation: (a) bottom of the front windshield, (b) side mirrors, (c) top corner of**
273 **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

291 In a second step, the operator is placed within the cabin. The room is filled with smoke and
292 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

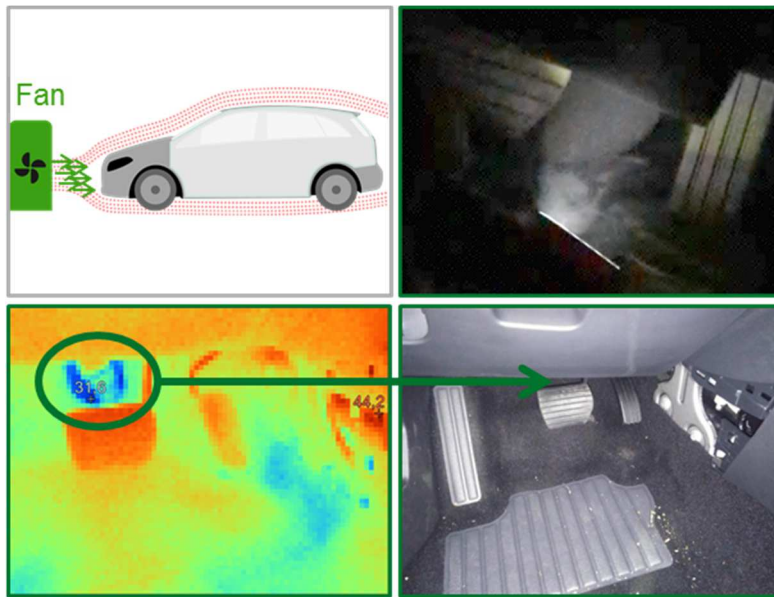
299 At the front of the vehicle, the infiltration paths are clearly visible below the dashboard, near
300 driver and passenger feet. This infiltration stream is more important than at the back of the
301 vehicle. Removing the carpet elements reveals several holes that could be connected to the
302 outside,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

318



319

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

321

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.

333

334

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

336 **4.1 Experimental setup and methodology**

337 The aim of this test campaign is the characterisation of the infiltration flow rate in a moving
 338 vehicle. The idea is to evaluate the cabin air exchange rate by monitoring the carbon dioxide
 339 (CO₂) concentration (mass fraction). The use of CO₂ as a tracer gas to monitor air exchange
 340 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 to the Figure 9, the test procedure is divided in three stages:

- 1st step: increase the CO₂ level in the cabin (at least up to 1000 ppm), occupants breathe in the cabin in recirculation mode
- 2nd step: set the desired vehicle speed and ventilation settings for the test
- 3rd step: monitor the decay of CO₂ in the cabin while occupant(s) breathe(s) out of the cabin with a snorkelling tube

