



**HAL**  
open science

## Effects of wind speed and atmospheric stability on the air pollution reduction rate induced by noise barriers

Nicolas Reiminger, Xavier Jurado, José Vazquez, Cédric Wemmert, Nadège Blond, Matthieu Dufresne, Jonathan Wertel

► **To cite this version:**

Nicolas Reiminger, Xavier Jurado, José Vazquez, Cédric Wemmert, Nadège Blond, et al.. Effects of wind speed and atmospheric stability on the air pollution reduction rate induced by noise barriers. *Journal of Wind Engineering and Industrial Aerodynamics*, 2020, 200, pp.104160. 10.1016/j.jweia.2020.104160 . hal-03041494v2

**HAL Id: hal-03041494**

**<https://hal.science/hal-03041494v2>**

Submitted on 5 Nov 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# 1 Effects of wind speed and atmospheric stability on the air pollution 2 reduction rate induced by noise barriers

3 Nicolas Reiminger<sup>1,2\*</sup>, Xavier Jurado<sup>1,2</sup>, José Vazquez<sup>2</sup>, Cédric Wemmert<sup>2</sup>, Nadège Blond<sup>3</sup>, Matthieu  
4 Dufresne<sup>1</sup>, Jonathan Wertel<sup>1</sup>

5 <sup>1</sup>*AIR&D, 67000, Strasbourg, France*

6 <sup>2</sup>*ICUBE Laboratory, CNRS/University of Strasbourg, 67000, Strasbourg, France*

7 <sup>3</sup>*LIVE Laboratory, CNRS/University of Strasbourg, 67000, Strasbourg, France*

8 <sup>\*</sup>*Corresponding author: Tel. +33 (0)6 31 26 75 88, Mail. [nreiminger@air-d.fr](mailto:nreiminger@air-d.fr)*

9

10 Please cite this paper as : Reiminger, N., Jurado, X., Vazquez, J., Wemmert, C., Blond, N.,  
11 Dufresne, M., Wertel, J., 2020. Effects of wind speed and atmospheric stability on the air  
12 pollution reduction rate induced by noise barriers. Journal of Wind Engineering and Industrial  
13 Aerodynamics 200, 104160. <https://doi.org/10.1016/j.jweia.2020.104160>

14

## 15 ABSTRACT

16 People around the world increasingly live in urban areas where traffic-related emissions can  
17 reach high levels, especially near heavy-traffic roads. It is therefore necessary to find short-term  
18 measures to limit the exposure of this population and noise barriers have shown great potential  
19 for achieving this. Nevertheless, further work is needed to better understand how they can act  
20 on pollution reduction. To do this, a Reynolds-Averaged Navier-Stokes model that takes into  
21 account thermal effects is used to study the effects of wind speed and atmospheric stability on  
22 the concentration reduction rates (*CRR*) induced by noise barriers. This study shows that the  
23 *CRR* behind the barriers may depend on both wind and thermal conditions. Although only the  
24 wind direction, and not the wind speed, has an impact on *CRR* in a neutral atmosphere, this  
25 parameter can be changed by both wind speed and thermal variations in non-neutral  
26 atmospheres. Stable cases lead to a higher *CRR* compared to unstable cases, while the neutral  
27 case gives intermediate results. Finally, it is shown that the variation of *CRR* is negligible for  
28 Richardson numbers ranging from -0.50 to 0.17.

29 **Keywords:** Computational fluid dynamics, Noise barrier, Air pollution, Wind speed, Thermal  
30 stratification

31

32

33 **Highlights**

- 34 • Wind speed does not change concentration reduction rates (*CRR*) for neutral cases.
- 35 • For neutral cases, perpendicular winds lead to the lowest *CRR*.
- 36 • The global *CRR* decreases as a function of height and distance from the barriers.
- 37 • *CRRs* are higher for stable cases ( $Ri > 0$ ) and lower for unstable cases ( $Ri < 0$ ).
- 38 • *CRRs* remain unchanged for a given Richardson number ranging from -0.50 to 0.17.

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59

60

61

62

63

64

65

## 66 1. Introduction

67 Nowadays, more than one in two people live in urban areas with 82% in the United States and  
68 74% in Europe, and this percentage will continue growing to reach 68% worldwide in 2050  
69 (United Nations, 2019). Traffic-related emissions can reach high levels in such areas,  
70 particularly near heavy-traffic roads. Concentrations of air pollutants such as nitrogen dioxide  
71 (NO<sub>2</sub>) and particulate matter (PM) can reach high values in the vicinity of this kind of road and  
72 lead to several diseases (Anderson et al., 2012; Kagawa, 1985; Kim et al., 2015). In addition, it  
73 has been shown that people living near these roads are more likely to be at risk (Chen et al.,  
74 2017; Finkelstein et al., 2004; Petters et al., 2004). In Europe, emissions and therefore  
75 concentrations of air pollutants are expected to decrease in the future as air quality regulations  
76 increase and actions are taken (European Commission, 2013). Nevertheless, it will take time to  
77 achieve a significant decrease and, in the meantime, many people will still live in areas where  
78 air quality is poor. It is now necessary to find ways to limit exposure to air pollution for people  
79 living near busy roads and to better understand solutions that have already been found, like  
80 noise barriers.

81 Noise barriers are civil engineering elements located along roadways and designed to protect  
82 inhabitants from noise pollution. These elements, often placed between heavy-traffic roads and  
83 residences, also have a beneficial impact on air quality. Indeed, several authors have  
84 investigated the efficiency of noise barriers in reducing atmospheric pollutant concentrations  
85 behind the barriers using in-field (Baldauf et al., 2008, 2016; Finn et al., 2010; Hagler et al.,  
86 2012; Lee et al., 2018; Ning et al., 2010), wind tunnel (Heist et al., 2009) measurements and  
87 numerical models (Bowker et al., 2007; Hagler et al., 2011; Schulte et al., 2014). Some authors  
88 have studied the effects of barrier heights and distances on pollution reduction (Amini et al.,  
89 2018; Gong and Wang, 2018). Other authors have studied the effects of barrier shapes and  
90 locations on improving the reduction of atmospheric pollutants (Brechler and Fuka, 2014;  
91 Enayati Ahangar et al., 2017; Wang and Wang, 2019). However, although some of these works  
92 have been performed by considering different atmospheric stabilities, knowledge is lacking on  
93 how the combination of wind conditions and thermal effects can affect pollutant reductions  
94 behind barriers. Further work is thus required in this direction.

95 The aim of this work is to study the combined effects of wind and thermal effects on the  
96 reduction of pollutant concentrations behind the noise barrier. The scope of the study is limited  
97 to the study of the effects of the noise barriers and doesn't include the possible effects of

98 buildings before and after the barriers. More specifically, computational fluid dynamics (CFD)  
99 simulations are used to assess the evolution of the concentration reduction rate behind noise  
100 barriers for several wind speeds and atmospheric stabilities, ranging from very unstable to stable  
101 conditions, including all the intermediate conditions (unstable, slightly unstable, neutral and  
102 slightly stable). The two key parameters of this study are defined and described in Section 2.  
103 The numerical model, including the governing equations, boundary conditions and model  
104 validation used in this work, is presented in Section 3. The results of the study are presented in  
105 Section 4, after which these results are discussed in Section 5.

## 106 2. Description of the study

107 This paper examines the impact of wind speed and atmospheric stability on the reduction of  
108 downwind air pollution induced by the presence of noise barriers. It is therefore necessary to  
109 define two recurring parameters: the Richardson number and the concentration reduction rate.

110 The thermal effects can be quantified using the Richardson number noted  $Ri$ . The  
111 corresponding equation taken from (Woodward, 1998) is given in (1).

$$112 \quad Ri = \frac{gH (T_H - T_w)}{U_H^2 T_{air}} \quad (1)$$

113 where  $g$  is the gravitational acceleration [ $\text{m}\cdot\text{s}^{-2}$ ],  $H$  is the noise barrier height [m],  $U_H$  is the  
114 reference velocity (which is the velocity at  $z = H$  in this study) [ $\text{m}\cdot\text{s}^{-1}$ ],  $T_{air}$  is the ambient  
115 temperature [K],  $T_H$  is mean air temperature at  $z = H$  [K], and  $T_w$  is the surface temperature of  
116 the heated ground [K]. The difference  $T_H - T_w$  will be noted  $\Delta T$  in the following.

117 The Richardson number is also an indicator of atmospheric stability:  $Ri = 0$  corresponds to  
118 isothermal (neutral) cases,  $Ri < 0$  corresponds to unstable cases, and  $Ri > 0$  to stable cases. A  
119 better discretization of atmospheric stability, related to Pasquill's stability classes, also exists  
120 (Woodward, 1998) and is summarized in Table 1.

121 Table 1. Atmospheric stability correlated with the Richardson number (Woodward, 1998).

Atmospheric stability	Richardson number
Very unstable	$Ri < -0.86$
Unstable	$-0.86 \leq Ri < -0.37$
Slightly unstable	$-0.37 \leq Ri < -0.10$
Neutral	$-0.10 \leq Ri < 0.053$
Slightly stable	$0.053 \leq Ri < 0.134$
Stable	$0.134 \leq Ri$

122 The reduction of the pollution behind the noise barriers compared to an area without these  
123 barriers is quantified using an indicator called concentration reduction rate ( $CRR$ ) given in (2).

$$124 \quad CRR (\%) = \left(1 - \frac{C_{nb}}{C_{ref}}\right) \times 100 \quad (2)$$

125 where  $C_{nb}$  is the concentration with a noise barrier [ $\text{kg}\cdot\text{m}^{-3}$ ] and  $C_{ref}$  is the reference  
126 concentration corresponding to the same case but without noise barriers [ $\text{kg}\cdot\text{m}^{-3}$ ].

