cityAIR: a new air quality index for cities

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Due to a generalised increase of mobility and road traffic in urban areas, the total emissions from road traffic have risen significantly, assuming the main responsibility for the disregard of air quality standards. Pollutant concentrations are evaluated through monitoring, using permanent measurement stations or mobile units, and prediction models based on emissions and meteorological conditions. In order to find an air quality index, the pollutant concentrations are combined through a classification scale anchored on the legal limits and, on the other side, on the impacts over human heath. Typically these classification models consider only the worse pollutant, i.e. the one which concentration is higher given a certain scale.

The objective of this paper is to present a new air quality index, cityAIR, developed for urban contexts. The mathematical formulation of cityAIR stands on two logics: whenever at least one of the pollutants considered overcomes the legal limits for the concentration, this will be the only relevant one for the index calculation, and the value will be the minimum of the scale (zero or red); when there is no limit violation, then all the pollutants are considered for the overall air quality, which is calculated through a multi-criteria combination of the concentrations, where trade-off is allowed.

A case study is presented, where a cityAIR values surface was calculated for Viana do Castelo, a mid-sized Portuguese city, considering concentrations of CO, NO2, O3, C6H6 and PM10.

Keywords: Urban air pollution index; Air pollution modelling

1 Introduction

Urban air pollution became one of the main factors of degradation of the quality of life in cities. This problem tends to worsen due to the unbalanced development of urban spaces and the significant increase of mobility and road traffic. As a consequence, the total emissions from road traffic have risen significantly, assuming the main responsibility for the disregard of air quality standard (Butterwick, L. et al., 1991).

The atmospheric pollutants are emitted from existent sources and, subsequently, transported, dispersed and several times transported in the atmosphere reaching several receivers through wet deposition (through rainout and washout of the rain and snow) or dry deposition (through the adsorption of particles). In urban environment the typical anthropogenic sources are mainly the road traffic and, when existing, the industrial activity.

The combustion of hydrocarbon fuel in the air generates mainly carbon dioxide (CO2) and water (H2O). However, the combustion engines are not totally efficient, which means that the fuel is not totally burned. In this process the product of the combustion is more complex and could be constituted by hydrocarbons and other organic compounds, carbon monoxide (CO) and particles (PM) that contain carbon and other pollutants. On the other hand, the combustion conditions - high pressures and temperatures - originate partial oxidation of the nitrogen present in the air and in the fuel, forming oxides of nitrogen (mainly nitric oxide and some nitrogen dioxides) conventionally designated by NOx.

Air pollution caused by road traffic is the most often nuisance cited by roadside residents. For existing roads, it is first of all necessary to define the magnitude of the problem. New infrastructure can improve the surrounding area by easing traffic flow on existing roads. Hence the construction of new roads can bring about environmental benefits through a better distribution of traffic flows in the network and the various associated transport systems. The quantitative evaluation of traffic air pollution levels is the basis on which air pollution control policies stand.

The evaluation of air quality may be occasional or long-term. Occasional evaluation is useful in the context of information and alert systems for the population, working normally in real or almost-real time. Data is acquired through measurements made on a hourly or daily average basis and concentration episodes are evaluated and reported. When long-term data (6-month or yearly evaluations) is considered, then we talk about long-term trend analysis.

In this paper, two air quality evaluation models are referred, both working in real time: a Canadian and a Portuguese experience. A long-term model is proposed and applied to a mid-sized Portuguese city.

2 Existing air quality evaluation models

2.1 Canada, Vancouver

Integrated in a public information system of Vancouver, the FPCAP (Federal-Provincial Committee on Air Pollution) provides the information on pollution levels in form of an Air Quality Index (AQI).

The AQI is based on measurements taken throughout the region of Greater Vancouver (Butterwick, L ; et al., 1991). The AQI is expressed as a single value taking into consideration the concentrations of five major air pollutants (CO, NO2, O3, SO2, PM). The index is based on the pollutant with the highest concentration relative to Federal and Provincial air criteria. This pollutant is called the Index Pollutant. The values of the other four pollutants are then disregarded.