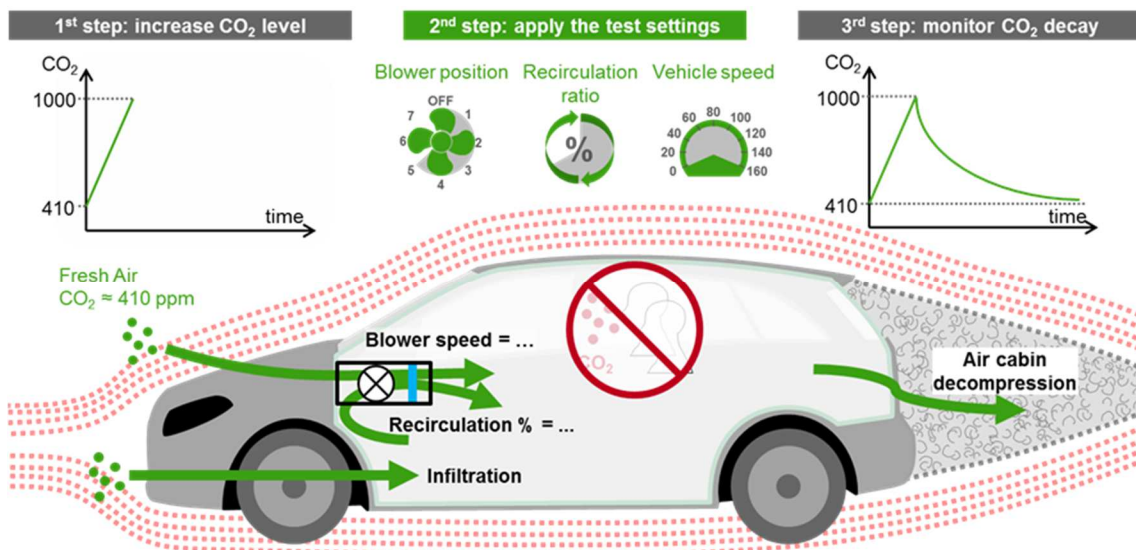


Figure 9 Methodology to evaluate infiltration using CO₂ as tracer gas

The methodology concept is based on the temporal decay of CO₂ 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.

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

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

The cabin CO₂ concentration depends on the cabin volume V , the exterior CO₂ concentration $C_{CO_2 \text{ amb}}$ 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) CO₂ concentration is constant in space and time
- c) CO₂ is chemically stable and inert (no reactions with other molecules)

- 362 d) CO₂ is not absorbed by any cabin material (roof, seats, doors...)
363 e) No in-cabin source (nor sink) of CO₂ (driver does not inhale nor exhale within the
364 cabin)

365

366 Assumption a) is the consequence of having a single CO₂ sensor but also to have data in order
367 to develop a 0D model. This sensor is placed in the middle of the cabin between the four
368 headrests. Within the cabin, the air is mixed by the air coming from the central ventilation
369 grid, apart from for tests with blower off. The sensor is a Vaisala GMP343 with a response
370 time (90%) of two seconds without the filter attached. Its accuracy in standard ambient
371 conditions is +/- (5 ppm + 2% of reading).

372

373 For assumption b) no CO₂ sensor is placed outside the cabin to directly validate this
374 statement. The exterior concentration is measured at the beginning of each test. Besides the
375 final cabin CO₂ concentration converges toward the exterior concentration. The tests are time
376 limited (a few minutes), thus space limited (a few kilometres). Because of these limitations,
377 the final cabin stability is not reached for all tests. In cases that reached stability the initial and
378 final CO₂ concentrations are similar with a +/- 7 ppm margin. It suggests that the atmospheric
379 concentration is stable in time (over a few minutes) and space (a few kilometres).

380

381 Assumptions c), d) and e) induce that CO₂ concentration is only governed by air renewal. In
382 other words, the cabin CO₂ level is only influenced by the flow rate of air coming from the
383 outside to the cabin. This flow rate is the sum of the infiltration flow rate and the fresh air
384 blower flow rate (itself depending on the blower position and recirculation ratio).

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

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**

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

- 397 • Vehicle X (previously presented) from 2018, total mileage 3800 km
- 398 • Vehicle Y (gasoline engine) from 2016, total mileage 6000 km

399

400 Both models are relatively common in the automotive market amongst mid-size or compact
401 vehicles (cabin of 2.5 m³). 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 CO₂ level in the cabin. The CO₂ 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

411 The tests are performed on open roads between the area of Nantes and Angers (France). The
412 road selection and time of tests are selected to minimise wind influence and traffic conditions.
413 However, random wind gust or passing cars can have an influence on the results. Static tests
414 (0 km/h) are performed in a parking lot or within a ventilated room. Tests are performed at
415 different vehicle speeds and ventilation settings (blower position and recirculation ratio):

- 416 • Blower speed: 3 positions (off, medium speed, full speed). On the dashboard, it
417 corresponds respectively to positions 0, 4 and 8 for vehicle X, and positions 0, 3 and 6
418 for vehicle Y.
- 419 • Recirculation mode: 2 positions (ON/OFF). Distinct pressurization tests in static
420 conditions (0 km/h) have confirmed that for both vehicles the ON position
421 corresponds to a true 100% recirculation mode. It is not fully confirmed that the OFF
422 position corresponds to a true 0% recirculation, although it is most likely the case.
- 423 • 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 CO₂
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). The
428 few tests performed twice are very consistent.