127 The  $CRR$  provides information on both the positive and negative impact of noise barriers  
128 ( $CRR > 0$  means that noise barriers reduce downwind pollution;  $CRR < 0$  means that noise  
129 barriers increase downwind pollution) and their effectiveness ( $CRR = 40\%$  means that the  
130 concentration behind noise barriers is reduced by 40% compared to the same case without  
131 them).

### 132 **3. Numerical model**

#### 133 3.1. Governing equations

134 Simulations were performed using the *buoyantPimpleFoam* solver from OpenFOAM 6.0. This  
135 transient solver is able to resolve Navier-Stokes equations for buoyant and turbulent flows of  
136 compressible fluids including the effects of forced convection (induced by the wind) and natural  
137 convection (induced by heat transfers).

138 A Reynolds-averaged Navier-Stokes (RANS) methodology was used to resolve the equations.  
139 When using this methodology, a new term called Reynolds stress tensor appear and it is  
140 necessary to choose a turbulence model to resolve it. The RNG k- $\epsilon$  turbulence model proposed  
141 by Yakhot et al. (1992) has been selected because it gives significant improvements compared  
142 to the standard turbulence model for recirculatory flows (Papageorgakis and Assanis, 1999),  
143 whereas anisotropic models such as the Reynolds Stress Model (RSM) may not improve the  
144 results (Koutsourakis et al., 2012) for a higher calculation cost and more calculation  
145 instabilities.

146 The corresponding continuity (3), momentum (4) and energy (5) equations are given below:

$$147 \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (3)$$

$$148 \quad \rho \left( \frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla p + \nabla \cdot \left( 2\mu_{eff} D(u) \right) - \nabla \cdot \left( \frac{2}{3} \mu_{eff} (\nabla \cdot u) \right) + \rho g \quad (4)$$

149 
$$\frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho u e) + \frac{\partial \rho K}{\partial t} + \nabla \cdot (\rho u K) + \nabla \cdot (u p) = \nabla \cdot (\alpha_{eff} \nabla e) + \rho g \cdot u \quad (5)$$

150 
$$D(u) = \frac{1}{2} [\nabla u + (\nabla u)^T] \quad (6)$$

151 
$$K \equiv |u|^2/2 \quad (7)$$

152 where  $u$  is the velocity [ $\text{m}\cdot\text{s}^{-1}$ ],  $p$  the pressure [ $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-2}$ ],  $\rho$  the density [ $\text{kg}\cdot\text{m}^{-3}$ ],  $e$  the thermal  
153 energy [ $\text{m}^2\cdot\text{s}^{-2}$ ],  $D(u)$  the rate of strain tensor given in (6),  $K$  the kinetic energy given in (7)  
154 [ $\text{m}^2\cdot\text{s}^{-2}$ ],  $g$  the gravitational acceleration [ $\text{m}\cdot\text{s}^{-2}$ ],  $\mu_{eff}$  the effective viscosity defined as the sum  
155 of molecular and turbulent viscosity [ $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ ] and  $\alpha_{eff}$  the effective thermal diffusivity  
156 defined as the sum of laminar and turbulent thermal diffusivities [ $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ ].

157 No chemical reactions are considered in this study. Thus, the equation governing passive scalar  
158 transport (8) has been added to the solver. This advection-diffusion equation is given below:

159 
$$\frac{\partial C}{\partial t} + \nabla \cdot (uC) - \nabla \cdot \left[ \left( D_m + \frac{\nu_t}{Sc_t} \right) \nabla C \right] = E \quad (8)$$

160 where  $C$  is the pollutant concentration [ $\text{kg}\cdot\text{m}^{-3}$ ],  $D_m$  is the molecular diffusion coefficient [ $\text{m}^2\cdot\text{s}^{-1}$ ],  
161  $\nu_t$  the turbulent diffusivity [ $\text{m}^2\cdot\text{s}^{-1}$ ],  $Sc_t$  the turbulent Schmidt number [-] and  $E$  the  
162 volumetric source term of the pollutants (emissions) [ $\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$ ].

163 Each simulation was performed using second order schemes for all the gradient, divergent and  
164 Laplacian terms. The streamwise velocity  $U$  and the pollutant concentration  $C$  were monitored  
165 for several locations behind the downwind noise barrier and the results were checked to ensure  
166 that each simulation has converged. At the end of the simulations, all the residuals were under  
167  $10^{-5}$ .

### 168 3.2. Computational domain and boundary conditions

169 This study focuses on the concentration reduction rates induced by the presence of noise  
170 barriers. Thus, to quantify this reduction, two distinct cases have to be considered in terms of  
171 computational domain: a case with noise barriers and a case without them. Fig. 1 shows a sketch  
172 of the computational domain and the boundary conditions used for the case with noise barriers.  
173 The second case is strictly the same but without the noise barriers.

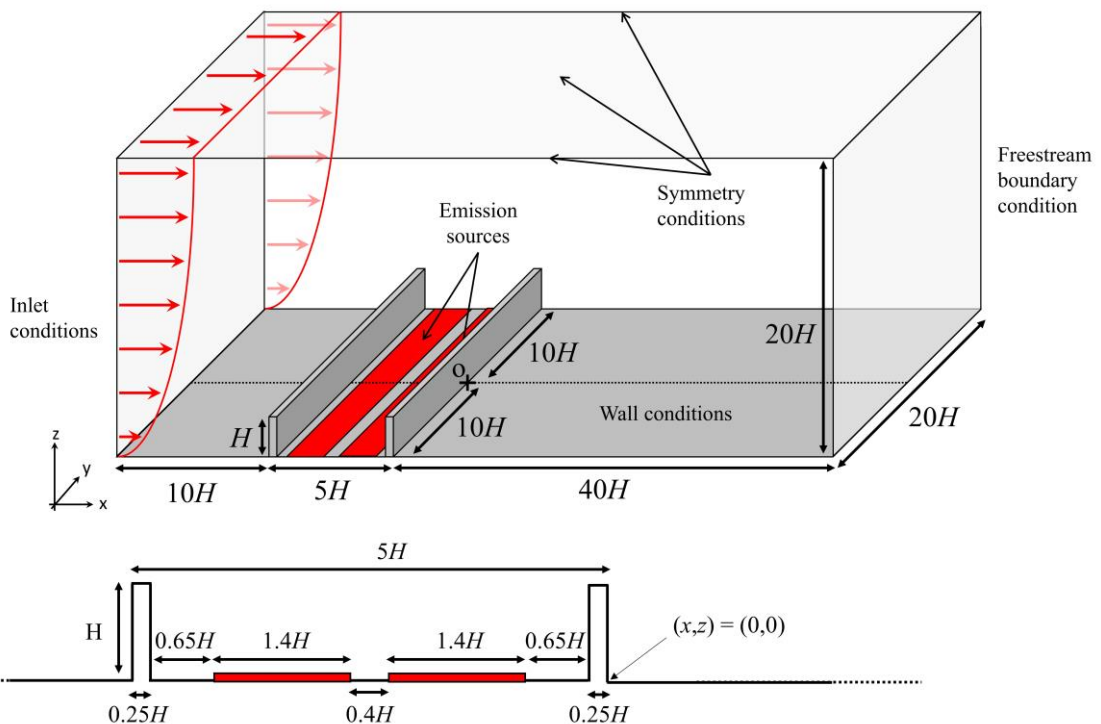


Fig.1. Sketch of the computational domain with  $H = 5$  m.

174

175

176

177 The recommendations given by Franke et al. (2007) were followed concerning the boundary  
 178 conditions and domain size. The inlet boundary is localized  $10H$  before the upwind noise barrier  
 179 where velocity, turbulence and temperature profiles are specified using a perpendicular wind  
 180 direction, unless otherwise stated. The outlet boundary is placed  $40H$  behind the downwind  
 181 noise barrier with a freestream condition to allow the flow to fully develop. Symmetry  
 182 conditions are applied for the upper and lateral limits, with the top of the calculation domain  
 183 placed  $20H$  from the ground and the lateral limits located  $20H$  from each other. No-slip  
 184 conditions are applied to any other boundaries including the ground and the two noise barriers,  
 185 where the temperature can be specified to simulate stable and unstable cases. Finally, traffic  
 186 exhausts are modeled by two volumetric sources along the  $y$ -direction, with a width of  $1.4H$   
 187 each, and over one mesh height ( $0.25$  m) where an emission source term is added in the pollutant  
 188 transport equation. A mass flow rate of  $100$  g/s is used for all the simulations performed. Further  
 189 information can be found in Table 2.

190

191

192

193

194



Table 2. Summary of the boundary conditions.

