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How wide should be the adjacent area to an urban motorway to prevent potential health impacts from traffic emissions?

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ABSTRACT

In recent years, several studies show that people who live, work or attend school near the main roadways have an increased incidence and severity of health problems that may be related with traffic emissions of air pollutants. The concentrations of near-road atmospheric pollutants vary depending on traffic patterns, environmental conditions, topography and the presence of roadside structures. In this study, the vertical and horizontal variation of nitrogen dioxide (NO_2) and benzene (C_6H_6) concentration along a major city ring motorway were analysed. The main goal of this study is to try to establish a distance from this urban motorway considered "safe" concerning the air pollutants human heath limit values and to study the influence of the different forcing factors of the near road air pollutants transport and dispersion. Statistic significant differences ($p = 0.001$, Kruskal–Wallis test) were observed between sub-domains for NO_2 representing different conditions of traffic emission and pollutants dispersion, but not for C_6H_6 ($p = 0.335$). Results also suggest significant lower concentrations recorded at 100 m away from roadway than at the roadside for all campaigns ($p < 0.016$ (NO_2) and $p < 0.036$ (C_6H_6), Mann–Whitney test). In order to have a "safe" life in homes located near motorways, the outdoor concentrations of NO_2 must not exceed 44–60.0 $\mu g\, m^{-3}$ and C_6H_6 must not exceed 1.4–3.3 $\mu g\, m^{-3}$. However, at 100 m away from roadway, 81.8% of NO_2 receptors exceed the annual limit value of human health protection (40 $\mu g\, m^{-3}$) and at the roadside this value goes up to 95.5%. These findings suggest that the safe distance to an urban motorway roadside should be more at least 100 m. This distance should be further studied before being used as a reference to develop articulated urban mobility and planning policies.

1. Introduction

In many European cities and despite past measures and many improvements, air pollution is still high and above healthy limits, leading to different types of disease and shortening life expectancy (EEA, 2011). Commonly the road traffic emissions represent the major source of air pollution in these large cities (EEA, 2011). Two of the main pollutants emitted by road traffic are the nitrogen dioxide (NO_2) and the benzene (C_6H_6) that represents serious hazards for the human health. Frequent exposition at high levels of NO_2 can cause serious respiratory damages in children and asthmatics. On the other hand, the C_6H_6 is a carcinogen volatile organic compound, which may also cause skin disease, somnolence, cough and teratogenic effects (WHO, 2000).

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Several conditions are needed to record air quality problems. The proximity to source emissions, e.g. in a busy traffic axis, the urban planning conditions and/or local microclimate may promote poor air dispersion conditions giving rise to contamination hotspots. Within busy streets, pedestrians, cyclists, drivers and residents are likely to be exposed to pollutant concentrations exceeding current air quality standards (Vardoulakis et al. 2003). The concern about this problem is supported considering that approximately 9% of the EU25 (European Union) population lives closer than 200 m from a road with more than three million vehicles per year, and as many as 25% of people lives within 500 m (ENTEC, 2006).

In order to understand the impact of air pollutants in human health, it is required to measure the pollutants concentrations continuously, by means of fixed monitoring stations, and occasionally through specific campaigns. In urban cities, this monitoring should be developed in locals with high road traffic and nearby residential areas. The results must then be compared with the limit values in order to identify and understand new human health problems and evaluate the needs of a further adaptation of these standard values.

Due to lack of air pollution data, usually in epidemiologic air pollution studies the distance to the source emission is commonly one of the key variables used (Pearson et al. 2000; Langholz et al. 2002; Draper et al., 2005; Knox, 2006; van den Hooven et al. 2009). In a revision of some of these studies Karner et al. (2010), synthesized 41 studies concluding that mostly concentration' pollutants had a persistent decay with increasing distance from the road.

Table 1 presents some relevant studies of NO_2 and C_6H_6 concentration near the road. For each study the local, year, road type, average number of vehicles and NO_2 and C_6H_6 concentrations, modelled and/or measured, at different distances from the road are presented.

As showed in Table 1, the majority of the studies of near road concentrations were performed in roadways (7 of the 13 studies). Only one was done in a highway, two in motorways and two in freeways. The average number of vehicles varies from 30,000 to 152,000 per day. On the other hand, only three of the 12 studies were made in Europe. The majority of the studies were done between 6 m and above 400 m from the road and using measurement techniques to quantify NO_2 and C_6H_6 concentrations. Some of the research studies presented in Table 1 were also done in indoor environments. However, only one of the studies with more than 100,000 vehicles per day assesses the impact of the road in indoor air quality. This study performed by Janssen et al. (2001) shows a ratio of 0.5 and 1.5 between indoor and outdoor of NO_2 and C_6H_6 concentrations, respectively. However, some differences in C_6H_6 due to the reduction of their content in fuel are expected. Other two studies make this comparison in roads with less than 100,000 vehicles per day. Kingham et al. (2000) found in these roads a C_6H_6 concentration ratio of indoor and outdoor environments of 2.0 in distances less than 50 m and 1.0 in distances higher than 50 m. Lawson et al. (2011) found ratios of 0.9 and 1.7 in distances less than 50 m to NO_2 and C_6H_6 concentrations respectively. For distances higher than 300 m from the roadside, ratios of 0.8 and 1.1 were found for these two pollutants, respectively.

Most of the studies present C_6H_6 concentrations around 1–3 $\mu g\ m^{-3}$, for both environments- indoor and outdoor- except for the study performed by Al Madhoun et al. (2011) where C_6H_6 concentrations of 355.3 and 195.0 $\mu g\ m^{-3}$ were obtained for morning peak and afternoon peak, respectively. NO_2 concentrations presented in Table 1 are very dissimilar, ranging from 13.8 to 47.8 $\mu g\ m^{-3}$.

The literature review shows a lack of knowledge about the impact of NO_2 and C_6H_6 emissions from urban motorways with heavy traffic. The impact of this carcinogenic pollutant is a major concern namely in large urban centres. In some of these cities, the impact can be higher when the buildings are located only a few meters from large roads with more than 100,000 vehicles per day. However, the behaviour of the gradient of concentrations depends on several parameters, such as meteorology, direction and wind speed, and is not linear with the distance to the source emission (Karner et al., 2010). Moreover, the concentration of these pollutants in indoor environments depends also on several aspects as the type of materials, activity of the occupants or maintenance/ cleanliness routines of the building.

In order to address these questions, the main purpose of this paper is to identify and quantify the key factors which can influence the lateral and vertical behaviours of atmospheric NO_2 and C_6H_6 emissions along the distance from the motorways and establish a "safe" distance to an urban motorway roadside regarding human health protection. To do this, an important urban motorway was selected, the VCI in Oporto city, Portugal. Three air quality field campaigns were performed during spring, autumn and winter. A brief analysis will also be presented in order to compare the air quality results with human protection limit values imposed by the Directive 2008/50/EC. Additionally, indoor concentrations were also measured in different microenvironments types using buildings located a few meters of distance from the roadside.

The main questions addressed by this research are:

- Which are the main factors that can influence lateral and vertical behaviors of atmospheric NO_2 and C_6H_6 concentrations near urban motorways considering different meteorological conditions?
- Are 100 m of distance between an indoor environment and a major urban motorway enough to guarantee human health protection?

2. Materials and methods

2.1. Study domain

The VCI is a city ring motorway at Oporto city, Portugal, that splits the centre traffic of Oporto and its surroundings (Fig. 1). This city ring is the main connection between the centre and the outskirts intercepting all the main thoroughfares

Table 1
Relevant studies on impact of road traffic on air quality near roadways.

Reference	Local Study	Year of study	Road type				Traffic volume (vehicles/ day)	Distance from the road (m)	Nitrogen dioxide concentration (μg m^{-3})			Benzene concentration (μg m^{-3})			Air quality method
			Roadways	High-way	Motor-way	Freeway			Modelling	Observed		Modelling	Observed		
										Outdoor	Indoor		Outdoor	Indoor	
Roorda-Knape et al. (1998)	Dordrecht, Rotterdam, Voorburg, Delft, Leiderdorp	1995			x		80,000–152,000	15	–	47.8	–	–	2.6	–	Monitoring
								115	–	32.2	–	–	1.9	–	
								165	–	32.1	–	–	2.0	–	
								305	–	30.6	–	–	1.9	–	
								32	–	44.8	–	–	1.8	–	
								82	–	36.8	–	–	2.1	–	
								133	–	32.4	–	–	1.9	–	
								260	–	32.1	–	–	–	–	
Kingham et al. (2000)	Huddersfield (UK)	1995	x				28,800–60,000	<50	–	–	–	–	1.0	2.0	Monitoring
								>50	–	–	–	–	1.2	1.2	
Janssen et al. (2001)	Netherlands	1997–1998			x		~102,690	0–400	–	34.8	18.8	–	1.9	2.9	Monitoring
Cook et al. (2008)	New Haven (USA)	2002	x				n.a.	Different distances	–	–	–	0–50	–	–	CMAQ and AERMOD
EPA (2004)	Nunawading (Australia)	2003–2004	x				~250,000	6	–	~25.1	–	–	5.9	–	Monitoring
EPA (2005)	Brooklyn (Australia)	2004				x	100,000–130,000	10	–	~40.5	–	–	2.8	–	Monitoring
Cohen et al. (2005)	Portland (USA)	n.a.	x				n.a.	0–50	–	–	–	1.3	–	–	CALPUFF and a regression model
								50–200	–	–	–	0.6	–	–	
								200–400	–	–	–	0.4	–	–	
								>400	–	–	–	0.1	–	–	
Barzyk et al. (2009)	Michigan (USA)	2004–2007				x	~130,000	~200	–	–	–	–	2.7/1.7[a]	–	Monitoring
Venkatram et al. (2009)	Raleigh (USA)	2006	x				n.a.	45	–	–	–	2.1	1.9	–	AERMOD and monitoring
								50	–	–	–	1.7	1.6	–	
								57	–	–	–	1.4	1.5	–	
								63	–	–	–	1.2	1.4	–	
								75	–	–	–	0.9	1.3	–	
								90	–	–	–	0.7	1.2	–	
								105	–	–	–	0.6	1.1	–	
								125	–	–	–	0.4	1.2	–	