429

430

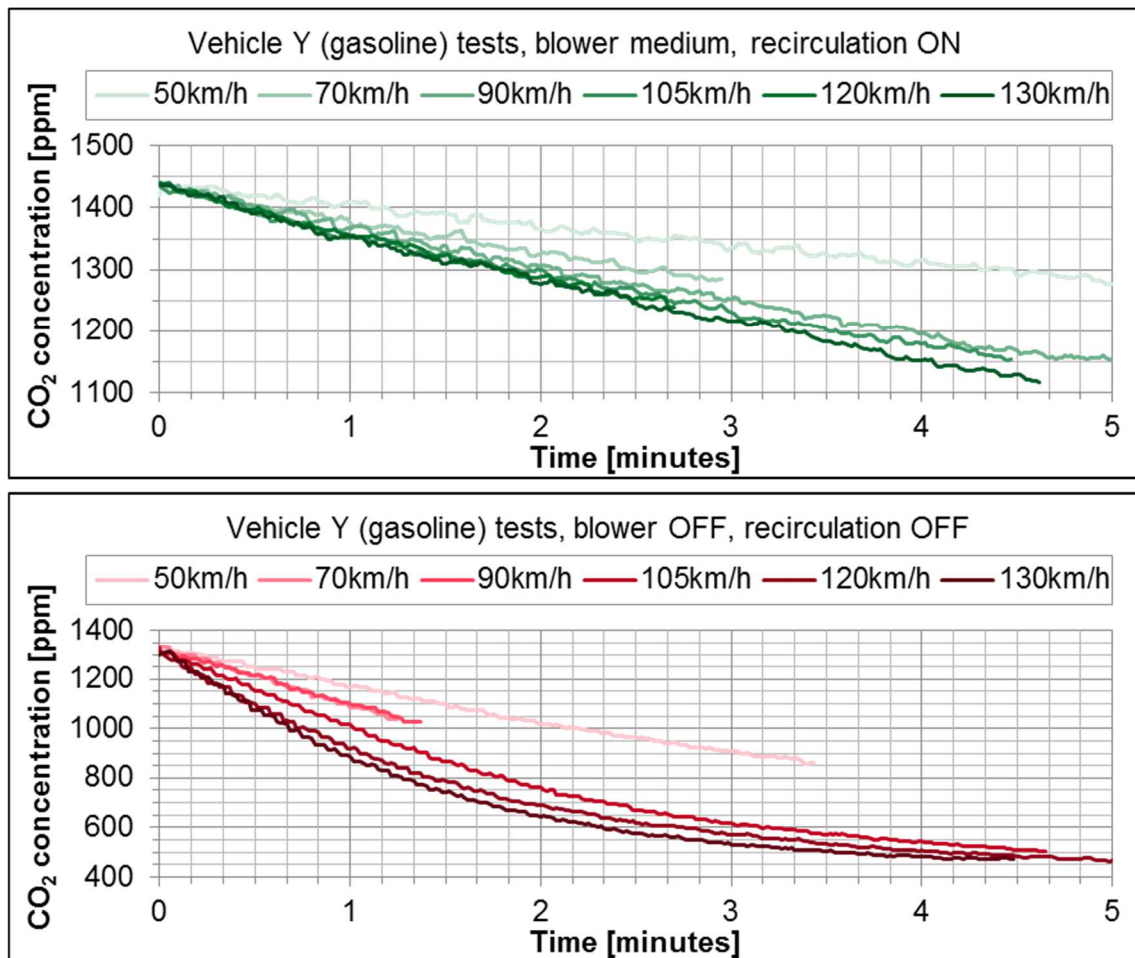
431 **4.2 Test results and primary analysis**

432 The results with the two vehicles lead to the same conclusions. Two main categories of CO₂
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 CO₂ 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 CO₂ decrease is solely due to infiltration.