	Velocity and turbulence profiles are calculated according to Richards and Hoxey (1993) and Richards and Norris (2011): $U = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (9) \quad k = \frac{u_*^2}{\sqrt{C_\mu}} \quad (10) \quad \varepsilon = \frac{u_*^3}{\kappa z} \quad (11)$
Inlet	with $U$ the wind velocity, $k$ the turbulent kinetic energy (TKE), $\varepsilon$ the dissipation of TKE, $u_*$ the friction velocity, $\kappa$ the von Kármán constant taken to 0.41, $z$ the altitude, $z_0$ the roughness height taken as 0.5 m, and $C_\mu$ a CFD constant taken as 0.085.  Fixed temperature: $T_{air} = 293$ K.
Outlet	Freestream outlet.
Top	Symmetry plane.
Lateral surfaces	Symmetry plane.
Ground and noise barriers surfaces	No-slip condition ( $U = 0$ m/s). Fixed temperature ( $T_w$ ) depending on the case studied.
Emission	Surface source with emission rate $q_m = 100$ g/s.

196 The most part of the simulations have been carried out considering a perpendicular incident  
 197 wind angle ( $90^\circ$ ) with respect to the noise barrier, but some simulations were also performed  
 198 with a  $60^\circ$  incident angle. The boundary conditions were the same in both configurations and  
 199 Fig. 2. presents how the incidence angle is defined.

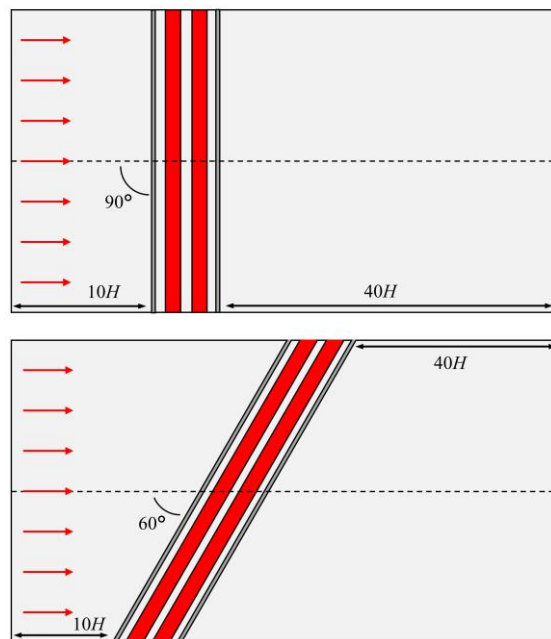
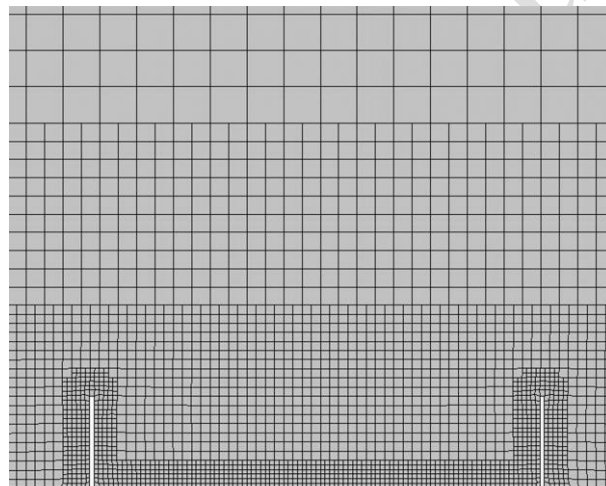


Fig.2. Definition of the wind incidence angle.

202 Mesh sensitivity tests were carried out to ensure that the results are fully independent of mesh  
203 size. Successive simulations were performed with different mesh sizes and the Grid  
204 Convergence Index (*GCI*) methodology (Roache, 1994) was used to assess the mesh-related  
205 errors on both the flow field and the concentration field. Mean *GCI*s of 2% and 1% were  
206 obtained for flow and concentration fields, respectively, when comparing the results from mesh  
207 sizes of 0.5 m and 0.25 m. Thus, a mesh size of 0.5 m was considered sufficient to avoid  
208 excessive calculation costs and was used for the study. This mesh size corresponds to the  
209 meshes localized between an altitude of  $z = 0$  and  $z = 2H$ . However, greater refinement was  
210 applied near the noise barrier walls and the road because of the strong gradients that can occur  
211 in these areas. This mesh size resulted in a total of 2.6 million meshes and an illustration of the  
212 meshes selected is provided in Figure 3. The meshing was done using the unstructured grid  
213 generator *snappyHexMesh* available with OpenFOAM.

214



215

216 Fig.3. Grid selected for computation.

217

218 Several simulations were performed to study the combined effects of wind speed and thermal  
219 effects on the concentration reduction rate behind the barriers. All the simulations performed  
220 with their specific conditions ( $U_H$  and  $\Delta T$ ) and their corresponding Richardson numbers are  
221 given in Table 3. Each of these conditions was simulated twice to obtain results with and  
222 without noise barriers to calculate the concentration reduction rates. A total of 64 simulations  
223 were carried out including:

- 224 - 24 simulations for the neutral case (6 simulations for each of the three turbulent Schmidt  
225 numbers considered to assess their impact on the concentration reduction rates and 6  
226 supplementary simulations for a non-perpendicular case);

- 227 - 20 simulations for the stable cases;  
 228 - 20 simulations for the unstable cases.

229 All the results were extracted at the center of the computational domain along  $y/H = 0$  with  
 230  $x/H = 0$  corresponding to the end of the downwind noise barrier wall.

231 Table 3. Summary of the simulations performed with wind velocity and thermal conditions ( $\Delta T = T_H - T_w$ ) and their  
 232 corresponding Richardson numbers.

$U_H$ [m/s]	1.18	1.96	3.15	5.51	7.87
$Ri$ [-]					
0	$\Delta T = 0$ K		$\Delta T = 0$ K	$\Delta T = 0$ K	
0.06				$\Delta T = 10$ K	
0.17			$\Delta T = 10$ K	$\Delta T = 30$ K	$\Delta T = 62$ K
0.33	$\Delta T = 7.5$ K		$\Delta T = 19.5$ K		
0.50	$\Delta T = 11.5$ K		$\Delta T = 29.5$ K		
1.20	$\Delta T = 10$ K	$\Delta T = 27.5$ K			
-0.06				$\Delta T = -10$ K	
-0.17			$\Delta T = -10$ K	$\Delta T = -30$ K	$\Delta T = -62$ K
-0.50	$\Delta T = -11.5$ K		$\Delta T = -29.5$ K		
-0.75	$\Delta T = -17.5$ K		$\Delta T = -44.5$ K		
-1.20	$\Delta T = -10$ K		$\Delta T = -71$ K		

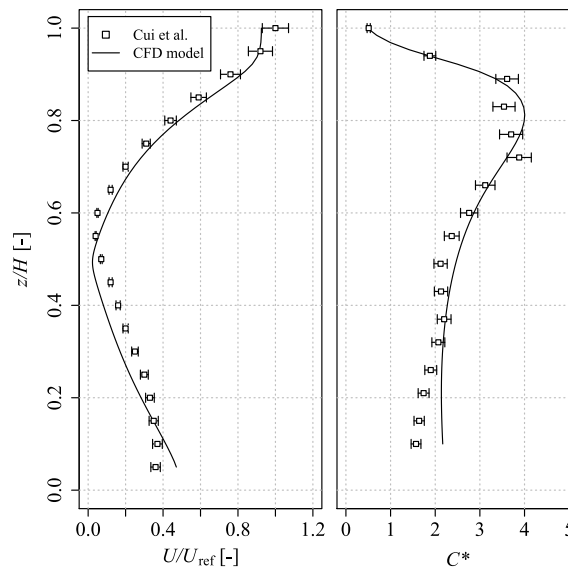
233

234 Finally, the turbulent Schmidt number ( $Sc_t$ ) is a dimensionless number found in air pollution  
 235 CFD to consider the effect of turbulent diffusivity. However, this number is widely spread  
 236 between 0.2 and 1.3, depending on the situation studied, and can significantly change the results  
 237 in terms of concentration (Tominaga and Stathopoulos, 2007). To assess the effect of this  
 238 parameter on noise barrier studies, three  $Sc_t$  were considered: 0.3, 0.7 and 1.1.

### 239 3.3. Model validation

240 The numerical model was compared against the experimental data proposed by Cui et al. (2016)  
 241 because they provided results on both velocity and the concentration field for a complex 3D  
 242 situation. Indeed, the experiment setup consists of two buildings with the downwind building  
 243 being higher than the upwind building. A gas is released at the top of the upwind building and  
 244 the ground between the two buildings is heated to simulate several atmospheric stabilities and  
 245 heat exchanges. The downwind building is opened and closed by two windows to simulate  
 246 indoor/outdoor pollutant exchanges.

247 Fig. 4 shows the comparison between the experimental data and the numerical model used in  
 248 this study for an unstable case where  $Ri = -1.22$  ( $U_{free\ stream} = 0.7$  m/s and  $\Delta T = -135$  °C) and for  
 249 a vertical profile localized between the two buildings. These results are presented in a  
 250 dimensionless form that can be found in the paper of Cui et al. (2016). The results show good  
 251 agreement between the numerical model and the experimental data on both velocity and  
 252 concentration profiles, with a mean difference of 6% between the experimental and numerical  
 253 concentration profiles. The numerical model is therefore capable of accurately reproducing  
 254 velocity and concentration profiles in a 3D case with a high thermal gradient. According to  
 255 these results, the numerical model was considered validated for the purpose of this study.