(*continued on next page*)

Table 1 (*continued*)

Reference	Local Study	Year of study	Road type				Traffic volume (vehicles/day)	Distance from the road (m)	Nitrogen dioxide concentration ($\mu g\ m^{-3}$)			Benzene concentration ($\mu g\ m^{-3}$)			Air quality method
			Roadways	High-way	Motor-way	Freeway			Modelling	Observed		Modelling	Observed		
										Outdoor	Indoor		Outdoor	Indoor	
Lawson et al. (2011)	Melbourne (Australia)	2008–2009	x				30,000–73,000	<50	–	22.7	20.3	–	0.9	1.5	Monitoring
								>300	–	17.2	13.8		0.8	0.9	
Kimbrough et al. (2012)	Las Vegas (USA)	2008–2009		x			206,000	20	–	48.8	–	–	–	–	Monitoring
								100	–	43.1/ 42.0[b]	–	–	–	–	
								300	–	37.9	–	–	–	–	
Kheirbek et al. (2012)	New York (USA)	2011	x				n.a.	Different distances	–	–	–	–	0.82	–	Monitoring
Al Madhoun et al. (2011)	Nibong Tebal (Malaysia)	n.a.		x			n.a.	"near"	–	–	–	–	355.3/ 195.0[c]	–	Monitoring

Notes:
[a] Summer and winter, respectively.
[b] East and west side, respectively.
[c] Morning peak and afternoon peak respectively; n.a.: not available.

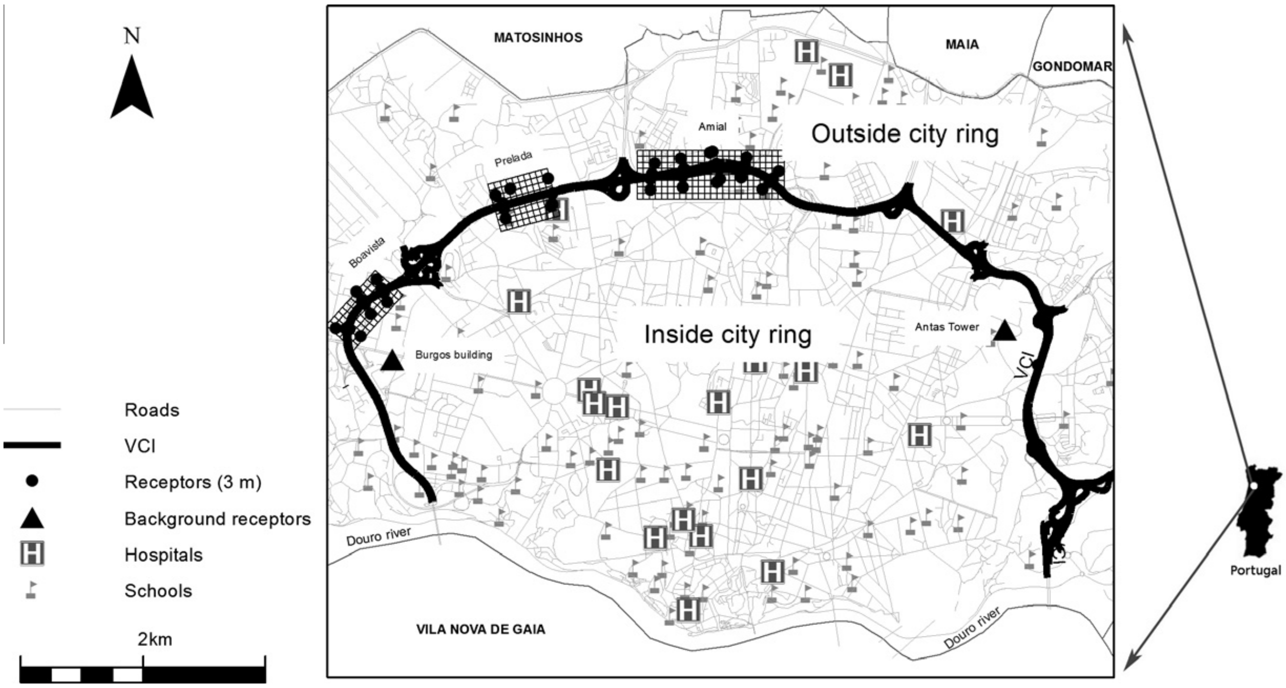

Fig. 1. Oporto city map with VCI (bold line) and study sub-domains (Boavista, Prelada and Amial).

of the city and linking the North and South of the country. This urban motorway records, in average, about 107,000 vehicles per day with more than 7,000 vehicles per hour during the rush hours in both ways (Barros et al. 2005). With nearly 10 km long and usually with three lanes (each way), VCI is surrounded by residential areas, schools and hospitals. The kerbsides are very narrow and, in some links, there are only about two meters away from buildings.

Due to the VCI length and variability of traffic emissions and dispersion conditions, the domain was subdivided in three representative sub-domains, keeping in mind also the sensible zones. The selected sub-domains were: Boavista (620 × 250 m), Prelada (400 × 500 m) and Amial (1200 × 400 m) (Fig. 1). All sub-domains present its own characteristics, containing all of them large and populated residential areas. Boavista is a street canyon type road. Prelada is a flat open air type with a school and a hospital placed at less than 100 m. Amial is a mix of a flat open air type with a particular intersection with Amial's street where VCI is elevated by a viaduct surrounded by two schools, a senior day care center and, as an additional source, a petrol-station.

2.2. Meteorological data

Meteorological data, as well as atmosphere stability condition, are key factors to study the phenomena of pollutants transport and dispersion (Seinfeld and Pandis, 2006). Thus, in order to record/estimate these factors, an Automatic Meteorological Station was installed in Amial's sub-domain, (41° 10′ 23.9″ N; 8° 37′ 21.6″ W) according to the specifications of the World Meteorological Organization (WMO, 2008). This meteorological station was used to record temperature, solar radiation and wind speed and direction, as well as its standard deviation. The meteorological parameters were validated according to EPA's method (2000).

Based on recorded data, the atmospheric stability (Pasquill-Gilford) has been estimated according to the σ method (WMO, 2008).

2.3. Road traffic emissions

To estimate emissions from road traffic in VCI, vehicle counting was made by sub-domain during two of the three campaigns of air quality. During the autumn campaign (September 2006), traffic counts were not made. In each of these campaigns, one week was selected to perform the vehicle counting in several sub-domains. The vehicle count was done on weekdays and weekends during 24 h using video cameras. In each hour, the counting was made only during two alternated periods of 15 min. These counts were done on each road side and by vehicle category (light passengers, light duty, heavy passengers, heavy duty and motorcycles).

To estimate road traffic emissions by vehicle category, the CORINAIR (2012) emission factors were used. The emission factors were weighed using several vehicle parameters of the Portuguese vehicle fleet as the vehicle age, fuel type, tare, road slope, etc. Two flow situations were considered: stop–start flow with 20 km h^{-1} of average speed and normal flow with

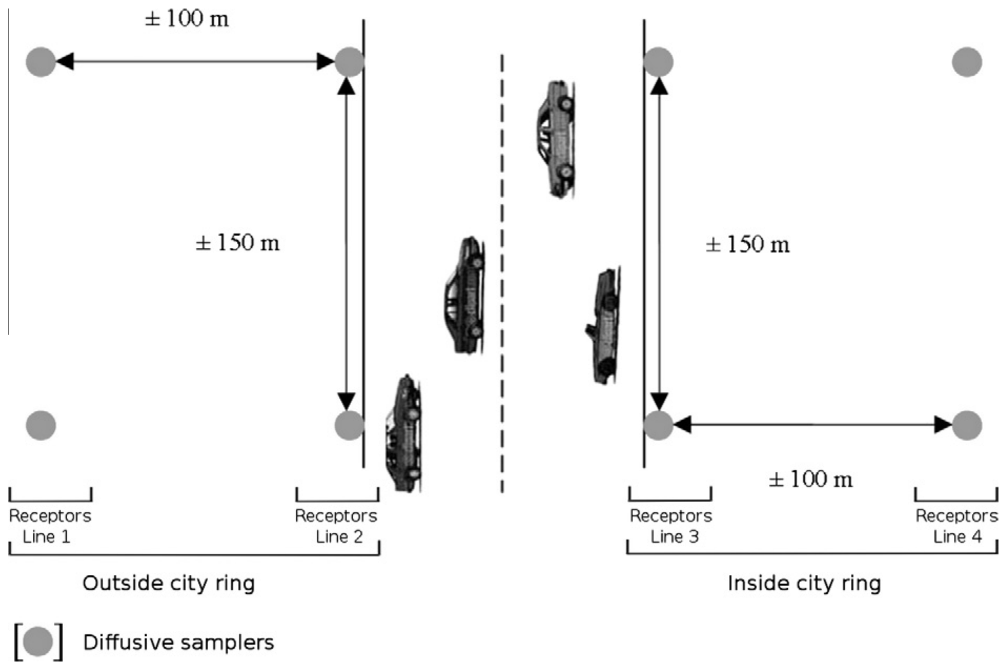

Fig. 2. Scheme of receptors location used during the field campaigns at VCI.