441

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

447



448

449 **Figure 10 Influence of vehicle speed on cabin CO₂ decay**

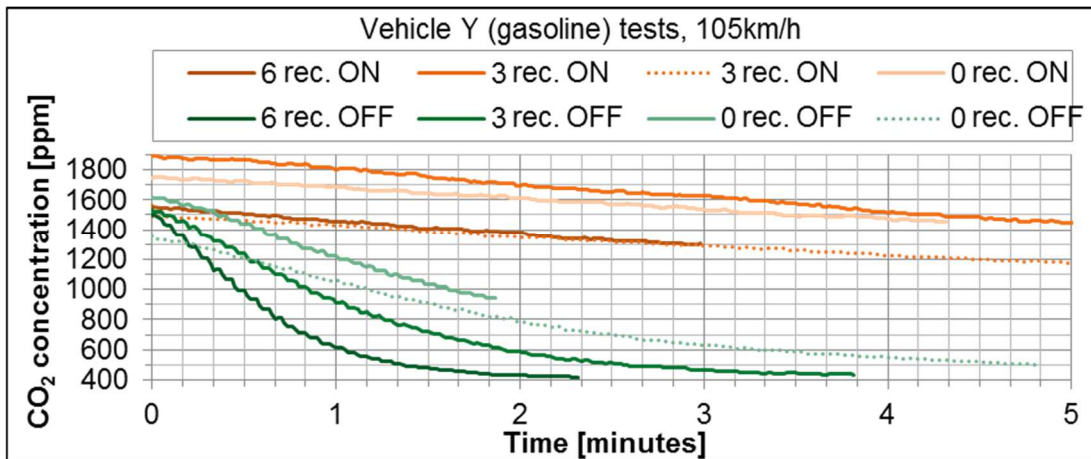
450

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 CO₂ 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 CO₂ 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

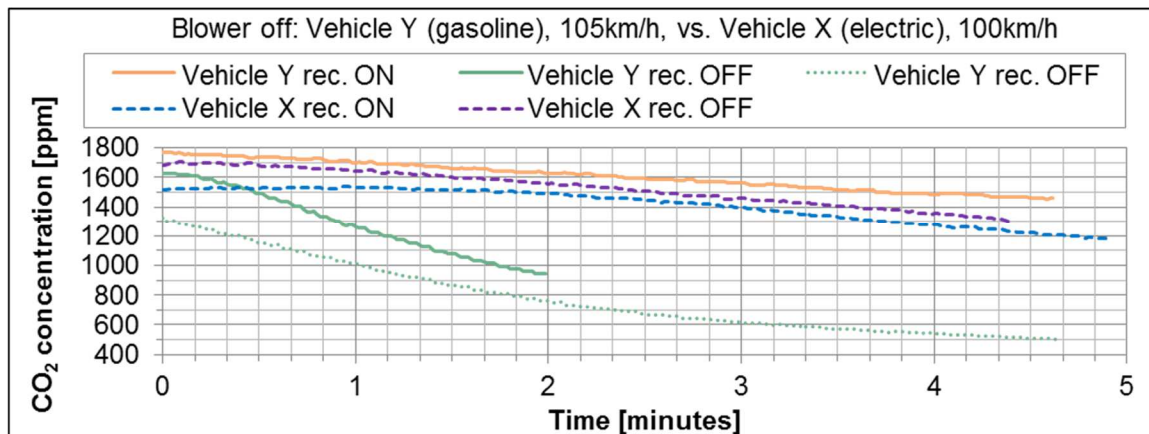
461 Similarly, the results can be displayed for a fixed vehicle speed and with varying ventilation
 462 settings. An example of the results at 105 km/h with vehicle Y is presented on Figure 11. The
 463 bottom curves represent the fresh air mode while the top curves are the recirculation mode.
 464 For 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 CO₂
 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 CO₂ concentration decreases more rapidly when the blower drives more fresh air into the
 469 cabin.
 470