The numeric value of the Air Quality Index is correlated to a classification system. For each category of air quality, information is provided on the associated general health effects and recommended precautionary action. Table 1 summarizes this information.

The AQI is calculated twice daily and more frequently during air pollution episodes.

Table 1. Great Vancouver Air Quality Index

AQI	**Air Quality**	**General Health Effects**	**Cautionary Statements**
0 – 25	Good	No measured effects are associated	No precautions are necessary
26 – 50	Fair	Is adequate protection against effects on general population	No precautions are necessary
51 – 100	Poor	Short-term exposure may result in irritation or mild aggravation of symptoms in sensitive persons.	Persons with heart or respiratory ailments should reduce physical action and outdoor activity
Over 100	Very poor	Significant aggravation of persons with heart and lung disease. Many people may notice symptoms.	Persons with respiratory and cardiovascular diseases should stay indoors and minimize physical activity.

Source: (Butterwick, L ; et al., 1991).

2.2 IQar, Portugal

The APA (Agência Portuguesa do Ambiente) of the Ministry of Environment of Portugal provides public information on pollution levels based on measurements taken through a pollution monitoring network. The information on pollutant levels is presented as an index called "Índice de Qualidade do Ar" (IQar) (APA, 2007). The IQar is based on 24–hour average concentrations, and therefore does not reflect short term peak levels.

The IQar is expressed as a single value taking into consideration the concentrations of five major air pollutants (CO, NO2, O3, SO2, PM). The index is based on the pollutant with the highest concentration relative to the Portuguese annual limit values for the protection of human health. The values of the other four pollutants are then disregarded. The calculation of IQar takes into account the following averages:

- Nitrogen Dioxide (NO2) – hourly average
- Sulphur Dioxide (SO2) – hourly average
- Ozone (O3) – hourly average
- Carbon Monoxide (CO) – 8-hour average
- Suspended Particulates (PM10) – daily average

The air quality assumes the classification from Poor to Good according to a classification system summarized in the Table 2.

Table 2. Classification of IQar for 2010

Pollutant	**CO (µg/m3)**		**NO2(µg/m3)**		**O3(µg/m3)**		**PM10(µg/m3)**		**SO2(µg/m3)**	
Classification	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
Very Poor	10000	-----	400	-----	240	-----	120	-----	500	-----
Poor	8500	9999	200	399	180	239	50	119	350	499
Fair	7000	8499	140	199	120	179	35	49	210	349
Good	5000	6999	100	139	60	119	20	34	140	209
Very Good	0	4999	0	99	0	59	0	19	0	139

Souce: (APA, 2007)

The classification of the air quality is based on the pollutant with the highest concentration relative to the Portuguese annual limit values for the protection of human health (Decreto-Lei 111/2002; Portaria 623/1996), [i.e. for an atmosphere with pollutants levels SO2 - 35 µg/m3 (very good), NO2 - 180 µg/m3 (fair); CO - 6000 µg/m3 (good), PM10 - 15 µg/m3 (very good) and O3 - 365 µg/m3 (very poor): Air Quality was Very Poor due to Ozone].

2.3 Discussion

Both models presented above are approaches which prevent trade-off between pollutant concentrations because they are based on the pollutant with the highest concentration relative to the legal limits. For situations were the concentrations are below the legal limit, i.e. when there is no limit violation, a model integrating all the pollutants could offer a more complete evaluation of the air quality. Such a model requires that whenever at least one of the pollutants considered overcomes the legal limits for the concentration (or any other limit assumed for this purpose), this one will be the only relevant for the index calculation, and the value will be the minimum of the scale.
In the next section a multicriteria air quality index is proposed, which allows for trade-off between pollutants whenever concentration values stay under the considered limits.