75 km h^{-1} of average speed. The emissions were estimated by sub-domain and campaign to nitrogen oxide (NO_x), and benzene (C_6H_6). The NO_x emissions were estimated as a measure of nitrogen dioxide (NO_2), the main focus of this study.

2.4. Outdoor air quality field campaigns

A passive sampler technique was used to measure NO_2 and C_6H_6 (PASSAM, 2011). In order to analyse different periods of the year, three field campaigns were done at VCI domain in spring (April 2005), winter and autumn (January and September 2006). Each campaign lasted for about three weeks as defined by passive sampler's vendor (PASSAM).

For each selected sub-domain, receptor lines were defined perpendicular to VCI axis and spaced by 150 m. Parallel to the axis, with a distance of 100 m, another two lines of receptors for each side of VCI were also defined. About 40 receptors were placed at 2–3 m height (Fig. 2). Data measurements collected at more than 100 m away from VCI were not considered in order to keep the statistic homogeneity, preventing in this way the increase of the influence of other urban emissions sources beyond the VCI.

To record urban canopy concentrations, two receptors have been placed at about 50 m high, at Burgos building and Antas tower roof-level (Fig. 1) – the highest buildings in the city. In both buildings, the receptor point was selected at a place away from the exhaust system of the building HVAC (heating, ventilation, and air conditioning), in order to avoid any contamination.

2.5. Indoor air quality field campaigns

To assess the indoor air quality, several campaigns were done (Mayan et al., 2005). Within the study domain, several areas were selected randomly. In these areas, the buildings more exposed to VCI were selected to collect samples. Data were collected during 2005 and 2007 in different types of environments: homes, schools, and offices located in Boavista ($n = 80$) and Prelada ($n = 66$), the two domains most densely populated. Moreover, a control group of buildings ($n = 50$) was selected. These control buildings are in Oporto but without direct influence of traffic. In all environments, NO_2 and C_6H_6 concentrations were assessed. Data collection was done with windows and doors closed and using only natural ventilation. Cleaning activities, food preparation and/or smoking were not allowed during sample data collection. To quantify the assessed parameters the methods presented on Table 2 were used.

Table 2
Methods of indoor air quality analysis.

Pollutant	Equipment	Time of data collection	Method
C_6H_6	Chromatograph Perkin Elmer, Auto System	45 min	Gas chromatography with thermal desorption and FID detector
NO_2	Passive sampler	8 h	Spectrophotometry

Table 3
Average of meteorological data recorded/estimated during each campaign: wind speed (m s^{-1}), temperature (°C), solar radiation (W m^{-2}) and frequency of occurrence of atmospheric stability (%).

	April (2005)	January (2006)	September (2006)
Wind speed (m s^{-1})	3.0 ± 1.4	2.6 ± 1.3	2.4 ± 1.5
Temperature (°C)	13.8 ± 2.7	8.7 ± 3.1	18.8 ± 3.0
Solar radiation[a] (W m^{-2})	291.1 ± 188.8	154.8 ± 106.1	284.6 ± 195.3
Frequency of occurrence of atmospheric stability (%)			
Class A	12.4	12.4	19.3
Class B	17.2	13.0	15.8
Class C	22.9	12.1	15.3
Class D	20.7	25.5	15.3
Class E	9.9	11.9	6.8
Class F	16.9	25.2	27.6

[a] Estimated only for the diurnal period (07:00H to 19:00H).

2.6. Statistical analysis

Meteorological data temporal series were analysed statistically considering spring, autumn and winter campaigns, between 2005 and 2006.

In order to perform a detailed statistical analysis of air quality, the Spearman correlation coefficient was applied between four different groups of receptors due to a non-linear relation found concerning their distance (roadside or 100 m away) and relative position (inside or outside) to the VCI city ring: set of receptors positioned in lines (parallel to the VCI axis) 1 and 2; set of receptors in lines 2 and 3; set of receptors in lines 1 and 4; and set of receptors in lines 3 and 4, as pointed out in Fig. 2. Albeit homogeneity of variance for all receptors in each sub-domain and campaign was obtained (Levene test, $p > 0.05$). Due to the small sample size, heterogeneity of sub-domain sample sizes and the non-normal pollutants' distribution, non-parametric tests had to be used in order to test for significant differences in central tendency parameters. Therefore, Kruskal–Wallis test was used to detect significant differences in median values (non-normal distribution) of pollutants concentration values and, whenever they were found, the Mann–Whitney test was applied to identify the particular significant differences between the four lines of receptors (1–4). In order to maintain the same number of receptors in each line on each side, only 32 receptors out of the existing 40 have been used for this analysis. Differences between campaigns and sub-domains were evaluated using the same tests. Significant differences between roadside and urban canopy pollutants concentrations (observation points at 50 m height) were checked using the Mann–Whitney test.

3. Results

The results will be presented in four different sections. First, the results concerning the meteorological and atmospheric stability conditions which will allow understanding and explaining of the dynamics of atmospheric transport and dispersion of pollutants emitted at the VCI domain. Afterwards, data concerning traffic flow and road traffic emissions will be presented, followed by the air quality data recorded during the three field campaigns performed at VCI and the indoor air quality data recorded in several buildings near this motorway will be presented.

3.1. Meteorological data

Table 3 presents the average of meteorological data recorded/estimated during each campaign. During the spring campaign (April 2005), Pasquill–Gifford stability class B, C and D prevails more than 60% of the time. The average wind speed was 3.0 m s^{-1} blowing predominantly from SW (Fig. 3a). The average solar radiation was 291.1 W m^{-2} during daylight. The temperature was, on average, 13.8 °C.

During the winter campaign (January 2006), Pasquill–Gifford stability class D and F prevails more than 50% of the time. The average wind speed was 2.6 m s^{-1}, blowing predominantly from SW (Fig. 3b). The average solar radiation was 154.8 W m^{-2} during daylight. The temperature was, on average, 8.7 °C.

During the autumn campaign (September 2006), Pasquill–Gifford stability F prevails more than 27% of the time. The average wind speed was 2.4 m s^{-1}, blowing predominantly from S–SW (Fig. 3c). The average solar radiation was, during daylight, about 284.6 W m^{-2}. The temperature was, on average, 18.8 °C.

3.2. Traffic and atmospheric emissions

Table 4 shows the number of vehicles and emissions (NO_x and C_6H_6) recorded during each campaign in each sub-domain of VCI. The results show that Prelada sub-domain records the highest number of vehicles with the highest estimated C_6H_6 emissions. On the other hand, the distribution of vehicle categories by sub-domain was not constant, with a high percentage

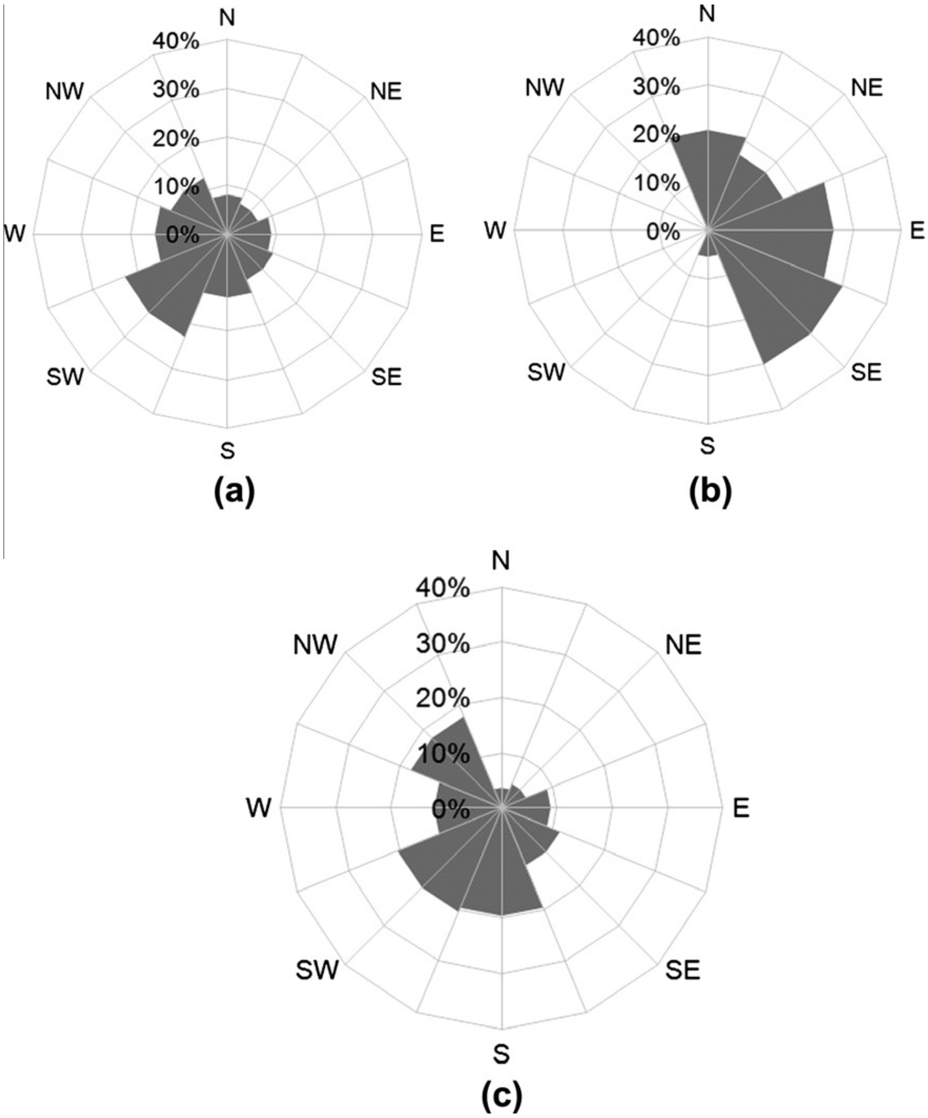

Fig. 3. Wind direction (°): (a) April of 2005; (b) January 2006; (c) and September 2006 at VCI.