471
 472 **Figure 11 Influence of ventilation settings on cabin CO₂ decay**

473
 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 CO₂ 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 CO₂ 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 CO₂ 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.
 485



486

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

488

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 CO₂. It induces that there is
 491 still an air renewal in the cabin although the lack of external flow rate removes the possibility
 492 for infiltration. This must be a consequence of diffusion effect, the vehicle is not airtight.
 493 Nevertheless, the CO₂ 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.

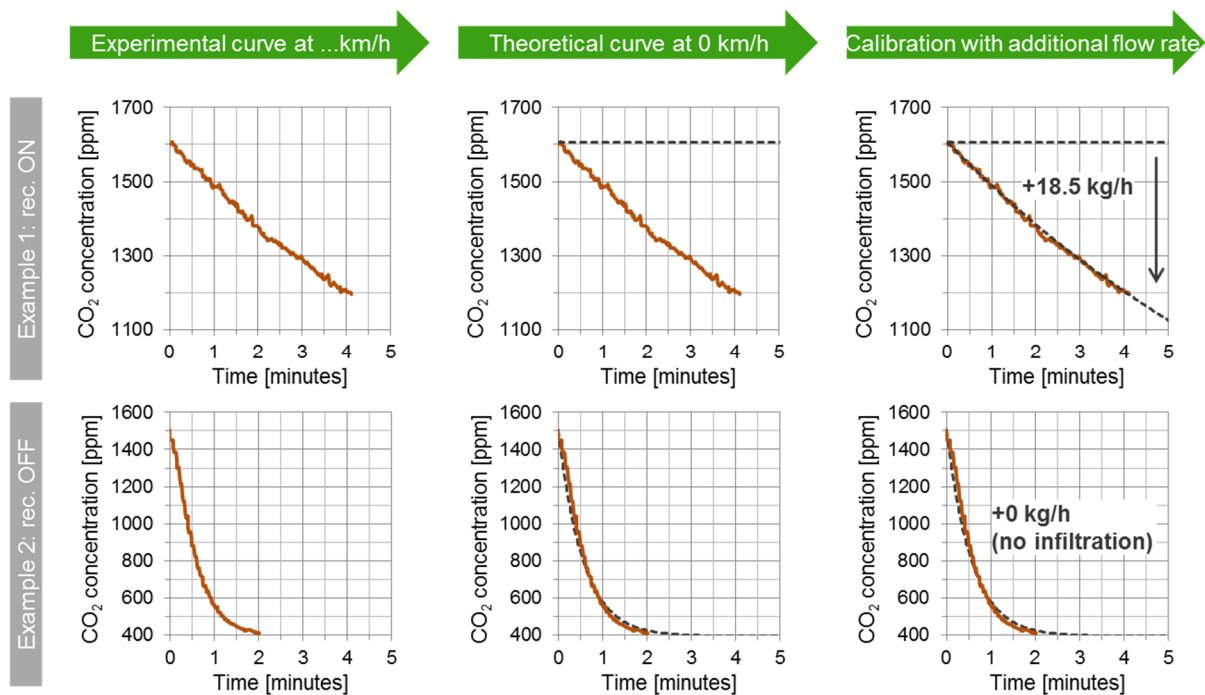
500

501

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 CO₂ concentration, the cabin volume and the outside air flow
 509 rate which is divided between the blower fresh air and the infiltration. The ambient CO₂
 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