256

257 Fig.4. Vertical distribution of dimensionless velocity and concentration for  $Ri = -1.22$  given by Cui *et al.* for the wind tunnel  
 258 measurements (Cui et al., 2016), and comparison with the CFD model used for this study with  $Sc_t = 0.25$ .

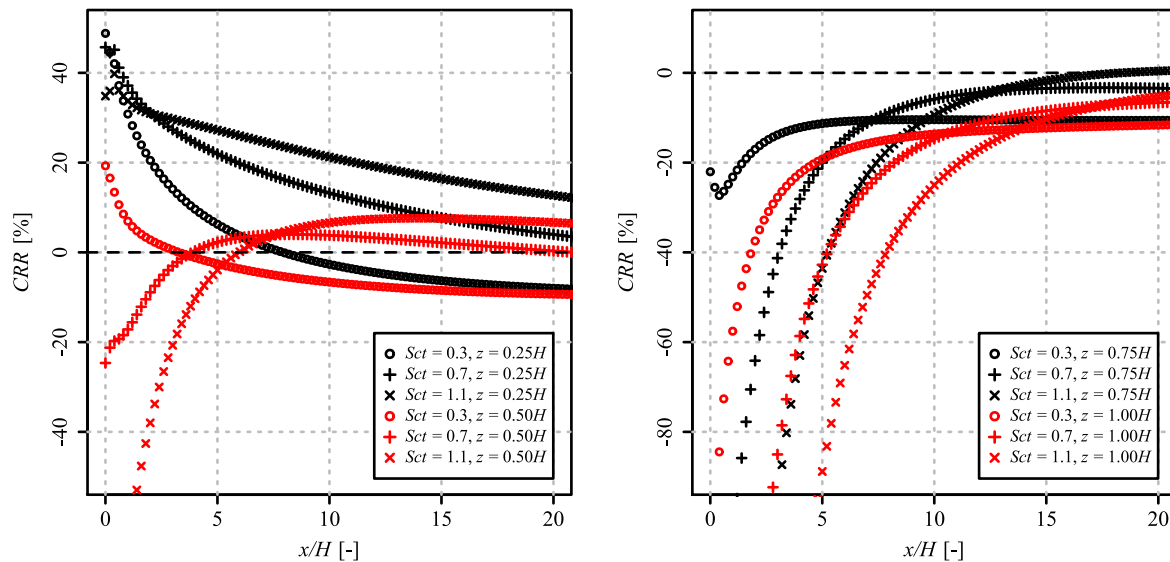
## 259 4. Results

### 260 4.1. Study without thermal effects

#### 261 4.1.1. Turbulent Schmidt number sensitivity

262 The evolution of the *CRR* behind the barriers for the three  $Sc_t$  considered and for four altitudes  
 263 ( $z = 0.25H$ ,  $0.50H$ ,  $0.75H$  and  $1.00H$ ) are presented in Fig. 5 as a function of the dimensionless  
 264 distance from the downwind noise barrier  $x/H$ , with  $z = 0.25H$  the pedestrian level  
 265 corresponding particularly to the size of a child (1.25 m). The results show considerable  
 266 variability for the concentration reduction rate as a function of the turbulent Schmidt number  
 267 and no general trend can be observed. Indeed, while for  $Sc_t = 1.1$  and  $z = 0.25H$  the *CRR* is

268 globally higher than for other turbulent Schmidt numbers, for the three other altitudes the *CRR*  
 269 is not globally higher. Additionally, while the *CRR* is globally lower with  $Sc_t = 0.3$  and  
 270  $z = 0.25H$ , this observation is no longer true for the other altitudes. Moreover, the turbulent  
 271 Schmidt number has also an impact on the distance after the barriers were there is a positive  
 272 impact of the noise barriers ( $CRR > 0$ ), this distance being higher for higher  $Sc_t$ .



273  
 274 Fig.5. Evolution of the concentration reduction rate behind the downwind wall as a function of  $Sc_t$  and for several altitudes  
 275 with the same wind profile ( $U_H = 1.18$  m/s).

276 According to these results, it is important to state that the turbulent Schmidt number is also a  
 277 very sensitive parameter when studying the impacts of noise barriers and its choice should be  
 278 considered carefully, especially when performing quantitative studies. For the rest of this paper,  
 279 and since no information or studies to determine the best turbulent Schmidt number for noise  
 280 barrier studies are available an intermediate turbulent Schmidt number of 0.7 is used, as in  
 281 Tominaga and Stathopoulos (2017), and the results are presented qualitatively rather than  
 282 quantitatively.

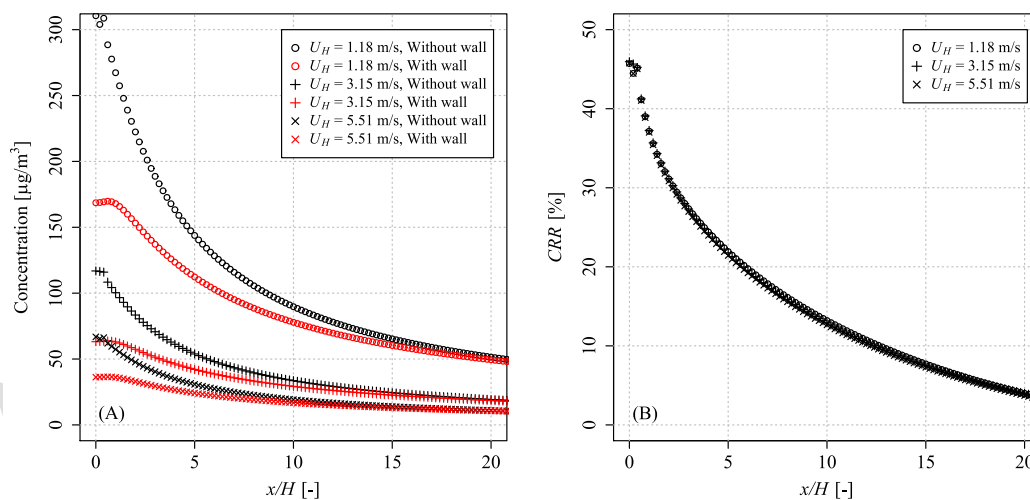
#### 283 4.1.2. Impact of wind speed and wind direction on the *CRR* in neutral atmosphere

284 The impact of wind speed and wind direction on the concentration reduction rate was first  
 285 studied in neutral atmosphere, thus, considering only forced convection (i.e. convection due to  
 286 the wind).

287 Fig. 6 shows the evolution of the pollutant concentrations behind the barriers for the cases with  
 288 and without barriers (A) and the corresponding concentration reduction rates (B) as a function  
 289 of the wind speed at  $z = 0.25H$ . According to Fig. 6 (A), regardless of the wind speed and for

290  $z = 0.25H$ , pollutant concentrations were generally higher without the noise barrier than with it.  
 291 Additionally, concentrations changed inversely with wind speed, leading to lower  
 292 concentrations for higher wind speeds. The concentrations were thus different as a function of  
 293 this parameter. However, as depicted in Fig. 6 (B), the *CRR* is the same whatever the wind  
 294 speed considered and this is also true for the other altitudes considered ( $z = 0.5H, 0.75H$  and  
 295  $1.00H$ ). This result is linked to the fact that, for a given wind direction and without thermal  
 296 stratification, the concentration was inversely proportional to the wind velocity (Schatzmann  
 297 and Leitl, 2011). Thus, since the concentration evolved in the same way with wind speed both  
 298 with and without noise barriers, the *CRR* remained unchanged for a given wind direction under  
 299 neutral conditions.

300 The effects of the wind direction under neutral conditions were also investigated and the results  
 301 are presented in Fig. 7 for a perpendicular wind ( $90^\circ$ ) and a wind oriented at  $60^\circ$ . Fig 7 (A)  
 302 shows that for the  $60^\circ$  case, the concentrations are lower with the noise barriers and higher  
 303 without the noise barriers compared to the perpendicular case. This inevitably leads to a lower  
 304 *CRR* for the perpendicular case, as shown in Fig. 7 (B) for  $z = 0.25H$  and  $z = 0.75H$ . The same  
 305 result was obtained for  $z = 0.50H$  and  $z = 1.00H$ . Therefore, the *CRR* are higher for oblique  
 306 wind directions.



307  
 308 Fig.6. Evolution of the concentrations with and without noise barriers (A) and the concentration reduction rates (B) as a  
 309 function of wind speed for a perpendicular wind direction at  $z = 0.25H$ .