Table 4
Number of vehicles and emissions (NO_x and C_6H_6) recorded during each campaign in each sub-domain of VCI. During the fall campaign (September 2006) traffic counts were not made.

	Campaigns	All domains	Sub-domains		
			Boavista	Prelada	Amial
Number of vehicles (veh day^{-1})	April/2005	141,037	134,788	145,850	142,471
	January/2006	–	132,629	–	–
NO_x emissions (kg km^{-1} day^{-1})	April/2005	189.8	198.2	188.5	198.2
	January/2006	–	181.5	–	–
C_6H_6 emissions (kg km^{-1} day^{-1})	April/2005	2.3	2.2	2.4	2.3
	January/2006	–	1.9	–	–

of heavy duty vehicles (with a higher NO_x emission factor) recorded on Boavista sub-domain when compared with the other sub-domains, namely Prelada, with a relative higher percentage of passenger vehicles. This explains the fact of the highest estimated NO_x emissions being for the Boavista sub-domain and not for Prelada. Nevertheless, a global view shows a very small difference between sub-domains traffic and pollutants emission (below 10%).

Table 5
Results of air quality using passive diffusion at 2–3 m height by pollutant (NO_2 and C_6H_6 ($\mu g\ m^{-3}$)), campaign and sub-domain (limit values as considered in Directive 2008/50/EC).

Pollutants	Limit Value ($\mu g\ m^{-3}$)[a]	Receptors location	Campaigns	Concentrations ($\mu g\ m^{-3}$)						
				All domains	Boavista		Prelada		Amial	
				$\overline{X} \pm$ SD	$\overline{X} \pm$ SD	n	$\overline{X} \pm$ SD	n	$\overline{X} \pm$ SD	n
NO_2	40	VCI roadside	April/2005	94.8 ± 4.7	128.4 ± 9.9	8	68.6 ± 17.8	4	87.3 ± 9.7	10
			January/2006	90.7 ± 2.0	122.0 ± 10.7	8	67.0 ± 12.6	4	83.1 ± 8.6	10
			September/2006	80.2 ± 2.5	115.4 ± 23.2	7	53.4 ± 18.9	4	71.9 ± 19.0	10
			All	88.6 ± 7.5	122.2 ± 7.7	23	63.0 ± 16.7	12	80.8 ± 14.4	30
		100 m away from VCI	April/2005	62.9 ± 5.6	63.3 ± 4.1	6	57.6 ± 12.1	4	67.9 ± 14.9	10
			January/2006	59.0 ± 3.8	60.1 ± 3.8	5	53.0 ± 10.1	4	63.7 ± 10.7	10
			September/2006	46.7 ± 6.1	48.6 ± 5.4	5	41.9 ± 11.3	4	49.7 ± 17.6	10
			All	56.2 ± 8.4	57.7 ± 7.7	16	50.8 ± 7.8	12	60.4 ± 16.2	30
		All	April/2005	80.4 ± 32.6	100.5 ± 34.3	14	63.1 ± 13.6	8	77.6 ± 15.8	20
			January/2006	77.2 ± 31.6	98.2 ± 32.5	13	60.0 ± 11.2	8	73.4 ± 13.7	20
			September/2006	65.3 ± 23.4	87.6 ± 38.6	12	47.6 ± 14.0	8	60.8 ± 21.1	20
			All	74.3 ± 7.9	95.7 ± 34.6	39	56.9 ± 14.2	24	70.6 ± 18.3	60
C_6H_6	5	VCI roadside	April/2005	2.5 ± 0.2	2.8 ± 0.5	5	2.2 ± 0.7	4	2.5 ± 0.3	9
			January/2006	3.1 ± 0.7	3.5 ± 1.6	5	2.5 ± 0.3	4	3.2 ± 0.5	10
			September/2006	2.1 ± 0.2	2.8 ± 0.6	5	1.5 ± 0.4	4	1.9 ± 0.2	10
			All	2.5 + 0.5	3.0 + 1.1	15	2.1 + 0.6	12	2.5 + 0.7	29
		100 m away from VCI	April/2005	1.9 ± 0.4	1.8 ± 0.1	6	1.7 ± 0.9	4	2.1 ± 0.5	10
			January/2006	2.3 ± 0.2	2.1 ± 0.3	5	2.0 ± 0.5	4	2.8 ± 0.7	10
			September/2006	1.4 ± 0.2	1.5 ± 0.1	5	1.4 ± 0.5	4	1.6 ± 0.6	10
			All	1.9 ± 0.5	1.8 ± 0.3	16	1.6 ± 0.4	12	2.1 ± 0.8	30
		All	April/2005	2.2 ± 1.0	2.4 ± 0.6	14	2.0 ± 0.6	8	2.2 ± 0.5	19
			January/2006	2.7 ± 1.3	3.0 ± 1.5	13	2.2 ± 0.3	8	3.0 ± 0.6	20
			September/2006	1.8 ± 0.7	2.3 ± 0.8	13	1.3 ± 0.4	8	1.7 ± 0.5	20
			All	2.2 ± 0.5	2.5 ± 1.0	40	1.8 ± 0.6	24	2.3 ± 0.7	59

$\overline{X}$: average; SD: standard deviation; n: number of receptors.
[a] Annual limit value for human health protection (Directive 2008/50/EC).

3.3. Outdoor air quality campaigns

Table 5 shows the main results concerning air quality. For each campaign and sub-domain, the average concentrations of NO_2 and C_6H_6 and the standard deviation of each pollutant as well as the annual limit values defined by Directive 2008/50/EC are presented. It should be emphasized that the comparison with the annual average limit value is only indicative, as the technique applied (passive diffusion), although corresponding to an integrated average, refers to three weeks of measurements in each of the three seasonal campaigns (winter, spring and fall) performed at the study domain.

A detailed analysis shows different profiles of spatial distributions of NO_2 and C_6H_6 concentrations for each analysed sub-domain. At the VCI roadside, the Boavista sub-domain presents consistently, in all campaigns and for both pollutants, the highest averages concentrations (115.7–128.4 $\mu g\ m^{-3}$ for NO_2 and 2.8–3.5 $\mu g\ m^{-3}$ for C_6H_6) and also the maximums concentrations (138.8–147.2 $\mu g\ m^{-3}$ for NO_2 and 3.3–7.4 $\mu g\ m^{-3}$ for C_6H_6). The average values recorded in the VCI roadside could be 9–32% times less than the maximum values of NO_2 and 12–52% times to C_6H_6. On the other hand, the lowest averages concentrations recorded at this distance, in all campaigns and for both pollutants, were recorded in Prelada sub-domain, ranging between 53.4 and 68.6 $\mu g\ m^{-3}$ for NO_2 and 1.5–2.5 $\mu g\ m^{-3}$ for C_6H_6. In this sub-domain was almost always recorded the lowest minimum pollutant concentrations (with exception of April 2005 to C_6H_6). At 100 m away from VCI, the highest averages concentrations, in all campaigns and for both pollutants, were recorded consistently in Amial for NO_2 (ranging between 49.7 and 67.9 $\mu g\ m^{-3}$) and for C_6H_6 (ranging between 1.6 and 2.8 $\mu g\ m^{-3}$). Typically, at this distance from VCI, the maximums concentrations were recorded in Amial sub-domain, ranging between 83.4–94.3 $\mu g\ m^{-3}$ for NO_2 and 2.7–3.8 $\mu g\ m^{-3}$ for C_6H_6. Moreover, at 100 m away, the average lowest concentrations were recorded at Prelada sub-domain (41.9–57.6 $\mu g\ m^{-3}$ for NO_2 and 1.4–2.0 $\mu g\ m^{-3}$ for C_6H_6) and the minimum concentrations (exception of January 2006 to NO_2) were also almost always recorded in this sub-domain.

Regarding the concentrations on different meteorological conditions for all sub-domains (Table 5, Fig. 4 i2 and Fig. 4 ii2), the pollutants concentrations had a maximum in April for NO_2 (80.4 ± 32.6 $\mu g\ m^{-3}$) and in January for C_6H_6 (2.7 ± 1.3 $\mu g\ m^{-3}$). On the other hand, the minimum concentrations were recorded in September (65.3 ± 23.4 $\mu g\ m^{-3}$ for NO_2 and 1.8 ± 0.7 $\mu g\ m^{-3}$ for C_6H_6).