3 The cityAIR index

3.1 Formulation

The cityAIR model proposed stands on the combination of long-term concentrations, which may result from past measurements or, differently, from mathematical simulation models providing in this case a prospective view of air quality.
When air pollution concentrations are computer-simulated for a city, the values for each point or area considered are compared against the limit (we will consider in this paper the legal limit) and a dummy variable is generated, assuming the value 0 when the limit is overcome and the value 1 otherwise.
The cityAIR index results from the weighted linear combination of normalised concentration values, which are subjected to the product of the dummy variables (equation 1).

$$cityAIR = \sum_i w_i c_i \times \prod_i v_i$$ **Equation 1**

Where:

w_i is the relative weight of the pollutant *i*;

c_i is the normalized concentration of the pollutant *i*;

v_i is the dummy variable of the legal limit violation L_i of pollutant *i*, defined as follows:

$v_i = 1$ when $c_i \le L_i$

$v_i = 0$ when $c_i > L_i$

The implementation of this model makes use of the multi-criteria techniques for the combination, aggregation and standardization of the pollutants concentrations.

3.2 Pollutants and weights

The selection of pollutants to be included in the cityAIR index may vary according to the type of sources or even the data availability. For the purpose of this paper we present the pollutants considered in the case study, which are typically result from road traffic:

- CO: Carbon Monoxide
- NO2: Nitrogen Dioxide
- PM10: Particulate < 10 μm
- C6H6: Benzene
- O3: Ozone

Equal weights were considered, which means 0,2 for each of the 5 pollutants.

3.3 Normalization of concentrations

Because of the different scales upon which concentrations are measured, it is necessary to standardize them before aggregation. The process of standardization is essentially identical to that of the fuzzification in fuzzy sets. The purpose of that process is to transform any scale to a normalize range (i.e. 0-1). In our case, the result express a membership grade that ranges from 0.0 to 1.0, indicating a continuous variation from non-membership (bad air quality) to complete membership (very good air quality), on the basis of the criterion (pollutant concentration) being fuzzified.

For the standardization a sigmoidal function has been adopted (equation 2).

$$score = \frac{1}{sen^2 \alpha} = \cos^2 \alpha$$ **Equation 2**

where,

$$\alpha = \left[\frac{(x - x_a)}{(x_b - x_a)} \right] \times \frac{\pi}{2} \qquad \textbf{Equation 3}$$

Where x is the concentration value being normalized, and x_a and x_b are control points in the function. Figure 1 shows a graphical view of this function, for the case of PM10, where control points are *a* (20 µg/m3) and *b* (40 µg/m3)

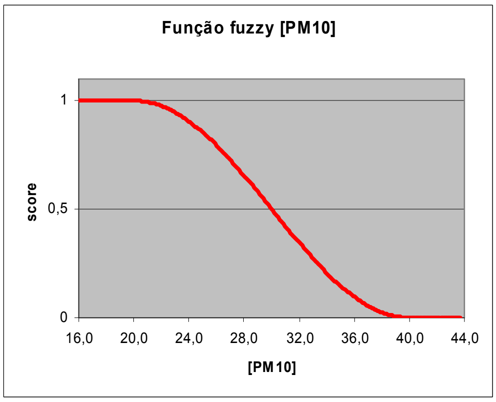


Figure 1. Normalization function for PM10

Control points of the sigmoidal functions were selected according to the following criteria: *score = 0* for the legal concentration limits considered in the portuguese legislation for human health protection; *score = 1* for the concentration guidance values recommended by the World Health Organisation (OMS, 2005) (in the case of NO2 and CO the values considered where the ones of a non-polluted atmosphere (Seinfeld, 1997)). Table 3 presents the values adopted.

Table 3. Control points of the fuzzy functions

	Score = 0	**Score = 1**	**Averaging period**
CO	[CO] > 10.0 mg/m3	[CO] ≤ 0.140 mg/m3	8 hours (rolling average) for calendar year
PM	[PM10] > 40.0 µg/m3	[PM10] ≤ 20.0 µg/m3	Calendar year
NO2	[NO_2] > 40.0 µg/m3	[NO_2] ≤ 20.0 µg/m3	Calendar year
O3	[O3] > 110.0 µg/m3	[O3] ≤ 100.0 µg/m3	8-hour average for calendar year
C6H6	[C6H6] > 5.0 µg/m3	[C6H6] ≤ 1.0 µg/m3	Calendar year

3.4 Dummy variables

Dummy variables switch from zero (0) to one (1) at the concentration limits mentioned above (third column of table 2). Figure 2 shows a graphical view of the dummy variable function for the case of PM10.