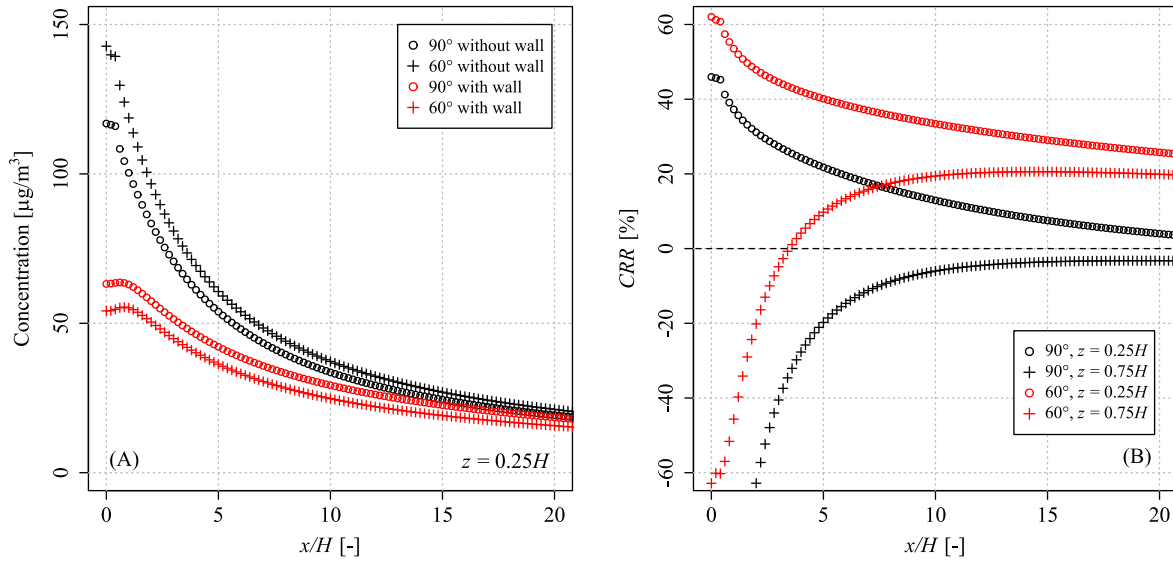


Fig.7. Evolution of the concentrations with and without noise barriers (A) and the concentration reduction rates (B) as a function of the wind direction and for a given wind speed ( $U_H = 3.15$  m/s).

310  
311  
312  
313

314 According to the previous results, when studying the CRR behind noise barriers for neutral  
315 cases, it is necessary to study only one wind speed for each wind direction. Moreover, if the  
316 minimal CRR is assessed, the study can be reduced to only one direction. Indeed, the  
317 perpendicular direction leads to the lowest CRR while the non-perpendicular directions lead to  
318 higher CRR.

319

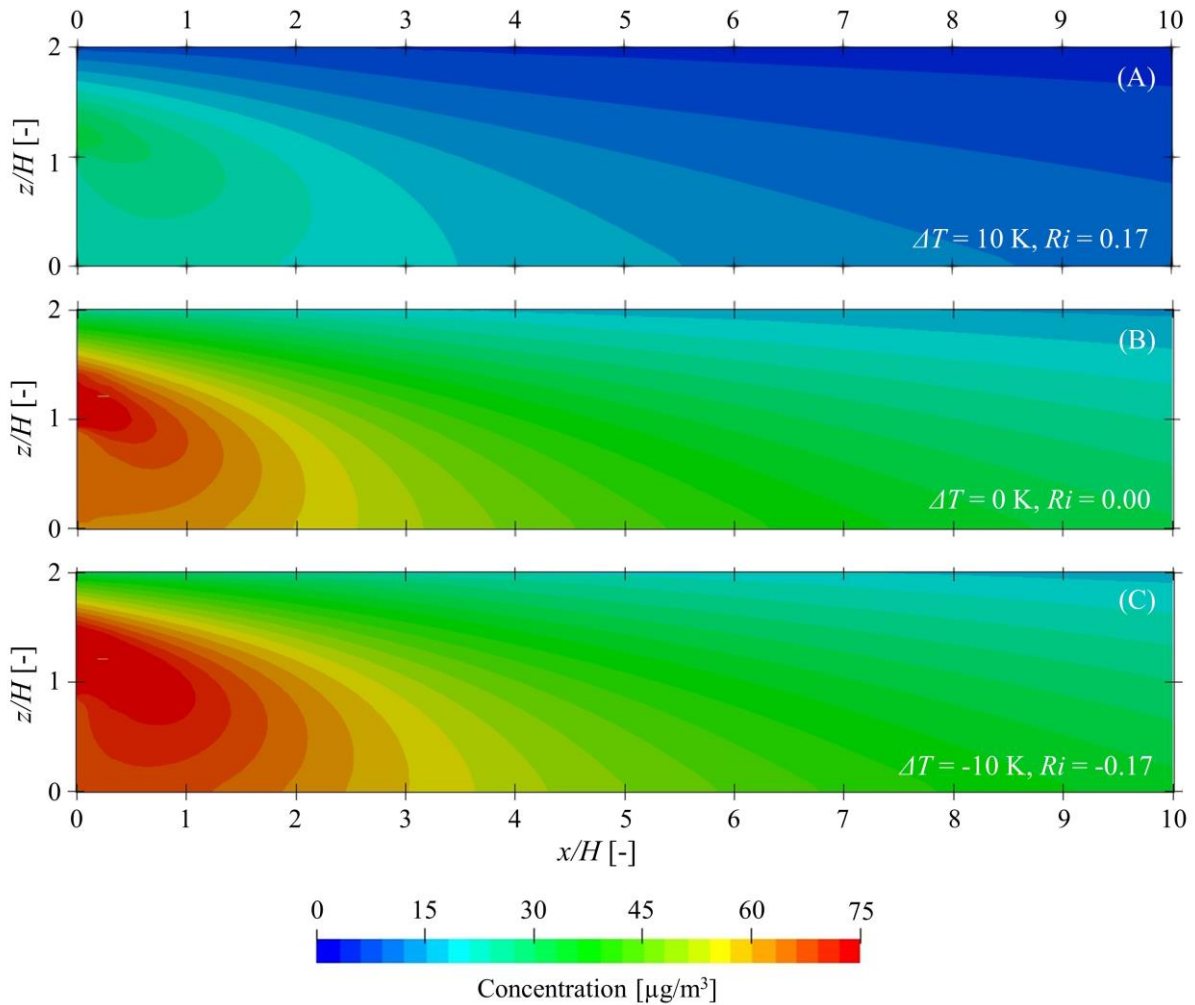
## 320 4.2. Study with thermal effects

### 321 4.2.1. Evolution of the CRR as a function of the atmospheric stability

322 The concentration reduction rate was then studied considering mixed convection: forced  
323 convection induced by wind speed and natural convection induced by thermal stratifications.  
324 The CRR was therefore studied as a function of the Richardson number which includes wind  
325 speed ( $U_H$ ) and thermal variations ( $\Delta T$ ).

326 The first results are presented in Fig. 8 for three different Richardson numbers: (A)  $Ri = 0.17$   
327 corresponding to a stable atmosphere; (B)  $Ri = 0$  corresponding to a neutral atmosphere; and  
328 (C)  $Ri = -0.17$  corresponding to a slightly unstable atmosphere, for the same wind conditions  
329 (perpendicular wind with  $U_H = 3.15$  m/s). Thus,  $\Delta T$  is the only variable here. For the three cases  
330 considered, the concentration is highest directly behind the barriers ( $x = 0$  m), just above them  
331 ( $h = 5$  m) and generally decreases as the distance from the barrier increases or the height

332 decreases. However, the concentrations are different depending on the case. Indeed, the  
 333 concentrations are lowest for the stable case (A) and highest for the slightly unstable case (C).  
 334 The neutral case (B) leads to intermediate results but closer to the unstable one. For a given  
 335 wind speed and direction, thermal effects therefore have a high impact on the concentration  
 336 behind the barriers and seem to have a greater impact for  $\Delta T > 0$  than for  $\Delta T < 0$ .