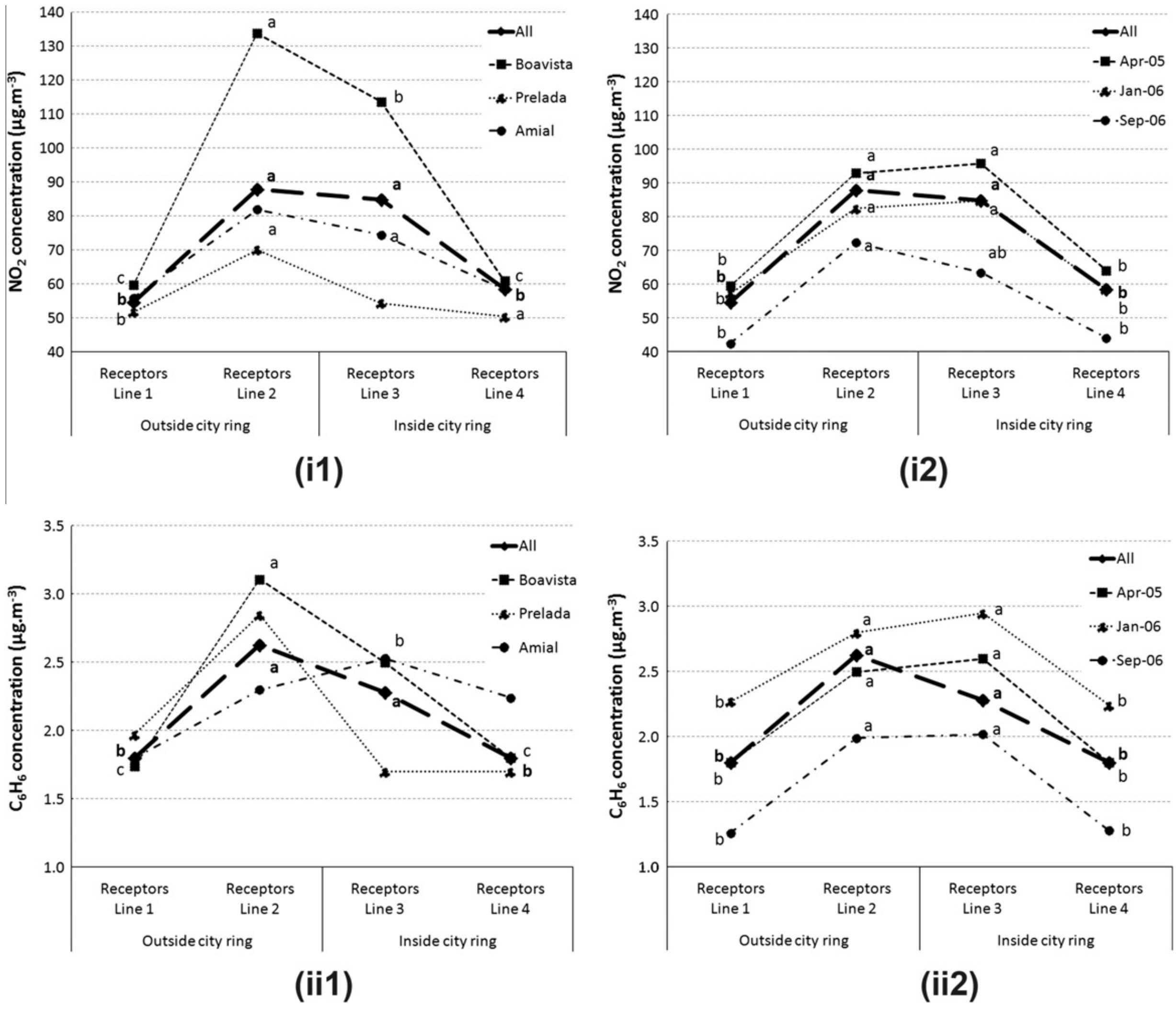

Fig. 4. Median values of NO_2 and C_6H_6 concentrations ($\mu g\ m^{-3}$): (i) all data, by sub-domain (Boavista, Prelada and Amial) and; (ii) by campaign (April of 2005, January 2006 and September 2006). a, b, c – Different letters stand for significant differences in relation to the distance from the road centre according to the Mann–Whitney test.

The average urban canopy concentration (measurements at about 50 m of height) were $42.3 \pm 6.1\ \mu g\ m^{-3}$ for NO_2 and $1.4 \pm 0.3\ \mu g\ m^{-3}$ for C_6H_6, which means that the average values in the VCI roadside (measurements at 2–3 m of height) were almost always the double for both pollutants when compared with the values recorded at 50 m of height.

As an example, the concentration field of NO_2 and C_6H_6 for September 2006 is presented in Figs. 5 and 6.

Correlation between receptors at each campaign and sub-domain for both pollutants varies considerably (Table 6), probably both due to natural variations and also to the small sample size. Mostly good and very good correlations were found between receptors at roadside of the motorway (set of receptors in lines 2 and 3 – Fig. 2) for NO_2, though they are only significant for all sub-domains to April 2005 and September 2006 and in Amial sub-domain for all campaigns. For C_6H_6, the correlation is only significant for all campaigns at Prelada sub-domain. To 100 m receptors (set of receptors in lines 1 and 4 – Fig. 2), the coefficient correlation is quite acceptable with mostly good/very good for both pollutants. Nevertheless, for NO_2, they are only significant for all sub-domains in September 2006 and in Amial for all campaigns. For C_6H_6 and for all sub-domains, correlations are significant with the exception of April 2005. For all campaigns, correlations for C_6H_6 are significant for Amial sub-domain only.

However, using data regarding both pollutants concentrations for January 2006 and September 2006 campaigns it was possible to establish that values recorded at 50 m of height were significantly lower than at roadside ($p < 0.01$ for NO_2 and $p < 0.008$ for C_6H_6, in both campaigns).

Statistical differences were also mainly detected between receptors located at VCI roadside and values recorded at 100 m away (set of receptors in lines 1 and 2 and set of receptors in lines 3 and 4 – Fig. 2) ($p < 0.001$, Mann–Whitney test), with the latter (100 m away) showing significant lower pollutant concentrations (Table 5 and Fig. 4). These significant differences were found in all campaigns ($p < 0.016$ (NO_2) and $p < 0.036$ (C_6H_6), Mann–Whitney test), especially in Boavista ($p < 0.001$ (NO_2); $p = 0.001$ (C_6H_6), Mann–Whitney test) and in Amial sub-domains ($p < 0.001$ (NO_2), Mann–Whitney test), while Prelada

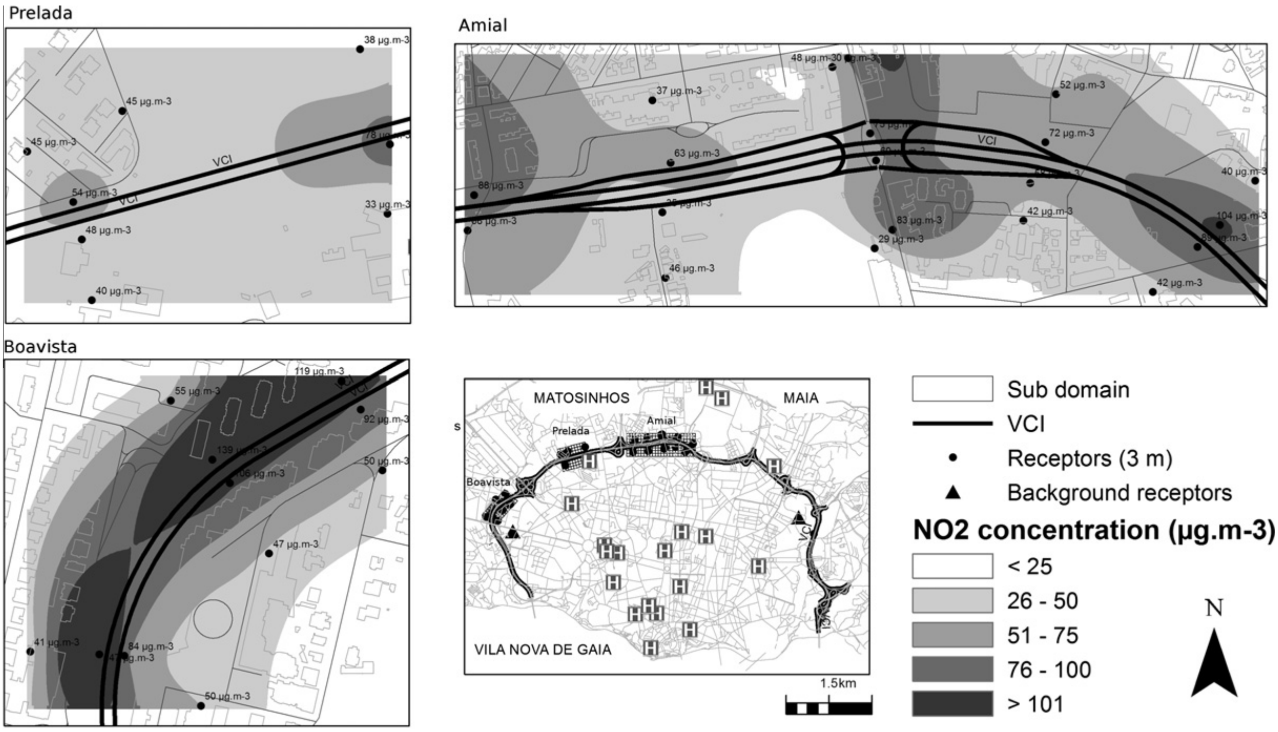

Fig. 5. Interpolation of measured NO_2 concentrations in September 2006 for each VCI sub-domain.