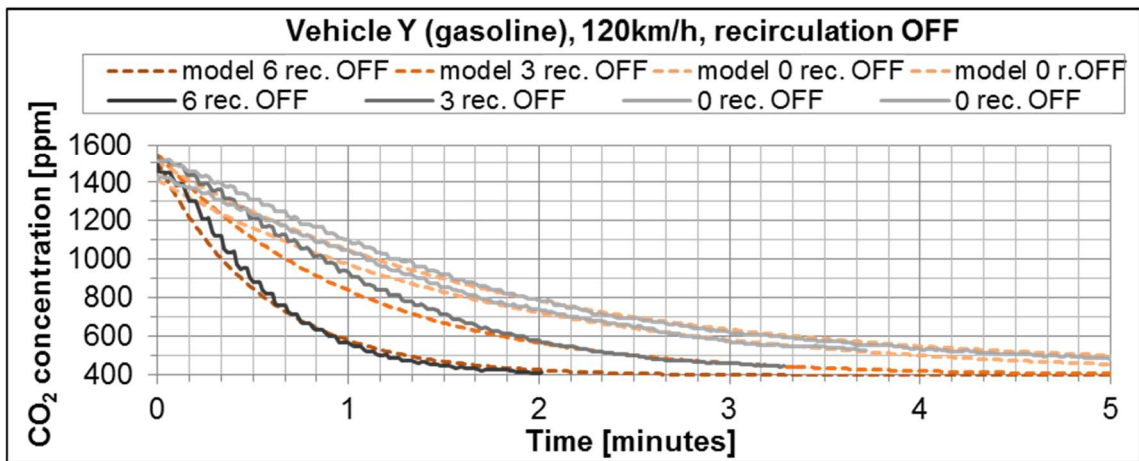
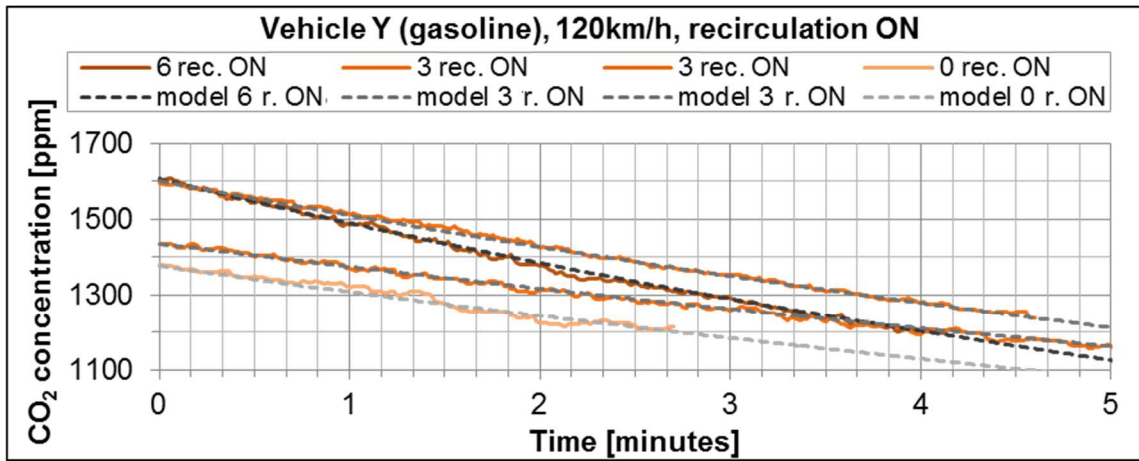
512 differential pressure – flow rate calibration. It is assumed that this flow rate is independent of
 513 the vehicle speed. In recirculation mode, this flow rate is null. The two remaining unknown
 514 parameters to adjust the model are the cabin volume and the infiltration flow rate. The raw
 515 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
 518 all tests. Indeed, there is the same equipment and constant number of occupants for all tests in
 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.
 526



527

528 **Figure 13 Simplified description of the process to estimate the infiltration flow rate**