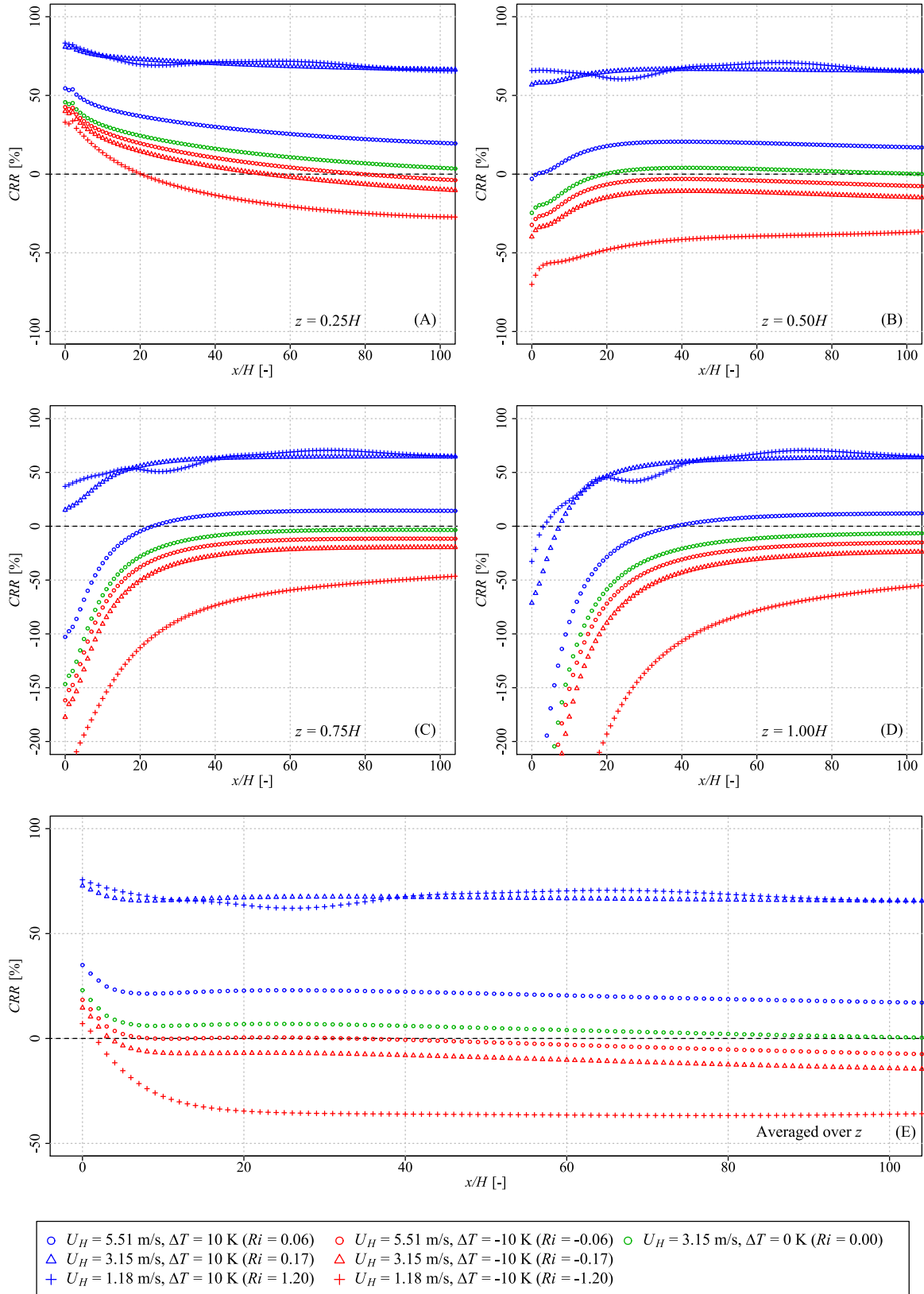
337  
 338 Fig.8. Evolution of the concentration behind the downwind barrier as a function of the temperature variation in the same  
 339 wind conditions (perpendicular wind,  $U_H = 3.15$  m/s).

340 The evolution of the *CRR* as a function of the distance from the downwind barrier was studied  
 341 for several atmospheric stabilities by changing both the wind speed ( $U_H$ ) and the thermal  
 342 variation ( $\Delta T$ ). The results for  $Ri = -1.20, -0.17, -0.06, 0.00, 0.06, 0.17$  and  $1.20$  are given in  
 343 Fig. 9 for  $z = 0.25H$  (A),  $0.50H$  (B),  $0.75H$  (C) and  $1.00H$  (D). Further results are presented in  
 344 Fig. 9 (E) and correspond to the *CRR* averaged over  $z$  for  $z$  ranging from 0 to 5 m giving global  
 345 information along the height of the noise barriers.



346 As can be seen in Fig. 9, the evolution of the *CRR* follow the same trends. Indeed, for all the  
347 altitudes considered and also for the *CRR* averaged over  $z = H$ , the results for the neutral case  
348 are bounded by the results for the stable cases and the unstable cases: the unstable cases lead to  
349 lower *CRRs* compared to the neutral case, with the lowest *CRR* being obtained for the highest  
350 instability level ( $Ri = -1.20$ ). On the contrary, the stable cases lead to higher *CRRs* with the  
351 highest *CRR* being obtained for the highest stability level ( $Ri = 1.20$ ). However, the evolution  
352 of the *CRR* according to the level of stability or instability is not equivalent between the two  
353 cases. Indeed, whereas the results are different for the three unstable cases presented in Fig. 9,  
354 the *CRR* for the two highest stable cases ( $Ri = 0.17$  and  $Ri = 1.20$ ) are very similar. Furthermore,  
355 the *CRR* changes more quickly as a function of the Richardson number for the stable cases than  
356 for the unstable cases, which is consistent with the previous results discussed in relation with  
357 Fig. 8. Thus, atmospheric stability has an impact on the *CRR*, leading to higher *CRRs* for stable  
358 cases ( $Ri > 0$ ), quickly reaching maximum values, while lower *CRRs* are obtained for unstable  
359 cases ( $Ri < 0$ ) and no maximum values were reached for the Richardson numbers considered in  
360 this study.

361 Fig. 9 also shows that the *CRR* not only depends on the distance from the barriers but also on  
362 their height. For a given atmospheric stability, the *CRR* decreases with height and can reach  
363 negative values corresponding to an increase in pollutant concentration due to the barriers.  
364 These observations are related to the heights at which the plumes spread in both configurations,  
365 with and without the barriers. Indeed, without the noise barriers the plume spreads along the  
366 ground, leading to lower concentrations at  $z = H$ , while with the noise barriers the plume spreads  
367 from the top of the barriers and the concentrations are generally lower at ground level compared  
368 to the case without barriers.



369

370

371

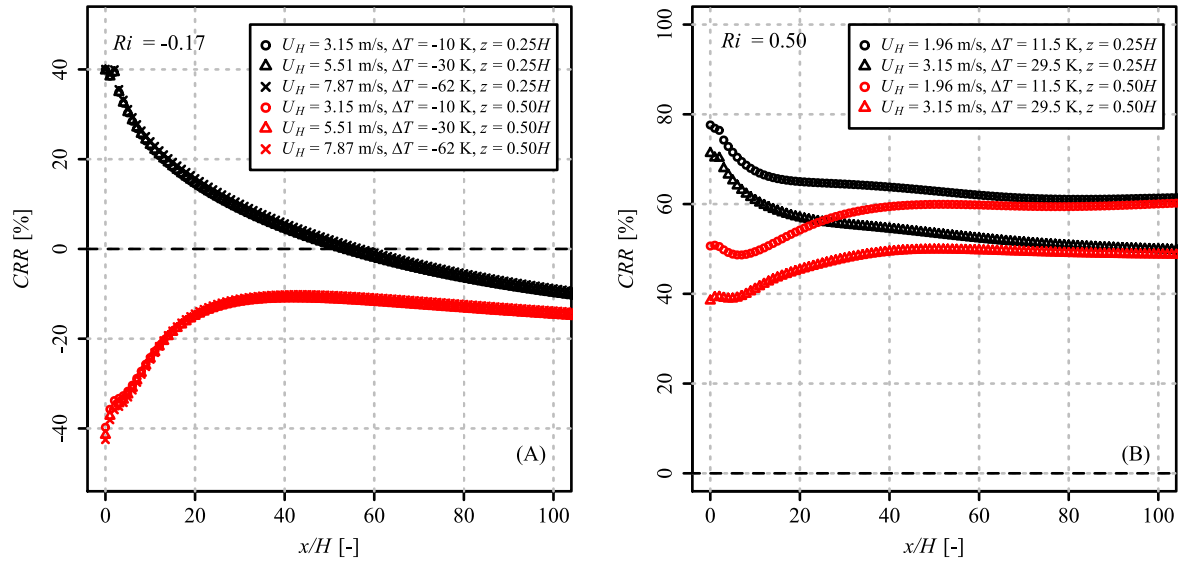
Fig.9. Evolution of the concentration reduction rates for 4 given altitudes (A—D) and averaged over the noise barrier height (E) as a function of the distance from the downwind barrier and for several Richardson numbers.

#### 372 4.2.2. Conservation of the *CRR* with the Richardson number

373 It has been shown previously that the concentration reduction rate for a given wind direction is  
374 constant when considering only forced convection (neutral atmosphere) due to an inversely  
375 proportional link between the pollutant concentrations and the wind speed. However, this link  
376 is no longer valid when considering both forced and natural convection. The question was then  
377 to assess if the *CRR* is still constant for stable and unstable cases. To answer this question,  
378 several simulations were performed for numerous Richardson numbers but with distinct couples  
379 of wind speed and thermal variations. The Richardson numbers considered were  $Ri = -1.20$ ,  
380  $-0.75$ ,  $-0.50$ ,  $-0.17$ ,  $-0.06$ ,  $0.00$ ,  $0.06$ ,  $0.17$ ,  $0.33$ ,  $0.50$  and  $1.50$ .