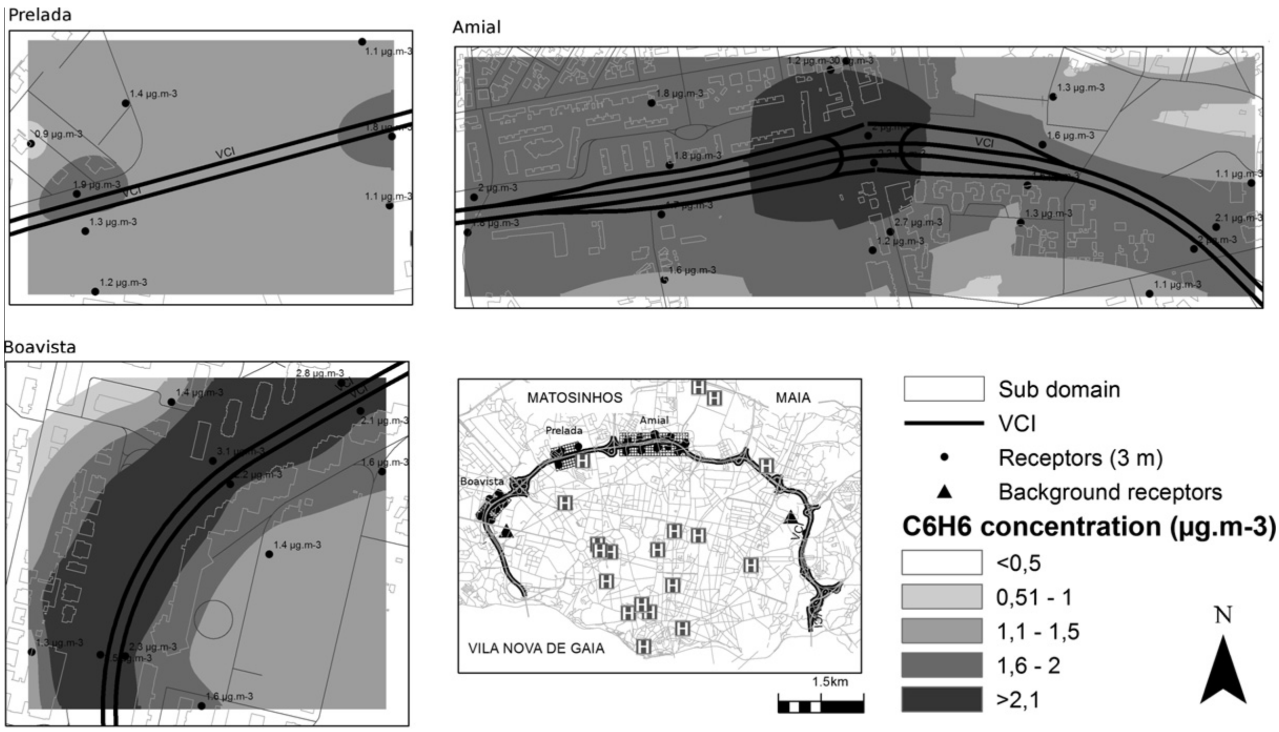

Fig. 6. Interpolation of measured C_6H_6 concentrations in September 2006 for each VCI sub-domain.

did not show significant differences for the roadside (0 m) and 100 m distances. These differences are more evident on the receptors located outside the city ring, i.e., roughly to north. This can be explained by wind transport. In fact, for all campaigns, the wind is from the southern quadrant, which promotes the pollution transport towards north, in particular at Prelada sub-domain because of its open field characteristics (Fig. 4 i1 and Fig. 4 ii1).

The results also suggest that meteorological conditions do not change the variability of concentrations recorded and thus physical characteristics of the domain have high importance to explain these variability (Fig. 4 i2 and Fig. 4 ii2).

Table 6
Values of the Spearman correlation coefficient for NO_2 and C_6H_6 concentration between the four set of recorded receptors at the VCI, for all sub-domains and campaigns. Significant differences (bold values; for level of significance please check table foot note) regarding median concentrations for both pollutants between these receptors.

Pollutants	Campaign	Sub-domain	n	Receptors 1 and 2 (Out 100 m / Out 0 m)	Receptors 2 and 3 (Out 0 m/ In 0 m)	Receptors 1 and 4 (Out 100 m/ In 100 m)	Receptors 3 and 4 (In 100 m / In 0 m)
NO_2	All	All	22	0.485	**0.908 ****	**0.788 ****	0.333
	Abr/2005	All	9	0.433	**0.883 ***	0.233	-0.167
	Jan/2006	All	7	0.357	0.750	0.643	0.000
	Set/2006	All	6	0.543	**0.943 ***	0.600	0.429
	All	Boavista	7	0.036	0.052	0.294	0.500
	All	Prelada	3	0.500	0.500	1.000	1.000
	All	Amial	12	0.196	**0.874 ****	**0.837 ****	0.070
C_6H_6	All	All	20	0.353	0.442	**0.789 ****	**0.719 ****
	Abr/2005	All	7	0.318	-0.355	-0.374	0.355
	Jan/2006	All	7	0.107	0.036	0.857	0.750
	Set/2006	All	6	0.029	0.657	**0.943 ***	0.543
	All	Boavista	7	0.306	-0.144	0.577	0.667
	All	Prelada	3	0.500	1.000	0.500	1.000
	All	Amial	10	0.176	0.455	**0.988 ****	0.552

Correlation: □ ⩽ 0.49: □ 0.50–0.74: ■ ⩾ 0.75.
n = Number of receptors; Out = receptors located in the outside of the city ring; In = receptors located inside of the city ring.
⁎Mann–Whitney test: level of significance of 5%.
⁎⁎Mann–Whitney test: level of significance of 1%.

Table 7
Results of indoor air quality concentration NO_2 and C_6H_6 (μg m^{-3}).

Pollutant	Environment type		Concentrations (average ± standard deviation) (μg m^{-3})								Outdoor limit value (μg m^{-3})
			Exposed						Control (non-exposed)		
			Boavista (n = 80)		Prelada (n = 66)		Average value (n = 146)		Average value (n = 50)		
			Av ± SD	I/O	Av ± SD	I/O	Av ± SD	I/O	Av ± SD	I/O	
NO_2	Home	Indoor	48.9 ± 23.4	0.7	49.5 ± 18.9	0.9	49.2	0.8	25.8 ± 18.1	0.8	200/40[a]
		Outdoor	74.3 ± 36.6		55.3 ± 18.9		64.8		32.9 ± 12.9		
	School	Indoor	–	–	51.1	0.7	51.1	0.7	–	–	
		Outdoor	–		68.6		68.6		–		
	Offices	Indoor	–	–	7.3	0.2	7.3	0.2	–	–	
		Outdoor	–		36.9		36.9		–		
C_6H_6	Home	Indoor	23.6 ± 60.2	3.4	9.9 ± 8.9	1.5	16.8	2.5	8.1 ± 3.4	0.9	5
		Outdoor	7.0 ± 3.0		6.6 ± 3.8		6.8		9.3 ± 2.9		
	School	Indoor	12.3	0.9	17.8 ± 14.4	1.2	15.1	1.0	8.5	0.7	
		Outdoor	14.0		15.0 ± 5.7		14.5		13.0		
	Offices	Indoor	–	–	22.0	4.4	22.0	4.4	9.6	1.5	
		Outdoor	–		5.0		5.0		6.5		

Notes:
Av ± SD: Average ± Standard Deviation; I/O: Indoor/Outdoor.
[a] Hourly average and annual average, respectively (Directive 2008/50/EC).

Notwithstanding the variability found between sub-domains, variance homogeneity was obtained for concentration readings recorded in all campaigns and sub-domains. The statistical comparison of NO_2 and C_6H_6 median concentrations for the three campaigns showed significant differences between values recorded in the roadside and values recorded at 100 m away ($p < 0.001$, Mann–Whitney test).

3.4. Indoor air quality campaigns

Table 7 shows the main results of indoor concentrations by environmental type and pollutant (Mayan et al. 2005).

As can be observed on Table 7, ratios of indoor and outdoor levels (I/O) vary across the microenvironment type. Regarding to NO_2, a prevalence of outdoor sources was recorded, namely in Boavista domain. Average concentration on Boavista's outdoor environment is significant higher (about 1.3 times more) comparatively with that recorded in Prelada. On the other hand, there is similar NO_2 concentration in indoor homes for both sub-domains, which may indicate that the outdoor source have a limited importance. For C_6H_6, indoor exposure environments have values higher than the non-exposed environments, which reflects, eventually, amplification of the indoor contamination from outdoor sources. For NO_2, ratios I/O are slightly below one in both exposed and non-exposed environments, but with higher values in the exposed environments, which may indicate a direct influence of the outdoor concentrations on indoor environments with a rapid indoor depletion of this pollutant in the absent of relevant emission sources.

A high variance is observed in indoor concentrations at home for C_6H_6. The concentrations of this pollutant at Boavista homes were 2.4 times higher than the ones measured in Prelada. On the other hand, there is a similarity of C_6H_6 concentrations between the sub-domains for all the other environments types. The highest I/O ratios of NO_2 and C_6H_6 were recorded in offices and homes and in homes and schools respectively.