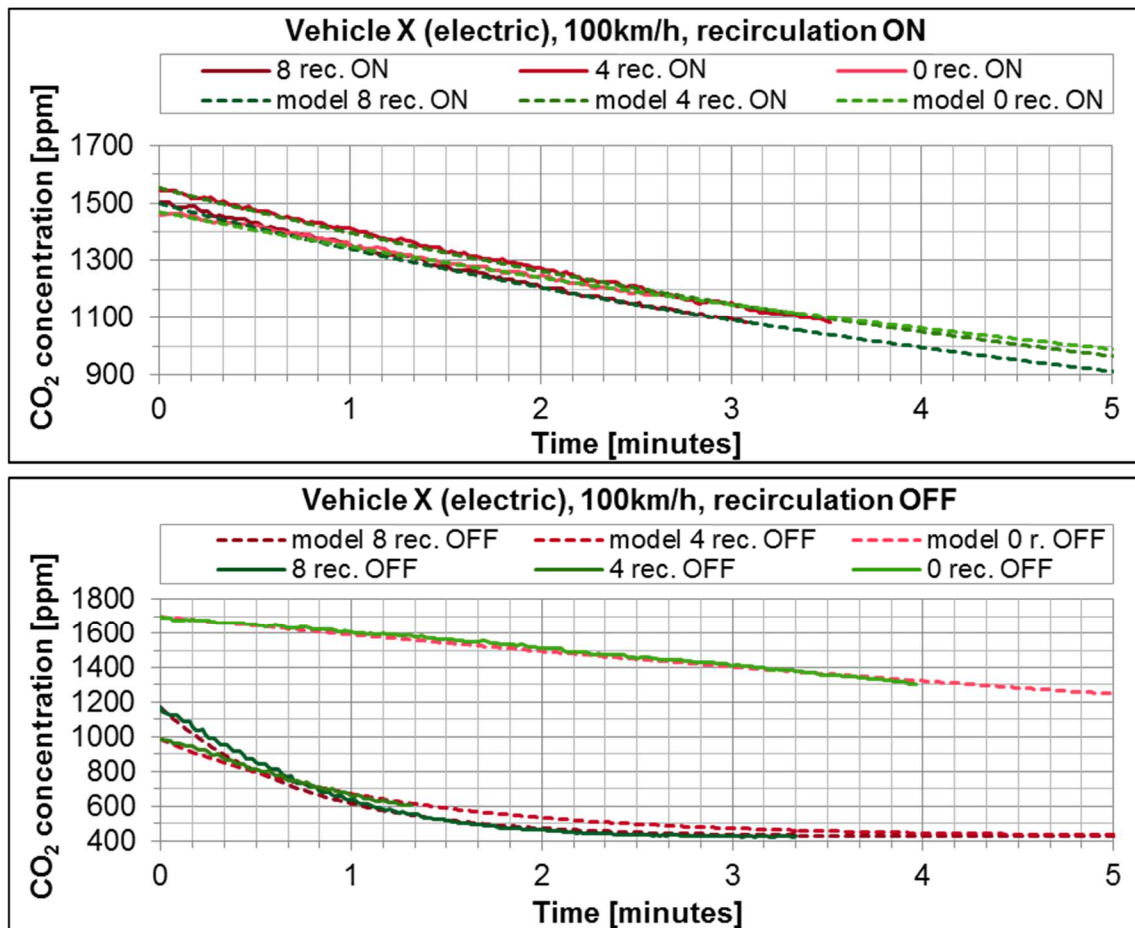
529



530

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

532



533

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

535

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 CO₂ 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 CO₂
 545 concentration in average (1349 ppm) than with vehicle Y (1502 ppm).