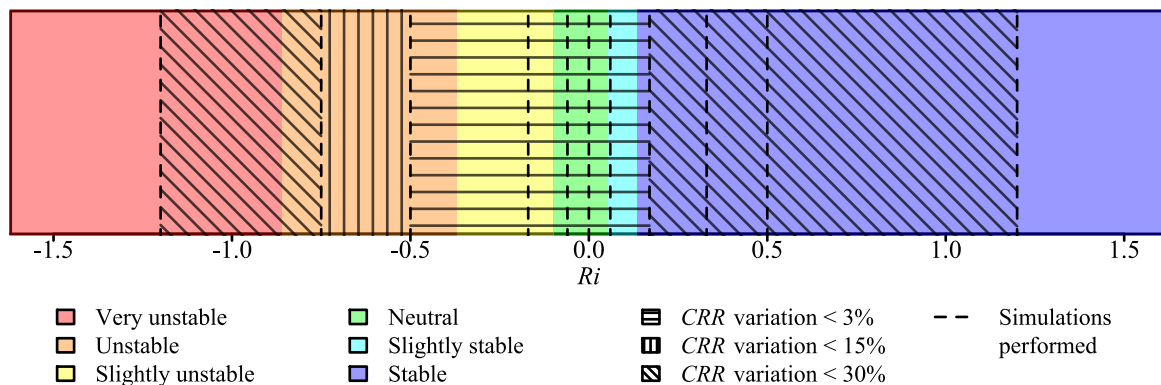
381 Fig. 10 (A) shows the evolution of the *CRR* for three couples of  $U_H$  and  $\Delta T$  giving  $Ri = -0.17$   
382 (slightly unstable atmosphere) while Fig. 10 (B) shows the evolution of the *CRR* for two couples  
383 giving  $Ri = 0.50$  (stable atmosphere). According to Fig. 10 (A), the *CRR* can be constant for a  
384 given  $Ri$ . Indeed, with  $Ri = -0.17$ , while the pollutant concentrations are not the same for the  
385 three couples of  $U_H$  and  $\Delta T$  considered, the *CRR* is quasi-constant ( $\pm 3\%$ ). However, this  
386 observation is not true for all the Richardson numbers according to Fig. 10 (B), which shows  
387 that for  $Ri = 0.50$  the *CRRs* are significantly different for the two couples of  $U_H$  and  $\Delta T$   
388 considered. Thus, the *CRR* can be constant for a given  $Ri$  but this is not generalizable.

389 The Richardson numbers for which the *CRR* can be considered constant were assessed and the  
390 results are presented in Fig. 11. The results show that, for a  $Ri$  ranging from  $-0.50$  to  $0.17$ , the  
391 variation over the *CRR* is less than 3% and the *CRR* can be considered as constant for a given  
392  $Ri$ . For Richardson numbers outside this range, the variation over the *CRR* for a given  $Ri$  can  
393 reach 15% for a  $Ri$  ranging from  $-0.75$  to  $-0.5$  and 30% for a  $Ri$  ranging from  $-0.75$  to  $-1.20$  and  
394 from  $0.17$  to  $1.20$ . According to these results, for a given  $Ri$  ranging from  $-0.50$  to  $0.17$ , a unique  
395 couple of  $U_H$  and  $\Delta T$  must be considered when assessing the concentration reduction rates  
396 behind noise barriers in non-neutral cases.



397

398 Fig.10. Evolution of the concentration reduction rate for  $Ri = -0.17$  (A) and  $Ri = 0.50$  (B) as a function of wind speed ( $U_H$ )  
 399 and thermal variation ( $\Delta T$ ) at  $z = 0.25H$  and  $z = 0.50H$ .  
 400



401

402

403 Fig.11. Conservation of the concentration reduction rate with the Richardson number.

## 404 5. Discussion

405 This study provides better understanding of how noise barriers can reduce air pollution and how  
 406 this reduction can vary with wind conditions and atmospheric stability. Additional work can be  
 407 done to further improve this understanding and is discussed below, as is the relevance of these  
 408 results.

409 This study considered only one noise barrier configuration, with two walls of the same height  
 410 placed on either side of a heavy-traffic road. Further studies could be performed to verify if the  
 411 results obtained for this configuration are generalizable, for example for noise barriers with  
 only one upwind or downwind wall and also with a combination of solid and vegetative barriers,

412 but also in presence of buildings before and after the barriers. Additionally, the height of  
413  $z = 0.25H$  (1.25 m) was considered to study the evolution of the  $CRR$  at the pedestrian level,  
414 which corresponds to the size of a child. The results were not provided for the size of adult  
415 people ( $z = 0.35H = 1.75$  m). However, results at this height can be approximated using both  
416 results at  $z = 0.25H$  and  $z = 0.50H$ , for example by the means of a linear interpolation such as  
417 given in equation (12).

$$418 \quad CRR_{0.35H} = 0.6 \times CRR_{0.25H} + 0.4 \times CRR_{0.50H} \quad (12)$$

419 where  $CRR_{0.35H}$  is the  $CRR$  at  $z = 0.35H$ ,  $CRR_{0.25H}$  is the  $CRR$  at  $z = 0.25H$  and  $CRR_{0.50H}$  is  
420 the  $CRR$  at  $z = 0.50H$ .

421 As shown in this paper, the turbulent Schmidt number has a different impact on the  $CRR$   
422 depending on the location. There is no specific trend in the vicinity of the noise barrier. Indeed,  
423 there is an increase in the  $CRR$  when  $Sc_t$  increases at the height of the noise barrier while at  
424 ground level little variations are found. However, farther from the noise barrier, trends can be  
425 identified: the  $CRR$  systematically increases with increasing  $Sc_t$ , whatever the height  
426 considered.

427 It was shown that for a given  $Ri$  ranging from -0.50 to 0.17, variations over the  $CRR$  are  
428 negligible. Moreover, the evolution of the  $CRR$  as a function of distance from the downwind  
429 barrier seemed to follow the same trends, as the curves appear the same. Thus, it may be  
430 possible to find relationships between the  $CRR$  and the Richardson number in the range -0.50  
431 to 0.17. If such relationships can be found, it will allow estimating all the  $CRRs$  in this  $Ri$  range  
432 by performing only one simulation, or with only one in-field measurement.

433 Finally, according to the results of this study, further studies can be simplified. Indeed, for  
434 future studies in neutral atmosphere (without thermal variations), they could be reduced to only  
435 wind direction and noise barrier configuration studies when assessing the evolution of the  $CRR$ .  
436 For studies including mixed convection (with thermal variations), for a  $Ri$  ranging from -0.50  
437 to 0.17, only one couple of wind speed and thermal variation is needed to assess the evolution  
438 of the  $CRR$ .

439

440

441

## 442 6. Conclusion

443 The effects of wind speed and atmospheric stability on the concentration reduction rate (*CRR*)  
444 of air pollutants induced by noise barriers were studied with a validated CFD model. This study  
445 considered both numerous wind conditions (wind speed and direction) and thermal variations,  
446 leading to different atmospheric stabilities ranging from very unstable cases to stable cases.  
447 Several CFD simulations were carried out and the main conclusions are as follows:

- 448 (a) When no thermal variations are considered, i.e. for a neutral atmosphere, the evolution  
449 of the *CRR* depends only on the wind direction: wind speed changes the pollutant  
450 concentrations behind the barriers but this parameter does not change the *CRR*.
- 451 (b) A non-perpendicular wind direction leads to higher pollutant concentrations without  
452 noise barriers and lower concentrations with the barriers compared to perpendicular  
453 cases. The *CRRs* are therefore minimal for a perpendicular wind.
- 454 (c) The *CRR* decreases with height due to the different locations of the plume for the two  
455 cases with and without noise barriers. The global *CRR* decreases with distance from the  
456 downwind barrier.
- 457 (d) The *CRR* obtained with forced convection (neutral atmosphere) is bounded by the *CRR*  
458 obtained with mixed convection (stable and unstable atmospheres): higher *CRRs* are  
459 obtained in stable conditions ( $Ri > 0$ ) while lower *CRRs* are obtained in unstable  
460 conditions ( $Ri < 0$ ).
- 461 (e) For a given Richardson number ranging from -0.50 to 0.17, the *CRR* is constant with a  
462 variation of less than 3%. For numbers outside this range the variation increases to 15%  
463 for a  $Ri$  ranging from -0.75 to -0.5 and 30% for a  $Ri$  ranging from -1.20 to -0.75 and  
464 from 0.17 to 1.20.

465 Finally, these results give insights to researchers and civil engineers to better understand  
466 variations of air pollutant concentrations behind noise barriers, for example for carrying out  
467 further assessment studies on the impact of noise barriers on the reduction of air pollution, and  
468 for in-field monitoring campaigns.

## 469 Acknowledgments

470 We would like to thank the ANRT (Association Nationale de la Recherche et de la Technologie)  
471 for their support.

472

473 **References**

- 474 Amini, S., Ahangar, F.E., Heist, D.K., Perry, S.G., Venkatram, A., 2018. Modeling dispersion  
475 of emissions from depressed roadways. *Atmospheric Environment* 186, 189–197.  
476 <https://doi.org/10.1016/j.atmosenv.2018.04.058>
- 477 Anderson, J.O., Thundiyil, J.G., Stolbach, A., 2012. Clearing the Air: A Review of the Effects  
478 of Particulate Matter Air Pollution on Human Health. *J. Med. Toxicol.* 8, 166–175.  
479 <https://doi.org/10.1007/s13181-011-0203-1>
- 480 Baldauf, R., Thoma, E., Khlystov, A., Isakov, V., Bowker, G., Long, T., Snow, R., 2008.  
481 Impacts of noise barriers on near-road air quality. *Atmospheric Environment* 6.  
482 <https://doi.org/10.1016/j.atmosenv.2008.05.051>
- 483 Baldauf, R.W., Isakov, V., Deshmukh, P., Venkatram, A., Yang, B., Zhang, K.M., 2016.  
484 Influence of solid noise barriers on near-road and on-road air quality. *Atmospheric*  
485 *Environment* 129, 265–276. <https://doi.org/10.1016/j.atmosenv.2016.01.025>
- 486 Bowker, G.E., Baldauf, R., Isakov, V., Khlystov, A., Petersen, W., 2007. The effects of roadside  
487 structures on the transport and dispersion of ultrafine particles from highways.  
488 *Atmospheric Environment* 41, 8128–8139.  
489 <https://doi.org/10.1016/j.atmosenv.2007.06.064>
- 490 Brechler, J., Fuka, V., 2014. Impact of Noise Barriers on Air-Pollution Dispersion. *NS* 06, 377–  
491 386. <https://doi.org/10.4236/ns.2014.66038>
- 492 Chen, H., Kwong, J.C., Copes, R., Tu, K., Villeneuve, P.J., van Donkelaar, A., Hystad, P.,  
493 Martin, R.V., Murray, B.J., Jessiman, B., Wilton, A.S., Kopp, A., Burnett, R.T., 2017.  
494 Living near major roads and the incidence of dementia, Parkinson’s disease, and  
495 multiple sclerosis: a population-based cohort study. *The Lancet* 389, 718–726.  
496 [https://doi.org/10.1016/S0140-6736\(16\)32399-6](https://doi.org/10.1016/S0140-6736(16)32399-6)
- 497 Cui, P.-Y., Li, Z., Tao, W.-Q., 2016. Buoyancy flows and pollutant dispersion through different  
498 scale urban areas: CFD simulations and wind-tunnel measurements. *Building and*  
499 *Environment* 104, 76–91. <https://doi.org/10.1016/j.buildenv.2016.04.028>