4. Discussion

The passive diffusion technique used on the present study is extensively used to assess air pollution. In fact, Gilbert et al. (2003) in a study of major highway in Montreal, Canada, showed that concentrations of NO_2 range from 38.6 to 95.1 $\mu g\ m^{-3}$. In São Paulo Silva et al. (2006) averages of NO_2 concentrations of 49–63 $\mu g\ m^{-3}$ are shown; in Las Vegas Kimbrough et al. (2012), values ranging between 38 and 49 $\mu g\ m^{-3}$ and in Netherlands Janssen et al. (2001) values ranging 26.8–44.4 $\mu g\ m^{-3}$ to NO_2 were found at 400 m of motorways. Janssen et al. (2001) report values ranging between 1.2 and 3.1 $\mu g\ m^{-3}$ to C_6H_6 and in New York Kheirbek et al. (2012) C_6H_6 concentrations of 0.82 $\mu g\ m^{-3}$ were found. The values achieved in these studies were similar to the average values recorded in the present study.

As presented before (see Section 3.3), it was also possible to establish that values recorded at the urban canopy (about 50 m of height) were significantly lower than at roadside ($p < 0.01$ for NO_2 and $p < 0.008$ for C_6H_6, in both campaigns), which demonstrates the influence of VCI traffic emissions on the surrounded air quality. In fact, the influence of the VCI traffic emissions on the near-road air quality has an average weight of 76.0 ± 41.3% related to NO_2 and 58.2 ± 29.4% related to C_6H_6 (Table 3).

On the other hand, although statistic significant differences ($p = 0.001$, Kruskal–Wallis test) were observed between sub-domains for NO_2 average levels, though not for C_6H_6 average levels ($p = 0.335$), a global view shows a very small difference between sub-domains traffic and pollutants emission (below 10%), which demonstrates that other factors should explain the changes that occur at the concentration levels observed in the different sub-domains, in particular for NO_2.

The concentrations recorded at 100 m away from VCI were reduced in average about 32.7 ± 15.9% related to NO_2 and about 25.7 ± 12.1% related to C_6H_6 when compared with the values measured at VCI roadside. In fact, this expected pattern can be verified with mostly good and very good correlations found between receptors at roadside of the motorway (set of receptors in lines 2 and 3 – Fig. 2) and 100 m receptors (set of receptors in lines 1 and 4 – Fig. 2), although not always significant (see Section 3.3).

At a first glance, the air quality variations may be mainly due to the local road traffic emissions dependency on the number of vehicles, their categories and driving patterns. However, a high number of vehicles and/ or low speed do not necessarily mean high levels of pollution. Emission from other sources, as roads that cross VCI or petrol stations placed nearby, may also influence the air quality of the study domain. Besides the emission sources, the atmospheric transport and dispersion conditions may play an important role in the urban air quality. At VCI, the large amplitude of observed concentrations indicates that in some areas the atmospheric dispersion is better than in others. Thus, a close look shows that the VCI design/surround and the meteorological conditions play an important role in order to explain the spatial variability of the recorded concentrations. The highest concentrations and amplitude were recorded in Boavista and in Amial sub-domains. In these sub-domains, both pollutant concentration values at the VCI roadside and 100 m away are significantly different. Actually, the statistical comparison of NO_2 and C_6H_6 median concentrations for the three campaigns showed significant differences between values recorded in the roadside and values recorded at 100 m away ($p < 0.001$, Mann–Whitney test) (Fig. 4ii1 and ii2). In these sub-domains, the pollutants transport and dispersion were conditioned by a canyon effect produced by the neighbour buildings and also a discordant wind direction, namely in the Boavista sub-domain. On the other hand, Prelada sub-domain is an open space domain, with only a few buildings away from VCI and surrounded by a large green park. The surround of this sub-domain allows better pollutants transport and dispersion, which makes this sub-domain one of the most unpolluted as well as the one with the smallest average amplitude between receptors in the VCI roadside and 100 m away (Table 5). In spite of the high level of traffic emission estimated for this sub-domain, the absence of obstacles justifies the low recorded concentrations.

Another important factor is the variation of transport and dispersion conditions of atmosphere concentrations between seasons. As expected, the atmosphere was more stable during the winter (January 2006 campaign) than during the spring or fall (April 2005 or September 2006 campaigns) (Table 5) in the study domain, which increases the probability of air quality problems in winter due to the more limited dispersion conditions in this season. Besides the stability of the atmosphere, during the spring and fall campaigns, other factors play an important role. The increase of sunlight hours promotes the photochemical reactions of NO_2 and the enhancement of C_6H_6 oxidation rate by the hydroxyl radical. In the study domain, a decrease of about 15% of NO_2 and about 33% of C_6H_6 concentrations was recorded in fall when compared with the winter values (year of 2006).

A comparison of the air quality results with the limit values of the European Directive 2008/50/EC was also made. It should be emphasized that the comparison with the annual average limit value is only indicative, as the technique applied (passive diffusion), although it corresponds to an integrated average, refers only to nine weeks of measurements, distributed by three seasonal campaigns (winter, spring and fall). Keeping that in mind, at VCI roadside, almost none C_6H_6 receptor exceeds the annual limit value for human health protection (5 μg m^{-3}). Nevertheless, about 100 m away from roadway, 81.8% of NO_2 receptors exceed the annual limit value of human health protection (40 μg m^{-3}) and at the roadside this value increases up to 95.5% for this pollutant. For C_6H_6, only about 0.8% of the receptors exceed the limit value of 5 μg m^{-3} to human health protection.

In exposed indoor environments, the air concentrations recorded mean is higher than the control values located outside the influence of VCI road traffic. In the detailed analysis of the I/O ratios of NO_2, a ratio of 0.2–0.8 was observed (0.8 in homes, 0.7 in schools and 0.2 in offices) (Table 7), showing a clear influence of outdoor sources. Moreover, for C_6H_6, I/O ratios show an average ratio of about 2.5 to homes, 1.1 to schools and 4.4 to offices in exposed environments (Table 7), which may indicate amplification of the indoor contamination from outdoor sources and strong indoor sources of this pollutant in homes and offices.

The ratios obtained for schools are in accordance with the study of Pegas et al. (2011) performed in fourteen schools in Lisbon, which achieved a ratio ranging from 0.35–1.00 to NO_2 and the results obtained with PEOPLE Project (2003), performed in some schools of Lisbon, achieved a ratio range of 0.42–1.55 to C_6H_6. For the other environments, the ratios were slightly higher than the ones obtained in these studies, but the results of I/O ratio of C_6H_6 are in accordance with the obtained by Janssen et al. (2001), existing a mainly prevalence of indoor sources for this pollutant which proves the significant importance of indoor sources and building materials (WHO, 2010; Pegas et al., 2011).

In accordance with the annual recommended limit value to NO_2 and C_6H_6 (40 μg m^{-3} and 5 μg m^{-3} respectively), exceedances in indoor and outdoor environments were recorded to all cases, except in offices. This can be explained by the presence of internal sources (natural gas stoves, e.g.) in case of homes and schools environments as well as outdoor forcing. In office environments these factors are absent, so the NO_2 and C_6H_6 concentration both for indoor and outdoor is relatively low here. Moreover, the exposed indoor environments in Prelada have higher C_6H_6 concentrations in offices than at home, being a typical situation- due to the presence of different sources such as printers (WHO, 2010) or smoke habits, which are not usually present in schools. The mean value obtained is high when compared with the mean office indoor concentrations in eight European countries (14.6 μg m^{-3}). However, it is remarkably lower than 87.1 μg m^{-3}, corresponding to the concentration measure in an office in Singapore (Zuraimi et al. 2006).

Considering the indoor/outdoor ratio to define a "safe" NO_2 concentration in homes (without exceedances to the limit value of human health protection of 40 μg m^{-3}), we conclude that outdoor concentrations must not exceed 44–60.0 μg m^{-3} (=ratio/limit value). During the campaigns, the average of NO_2 concentrations was 88.6 μg m^{-3} in the VCI roadside and 56.2 μg m^{-3} at 100 m away from VCI, both values recorded in Boavista. These results indicate that to guarantee a "safe" life in an indoor environment, at least 100 m of distance to the motorway roadside is required in this area. If we consider C_6H_6 concentrations, the average outdoor concentrations must not exceed 1.4–3.3 μg m^{-3} in order to prevent exceedances to the limit value of human health protection (5 μg m^{-3}) in all locals. During the campaigns, the average of C_6H_6 concentrations recorded was 2.5 μg m^{-3} in the VCI roadside and 1.9 μg m^{-3} at 100 m away from VCI. These results suggest that, in some locals, at least 100 m are required to guarantee a safe life – enhancing the conclusions obtained to NO_2.

It should be emphasized that this work focuses in the 100 m adjacent area of a motorway. It is not a goal of this work to try to find the global area of impact of an urban motorway, which is rather difficult due to the influence of other sources at an urban context. Thus, this work tries to establish a "safe" distance to an urban motorway roadside regarding human health protection.

This analysis suggests that the "safe" adjacent area to an urban motorway to prevent potential health impacts from traffic emissions should have more than 100 m. Even at this distance, some concentration levels are very high, which supports the idea that the urban planning should take into account this type of potential impacts on human health.

5. Conclusions

In recent years, several studies show that people who live, work or attend school near the main roadways have an increased incidence and severity of health problems that may be related with traffic emissions of air pollutants. The concentrations of near-road atmospheric pollutants vary depending on traffic patterns, environmental conditions, topography and the presence of roadside structures. In this study, the vertical and horizontal variation of nitrogen dioxide (NO_2) and benzene (C_6H_6) concentration along a major city ring motorway was analysed.