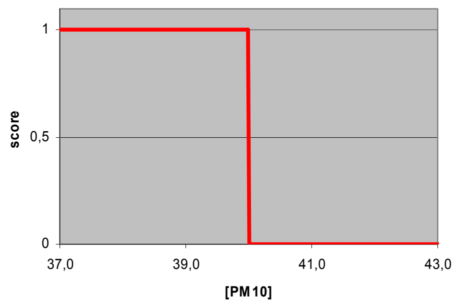


Figure 2. Dummy variable for PM10

4 Case study: air quality in the city of Viana do Castelo

The study undertaken aimed at evaluating the air quality in the Portuguese city of Viana do Castelo, located on the northwest seaside. This is a mid-sized city, which has a population of around 36 thousand living in an overall area of 37 Km2. The most remarkable air pollution source is a main road that crosses the city dividing it in two parts.

Based on traffic data and on the physical characteristics of the area, horizontal maps of the concentrations of five main pollutants were created: CO, NO2, C6H6, PM10 and O3. A range of numerical models were used to produce results. The ADMS-Urban model was used for the pollutants dispersion, the Hills model was used to calculate air flow and turbulence over complex terrain, including the effects of variable surface roughness (CERC, 2001) and the COPERT4 (COPERT4, 2007) based on CORINAIR v.5 (CORINAIR, 2006) was used to estimate traffic emissions.

The dispersion model, which is linked to a GIS (Geographical Information System), has been extensively validated in several works present in the literature (Goodwin, et al., 2001; Carruthers, et al., 1998).

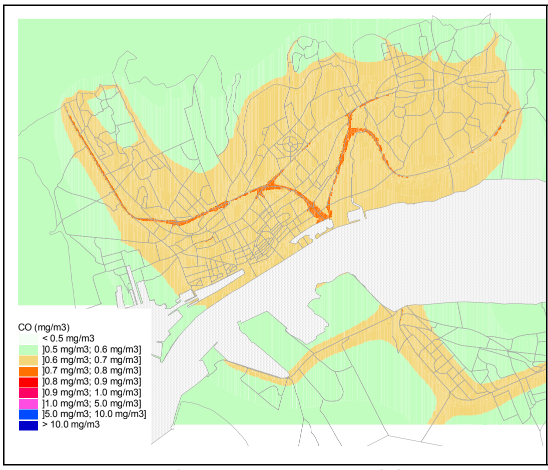
4.1 Calculation of horizontal air pollution maps

The modelling of dispersion of air pollution in built-up urban areas must integrate all the parameters which influence the dispersion, among others, the topography, the site, and meteorological condition like the wind and the heterogeneousness of the atmosphere.

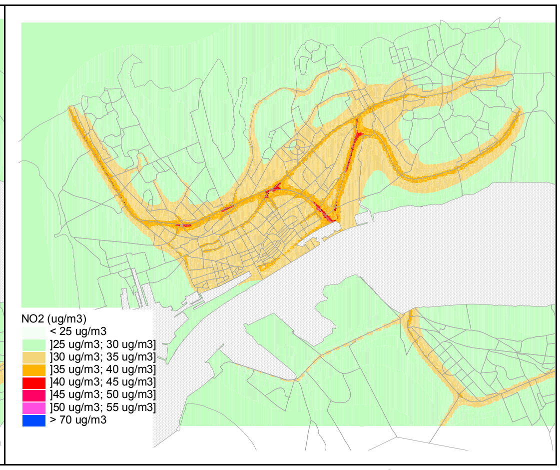
For the sources characterization, and considering that Viana do Castelo is a touristy seaside city, two traffic counting campaigns were carried out, one in winter time and another one in summer time, of which resulted the data for two scenarios. Each campaign included most of the city streets and traffic was counted round-the-clock in a typical week day.