546

547 All the resulting infiltration flow rates of both vehicles are presented on Table 1 and Table 2.
 548 In recirculation mode, the infiltration is triggered by higher vehicle speeds and upper blower
 549 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
 552 configurations, such as illustrated on the second example of Figure 13. However, there are
 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

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

Infiltration mass flow rate vehicle Y [kg/h]							
Recirculation ON				Recirculation OFF			
GPS speed [km/h]	Blower position [0-6]			GPS speed [km/h]	Blower position [0-6]		
	0	3	6		0	3	6
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	*	*

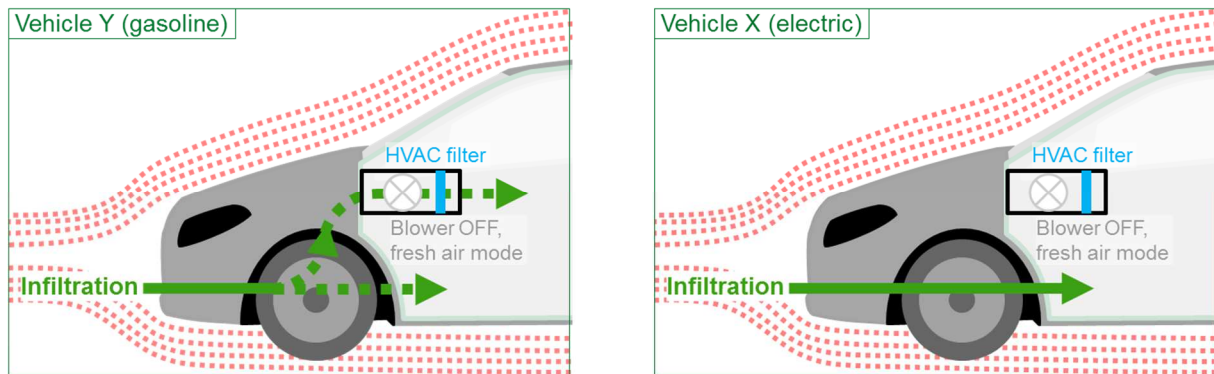
564

565 **Table 2 Estimation of infiltration mass flow rate on a modern electric vehicle for different ventilation**
 566 **settings and vehicle speeds**

Infiltration mass flow rate vehicle X [kg/h]							
Recirculation ON				Recirculation OFF			
GPS speed [km/h]	Blower position [0-8]			GPS speed [km/h]	Blower position [0-8]		
	0	4	8		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	*	*

567

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.
578



579
580 **Figure 16 Infiltration path on vehicle X and Y in fresh air mode with blower OFF configuration**

581
582 In recirculation mode, it appears that there is a higher infiltration flow rate with vehicle X
583 than with vehicle Y, particularly at high vehicle speed. For both vehicles and at a given
584 vehicle speed the infiltration flow rate slightly increases with upper blower position. The
585 explanation might be that the air is better mixed within the cabin with higher blower position.
586 Similarly than for the diffusion effect at zero vehicle speed this could stimulate the air
587 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

595 infiltrated air does not flow through the filter elements. Infiltration introduces polluted air into
596 the cabin.

597

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

602

603

604 **5. Conclusions**

605 A tracer gas technique using CO₂ is used to evaluate the air exchange rate of a cabin vehicle.
606 The experiment performed on two vehicles shows that there is an additional flow rate inlet
607 into the cabin with higher vehicle speed. The ventilation setting also has a broad impact.
608 Beside the vehicle speed, the infiltration flow rate is triggered by recirculation mode and
609 upper blower position. In fresh air mode with an active blower, the cabin is in a positive
610 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

623 Infiltration introduces non-filtered outside air directly into the cabin. Regarding the thermal
624 aspect (temperature, humidity) or air quality aspect (pollutants, particles) this is something
625 that should be avoided, or at least limited. It appears that at a given vehicle speed the best
626 strategy to avoid infiltration is to increase the amount of fresh air driven by the blower.
627 However, by doing so it also increases the amount of cold/hot air into the cabin, thus having a
628 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
630 that purpose a new filtration system (Lesage et al., 2019a, 2019b) coupled with a smart
631 control of the ventilation settings could be integrated in a vehicle.

632

633

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641

642

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