- 500 Enayati Ahangar, F., Heist, D., Perry, S., Venkatram, A., 2017. Reduction of air pollution levels  
501 downwind of a road with an upwind noise barrier. *Atmospheric Environment* 155, 1–  
502 10. <https://doi.org/10.1016/j.atmosenv.2017.02.001>
- 503 European Commission, 2013. Proposal for a Directive of the European Parliament and of the  
504 Council on the reduction of national emissions of certain atmospheric pollutants and  
505 amending Directive 2003/35/EC. European Commission (EC), Brussels, Belgium.
- 506 Finkelstein, M.M., Jerrett, M., Sears, M.R., 2004. Traffic Air Pollution and Mortality Rate  
507 Advancement Periods. *American Journal of Epidemiology* 160, 173–177.  
508 <https://doi.org/10.1093/aje/kwh181>
- 509 Finn, D., Clawson, K.L., Carter, R.G., Rich, J.D., Eckman, R.M., Perry, S.G., Isakov, V., Heist,  
510 D.K., 2010. Tracer studies to characterize the effects of roadside noise barriers on near-  
511 road pollutant dispersion under varying atmospheric stability conditions. *Atmospheric*  
512 *Environment* 11. <https://doi.org/10.1016/j.atmosenv.2009.10.012>
- 513 Franke, J., Hellsten, A., Schlünzen, H., Carissimo, B., 2007. Best practice guideline for the  
514 CFD simulation of flows in the urban environment. COST Action 732.
- 515 Gong, L., Wang, X., 2018. Numerical Study of Noise Barriers' Side Edge Effects on Pollutant  
516 Dispersion near Roadside under Various Thermal Stability Conditions. *Fluids* 3, 105.  
517 <https://doi.org/10.3390/fluids3040105>
- 518 Hagler, G.S.W., Lin, M.-Y., Khlystov, A., Baldauf, R.W., Isakov, V., Faircloth, J., Jackson,  
519 L.E., 2012. Field investigation of roadside vegetative and structural barrier impact on  
520 near-road ultrafine particle concentrations under a variety of wind conditions. *Science*  
521 *of The Total Environment* 419, 7–15. <https://doi.org/10.1016/j.scitotenv.2011.12.002>
- 522 Hagler, G.S.W., Tang, W., Freeman, M.J., Heist, D.K., Perry, S.G., Vette, A.F., 2011. Model  
523 evaluation of roadside barrier impact on near-road air pollution. *Atmospheric*  
524 *Environment* 45, 2522–2530. <https://doi.org/10.1016/j.atmosenv.2011.02.030>
- 525 Heist, D.K., Perry, S.G., Brixey, L., 2009. A wind tunnel study of the effect of roadway  
526 configurations on the dispersion of traffic-related pollution. *Atmospheric Environment*  
527 43(32). <https://doi.org/10.1016/j.atmosenv.2009.06.034>





- 528 Kagawa, J., 1985. Evaluation of biological significance of nitrogen oxides exposure. Tokai J.  
529 Exp. Clin. Med. 10, 348–353.
- 530 Kim, K.-H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne  
531 particulate matter. Environment International 74, 136–143.  
532 <https://doi.org/10.1016/j.envint.2014.10.005>
- 533 Koutsourakis, N., Bartzis, J.G., Markatos, N.C., 2012. Evaluation of Reynolds stress, k- $\epsilon$  and  
534 RNG k- $\epsilon$  turbulence models in street canyon flows using various experimental datasets.  
535 Environmental Fluid Mechanics 12, 379–403. [https://doi.org/10.1007/s10652-012-](https://doi.org/10.1007/s10652-012-9240-9)  
536 [9240-9](https://doi.org/10.1007/s10652-012-9240-9)
- 537 Lee, E.S., Ranasinghe, D.R., Ahangar, F.E., Amini, S., Mara, S., Choi, W., Paulson, S., Zhu,  
538 Y., 2018. Field evaluation of vegetation and noise barriers for mitigation of near-  
539 freeway air pollution under variable wind conditions. Atmospheric Environment 175,  
540 92–99. <https://doi.org/10.1016/j.atmosenv.2017.11.060>
- 541 Ning, Z., Hudda, N., Daher, N., Kam, W., Herner, J., Kozawa, K., Mara, S., Sioutas, C., 2010.  
542 Impact of roadside noise barriers on particle size distributions and pollutants  
543 concentrations near freeways. Atmospheric Environment 44, 3118–3127.  
544 <https://doi.org/10.1016/j.atmosenv.2010.05.033>
- 545 Papageorgakis, G.C., Assanis, D.N., 1999. COMPARISON OF LINEAR AND NONLINEAR  
546 RNG-BASED k-epsilon MODELS FOR INCOMPRESSIBLE TURBULENT FLOWS.  
547 Numerical Heat Transfer, Part B: Fundamentals 35, 1–22.  
548 <https://doi.org/10.1080/104077999275983>
- 549 Petters, A., von Klot, S., Heier, M., Trentinaglia, I., 2004. Exposure to Traffic and the Onset of  
550 Myocardial Infarction. The New England Journal of Medicine 351, 1721–1730.  
551 <https://doi.org/10.1056/NEJMoa040203>
- 552 Richards, P.J., Hoxey, R.P., 1993. Appropriate boundary conditions for computational wind  
553 engineering models using the k-E turbulence model 9.
- 554 Richards, P.J., Norris, S.E., 2011. Appropriate boundary conditions for computational wind  
555 engineering models revisited. Journal of Wind Engineering and Industrial  
556 Aerodynamics 99, 257–266. <https://doi.org/10.1016/j.jweia.2010.12.008>



- 557 Roache, P.J., 1994. Perspective: A Method for Uniform Reporting of Grid Refinement Studies.  
558 *Journal of Fluids Engineering* 116, 405. <https://doi.org/10.1115/1.2910291>
- 559 Schatzmann, M., Leitl, B., 2011. Issues with validation of urban flow and dispersion CFD  
560 models. *Journal of Wind Engineering and Industrial Aerodynamics* 99, 169–186.  
561 <https://doi.org/10.1016/j.jweia.2011.01.005>
- 562 Schulte, N., Snyder, M., Isakov, V., Heist, D., Venkatram, A., 2014. Effects of solid barriers  
563 on dispersion of roadway emissions. *Atmospheric Environment* 97, 286–295.  
564 <https://doi.org/10.1016/j.atmosenv.2014.08.026>
- 565 Tominaga, Y., Stathopoulos, T., 2017. Steady and unsteady RANS simulations of pollutant  
566 dispersion around isolated cubical buildings: Effect of large-scale fluctuations on the  
567 concentration field. *Journal of Wind Engineering and Industrial Aerodynamics* 165, 23–  
568 33. <https://doi.org/10.1016/j.jweia.2017.02.001>
- 569 Tominaga, Y., Stathopoulos, T., 2007. Turbulent Schmidt numbers for CFD analysis with  
570 various types of flowfield. *Atmospheric Environment* 41, 8091–8099.  
571 <https://doi.org/10.1016/j.atmosenv.2007.06.054>
- 572 United Nations, Department of Economic and Social Affairs, Population Division, 2019. World  
573 Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United  
574 Nations.
- 575 Wang, S., Wang, X., 2019. Modeling and Analysis of the Effects of Noise Barrier Shape and  
576 Inflow Conditions on Highway Automobiles Emission Dispersion. *Fluids* 4, 151.  
577 <https://doi.org/10.3390/fluids4030151>
- 578 Woodward, J.L., 1998. Estimating the flammable mass of a vapor cloud, A CCPS concept book.  
579 Center for Chemical Process Safety of the American Institute of Chemical Engineers,  
580 New York, N.Y.
- 581 Yakhot, V., Orszag, S.A., Thangam, S., Gatski, T.B., Speziale, C.G., 1992. Development of  
582 turbulence models for shear flows by a double expansion technique. *Physics of Fluids*  
583 A: Fluid Dynamics 4, 1510–1520. <https://doi.org/10.1063/1.858424>
- 584