A full survey, including topographic characteristics, location of reception points (points for which the air pollutants are to be calculated), surface roughness and the specification of the emission sources, cross and longitudinal profiles (for canyon roads) was carried out for the whole city.

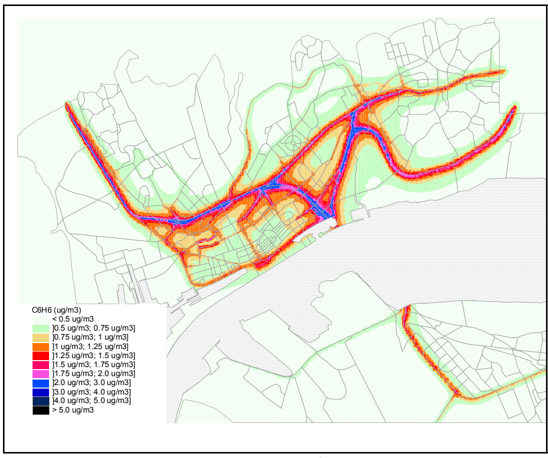
Taking the data gathered, the model was used to produce the horizontal concentration maps for winter and summer traffic-scenarios. These maps should be understood as the average situation of the atmospheric pollution i.e. representative maps of one year, winter and summer scenarios. Due to space limitations in this article the results presented are restricted to the summer scenario, the most critical (Figures 3a to 3e).



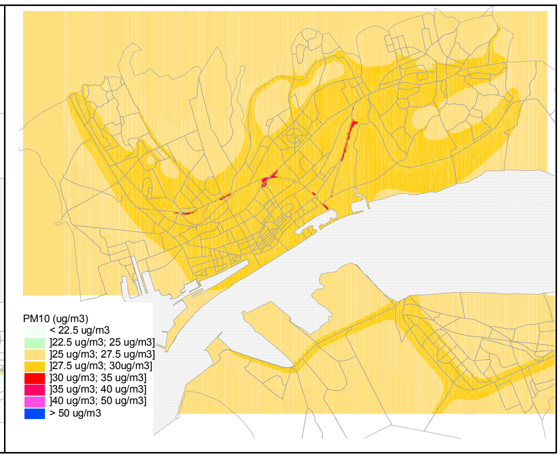
a) Carbon monoxide, CO



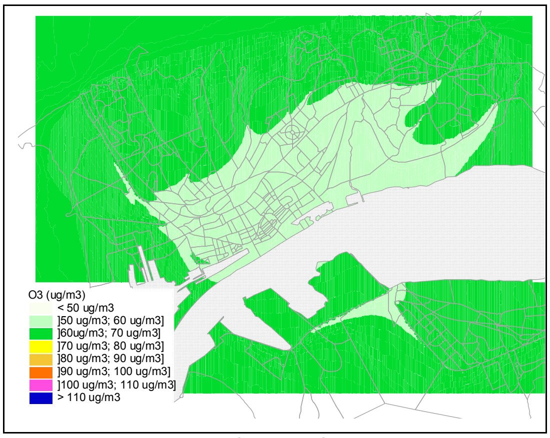
b) Nitrogen dioxide, NO2



c) Benzene, C6H6



d) Particulate matter, PM10



c) Ozone, O3

Figure 3. Air pollution maps, summer scenario (Silva, 2008)

4.2 Air quality index - cityAIR

The combination of the concentration maps, according to equation 1, results in an overall air quality map. Table 4 presents the classification frame adopted, which considers 5 categories from Very Poor to Very Good.

Table 4. Air Quality Classification

cityAIR value	Air Quality
0	Very Poor
]0 ; 0,35[	Poor
[0,35 ; 0,65[	Fair
[0,65 ; 0,85[	Good
[0,85 ; 1,0]	Very Good

The final map of air quality over the city for the summer scenario is presented in Figure 4.