Several evidences have been found:

– Traffic emissions from VCI have a high influence on the surrounding air quality; values recorded at the urban canopy (about 50 m of height) were significantly lower than at roadside ($p < 0.01$ for NO_2 and $p < 0.008$ for C_6H_6).
– The different sub-domains have different characteristics in relation to its surroundings and statistic significant differences ($p = 0.001$, Kruskal–Wallis test) were observed between sub-domains for NO_2 average levels, but not for C_6H_6 average levels ($p = 0.335$).
– Differences between traffic emissions of different sub-domains is minimal (below 10%); thus, the concentration differences observed between sub-domains are primarily due to nearby obstacles or other external forcing elements (e.g. other neighbour emission sources).
– The concentrations recorded at 100 m away from VCI were reduced in average about 32.7 ± 15.9% related to NO_2 and about 25.7 ± 12.1% related to C_6H_6 when compared with the values measured in the VCI roadside. The statistical comparison of NO_2 and C_6H_6 median concentrations for the three campaigns showed significant differences between values recorded in the roadside and values recorded 100 m away ($p < 0.001$, Mann–Whitney test).
– About 100 m away from roadway, 81.8% of NO_2 receptors exceed the annual limit value of human health protection (40 μg m^{-3}) and at the roadside this value increases up to 95.5% for this pollutant. For C_6H_6, only about 0.8% of the receptors exceed the limit values of 5 μg m^{-3} to human health protection.
– In order to have a "safe" life in homes located nearby motorways, the outdoor concentrations of NO_2 must not exceed 44–60.0 μg m^{-3} nor they must exceed 1.4–3.3 μg m^{-3} for C_6H_6.

Poor atmospheric air quality turns the ventilation of the buildings placed near major urban motorway less efficient, increasing existing indoor air quality problems and consequently increasing people's exposure to pollutants.

This global analysis suggests that the "safe" adjacent area to an urban motorway to prevent potential health impacts from traffic emissions should have more than 100 m. Even at this distance, some concentration levels are very high, supporting the idea that the urban planning should take in account this type of potential impacts on human health.

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References

Al Madhoun, W., Ramli, N., Yahaya, A., Yusuf, N.F., Ghazali, N., Sansuddin, N., 2011. Levels of benzene concentrations emitted from motor vehicles in various sites in Nibong Tebal, Malaysia. Air Quality, Atmosphere and Health 4, 103–109.
Barros, N., Fontes, T., Brás, C., 2005. Population exposure to traffic emissions of an urban highway. Environmental Health Risk, 14–16/09: WIT Transactions on Biomedicine and Health. Bologna, Italy, pp. 221–230.
Barzyk, T., George, B., Vette, A., Williams, R., Croghan, C., Stevens, C., 2009. Development of a distance-to-roadway proximity metric to compare near-road pollutant levels to a central site monitor. Atmospheric Environment 43, 787–797.
Cohen, J., Cook, R., Bailey, C., Carr, E., 2005. Relationship between motor vehicle emissions of hazardous pollutants, roadway proximity, and ambient concentrations in Portland, Oregon. Environmental Modelling and Software 20, 7–12.
Cook, R., Isakov, V., Touma, J., Benjey, W., Thurman, J., Kinnee, E., Ensley, D., 2008. Resolving local-scale emissions for modeling air quality near roadways. Journal of the Air & Waste Management Association 58, 451–461.
CORINAIR, 2012. Emission Inventory Guidebook – Road Transport. European Monitoring and Evaluation Programme (EMEP). EEA, Luxembourg.
Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe.
Draper, G., Vincent, T., Kroll, M.E., Swanson, J., 2005. Childhood cancer in relation to distance from high voltage power lines in England and Wales: a case-control study. BMJ 330, 1290.
EEA, 2011. Air Quality in Europe Cities and Towns. No 12/2011. European Environmental Agency, Copenhagen.
ENTEC, 2006. Development of a Methodology to Assess Population Exposed to High Levels of Noise and Air Pollution Close to Major Transport Infrastructure. Final Report April 2006. Entec UK Limited.
EPA, 2000. Meteorological Monitoring Guidance for Regulatory Modelling Applications. <http://www.epa.gov/scram001/guidance/met/mmgrma.pdf> (accessed October 2000).
EPA, 2004. Air Monitoring at Nunawading – October 2003 to February 2004 (948).
EPA, 2005. Air Monitoring alongside the Westgate freeway in Brooklyn – March to November 2004 (974).
Gilbert, N.L., Woodhouse, S., Stieb, D.M., Brook, J.R., 2003. Ambient nitrogen dioxide and distance from a major highway. The Science of The Total Environment 312 (1–3), 43–46.
Janssen, N.A.H., van Vliet, P.H.N., Harssema, H., Brunekreef, B., 2001. Assessment of exposure to traffic related air pollution of children attending schools near motorways. Atmospheric Environment 35, 3875–3884.
Karner, A., Eisinger, D., Niemeier, D., 2010. Near-roadway air quality: synthesizing the findings from real-world data. Environment Science Technology 44, 5334–5344.
Kheirbek, I., Johnson, S., Ross, Z., Pezeshki, G., Ito, K., Eisl, H., Matte, T., 2012. Spatial variability in levels of benzene, formaldehyde, and total benzene, toluene, ethylbenzene and xylenes in New York city: a land-use regression study. Environmental Health 11, 51.

Kimbrough, S., Baldauf, R.W., Hagler, G.S.W., Shores, R.C., Mitchell, W., Whitaker, D.A., Croghan, C.W., Vallero, D.A., 2012. Long-term continuous measurement of near-road air pollution in Las Vegas: seasonal variability in traffic emissions impact on local air quality. Air Quality, Atmosphere and Health. http://dx.doi.org/10.1007/s11869-012-0171-x.

Kingham, S., Briggs, D., Elliott, P., Fischer, P., Lebret, E., 2000. Spatial variations in the concentrations of traffic-related pollutants in indoor and outdoor air in Huddersfield, England. Atmospheric Environment 34, 905–916.

Knox, E.G., 2006. Roads, railways, and childhood cancers. Journal of Epidemiology and Community Health 60, 36–141.

Langholz, B., Ebi, L.K., Thomas, D.C., Peters, J.M., Londo, S.J., 2002. Traffic density and the risk of childhood leukemia in a Los Angeles case-control study. Annals of Epidemiology 12 (7), 482–487.

Lawson, S., Galbally, I., Powell, J., Keywood, M., Molloy, S., Cheng, M., Selleck, P., 2011. The effect of proximity to major roads on indoor air quality in typical Australian dwellings. Atmospheric Environment 45, 2252–2259.

Mayan, O., Barros, N., Bras, C., Madureira, J., 2005. Impacto na qualidade do ar e na saúde das grandes linhas de tráfego urbano: o caso da VCI do Porto – Impactair. Fundação para a Ciência e Tecnologia, Final Report. Proj n.° POCTI/ESP/47806/2002.

PASSAM, 2011. Passam AG Laboratory for Environmental Analysis. <http://www.passam.ch/> (accessed November).

Pearson, R.L., Wachtel, H., Ebi, K.L., 2000. Distance-weighted traffic density in proximity to a home is a risk factor for leukemia and other childhood cancers. Journal of the Air and Waste Management Association 50, 175–180.

Pegas, P., Alves, C., Evtyugina, M., Nunes, T., Cerqueira, M., Franchi, M., Pio, C.A., Almeida, S.A., Cabo Verde, S., Freitas, M.C., 2011. Seasonal evaluation of outdoor/indoor air quality in primary schools in Lisbon. Journal of Environment Monitoring 13, 657–667.

PEOPLE, 2003. PEOPLE – Population Exposure to Air Pollutants in Europe. PEOPLE. <http://www.people-pt.net/>.

Roorda-Knape, M., Janssen, N., De Hartog, J., Van Vliet, P., Harssema, H., Brunekreef, B., 1998. Air pollution from traffic in city districts near major motorways. Atmospheric Environment 32 (11), 1921–1930.

Seinfeld, J.H., Pandis, S.N., 2006. Atmospheric Chemistry and Physics, second ed. Wiley, EUA.

Silva, A.S., Cardoso, M.R., Meliefste, K., Brunekreef, B., 2006. Use of passive diffusion sampling method for defining NO_2 concentrations gradient in São Paulo, Brazil. Environmental Health: A Global Access Science Source 5, 19.

van den Hooven, E.H., Jaddoe, V.W.V., Kluizenaar, Y., Hofman, A., Mackenbach, J.P., Steegers, E.A.P., Miedema, H.M.E., Pierik, F.H., 2009. Residential traffic exposure and pregnancy-related outcomes: a prospective birth cohort study. Environmental Health 8, 59.

Vardoulakis, S., Fisher, B.E.A., Pericleous, K., Gonzalez-Flesca, N., 2003. Modelling air quality in street canyons: a review. Atmospheric Environment 37, 155–182.

Venkatram, A., Isakov, V., Seila, R., Baldauf, R., 2009. Modeling the impacts of traffic emissions on air toxics concentrations near roadways. Atmospheric Environment 43, 3191–3199.

WHO, 2000. Air Quality Guidelines for Europe. World Health Organization, Copenhagen.

WHO, 2010. WHO Guidelines for Indoor Air Quality: Selected Pollutants. Word Health Organization, Copenhagen.

WMO, 2008. Guide to Meteorological Instruments and Methods of Observation, seventh ed. N. 8. World Meteorological Organization, Geneva.

Zuraimi, M.S., Roulet, C.A., Tham, K.W., Sekhar, S.C., David, Cheong, K.W., Wong, N.H., Lee, K.H., 2006. A comparative study of VOCs in Singapore and European office buildings. Building and Environment 41 (3), 316–329.