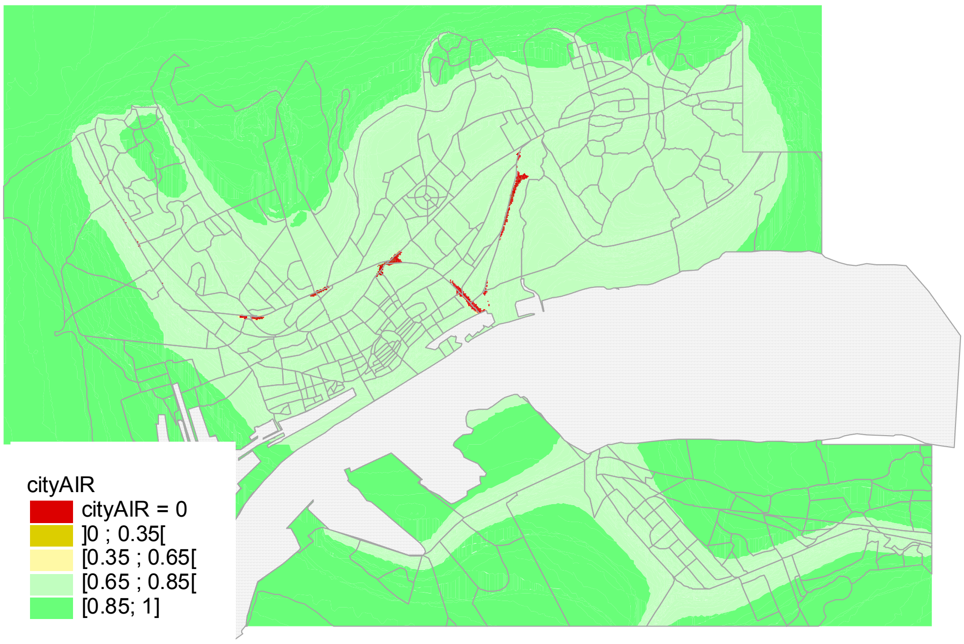


Figure 4. cityAIR, summer scenario (Silva, 2008)

5 Analysis and Conclusions

The calculation and distribution of the cityAIR index over the city revealed that air quality is globally Good or Very Good in Viana do Castelo. However, the maps presented before show a few zones of small dimension which may be potentially problematic. These zones include Av. 25 de Abril (ramp to the bridge), roundabouts of the Hospital and the Football Field, and access to the main road IC1, and the reason is mainly the high levels of NO2 (over the legal limit)

The results of the model were overlaid with a population GIS layer in order to estimate the population affected. The Very Poor quality level affects only 0,2% of the population (69 pop.) in Summer. In the same period of the year, 71,7% of the population has the benefit of Good and 28,0% Very Good air quality.

Table 5 presents a synthesis of the area and population affected by air pollution in the city.

Table 5. Areas and population affected by air pollution

cityAIR		Summer scenario				Winter scenario			
		Population		Area		Population		Area	
		hab	%	m^2	%	hab	%	m^2	%
= 0	Very Poor	69	0,2%	26332	0,2%	1	0,0%	350	0,0%
[0 ; 0,35[	Poor	0	0,0%	0	0,0%	0	0,0%	0	0,0%
[0,35 ; 0,65[	Fair	9	0,0%	3296	0,0%	0	0,0%	0	0,0%
[0,65; 0.85[	Good	20477	71,7%	5152484	47,3%	2955	10,3%	846608	7,8%
[0,85; 1.0]	Very Goog	8002	28,0%	5711768	52,4%	25601	89,6%	10046922	92,2%
Total		28557	100%	10893880	100%	28557	100%	10893880	100%
(Silva, 2008)									

The results of the analysis were presented to the public and the cityAIR index proved to be well understood and quite intuitive. For the problematic areas, a Monitoring & Mitigation Plan is being prepared.

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