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The impact of street canyon morphology and traffic volume on NO_2 values in the street canyons of Antwerp

D. Voordeckers [a,*], F.J.R. Meysman [b,c], P. Billen [d], T. Tytgat [e], M. Van Acker [a]

[a] Research Group for Urban Development, Department of Architecture, Interior Design and Urban Planning, Faculty of Design Sciences, University of Antwerp, Belgium
[b] Department of Biology, University of Antwerp, Belgium
[c] Department of Biotechnology, Delft University of Technology, Belgium
[d] BioGEM, Department of Chemistry and Biochemistry, Faculty of Applied Sciences, University of Antwerp, Belgium
[e] Research Group Sustainable Energy, Air & Water Technology, Department of Bioscience Engineering, Faculty of Science, University of Antwerp, Belgium

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ABSTRACT

Air pollution remains a major environmental and health concern in urban environments, especially in street canyons that show increased pollution levels due to a lack of natural ventilation. Previous studies have investigated the relationship between street canyon morphology and in-canyon pollution levels. However, these studies are typically limited to the scale of a single street canyon and city-wide assessments on this matter are scarce. In 2018, NO_2 concentrations were measured in 321 street canyons in the city of Antwerp (Belgium) as part of the large-scale citizen-science project “CurieuzeNeuzen”. In our research, this data was used to study the correlation between morphological indices (e.g. aspect ratio (AR), lateral aspect ratio (LAR), presence of trees) and the traffic volumes on a city-wide scale. The maximum hourly traffic volume (TV_{max}) and AR correlated significantly with the measured NO_2 values, making them useful indicators for air quality in street canyons. For street canyons with AR $>$ 0.65, a TV_{max} of 300 vehicles/hour was found as a threshold value to guarantee acceptable air quality. No significant correlations were found for the other parameters. Finally, a number of typical street canyon types were defined, which can be of fundamental interest for further research and spatial policy making.

1. Introduction

In 2016, the World Health Organization (WHO) proclaimed air pollution as the biggest environmental risk to human health [1]. Despite actions (e.g. traffic management, low emission zones), cities worldwide still suffer from severe air pollution, characterized by levels of particulate matter and nitrogen dioxide (NO_2) that exceed legal thresholds [1,2]. In urban environments, the problem of air pollution is exacerbated, as pollutants get trapped and accumulate in the urban canopy layer (the layer of air extending from the ground surface up to the level of the buildings), so that human exposure to these pollutants is high. In cities, this urban canopy layer is composed of numerous street canyons, which are narrow inner urban roads, flanked by a continuous row of high buildings on both sides. These street canyons promote the accumulation of traffic-induced pollution due their lack of natural ventilation [3–5]. Still, it is known that street levels of pollution can vary widely between canyons, due variability associated with meteorological conditions (e.g. wind speed, wind direction relative to the canyon axis), difference in emissions (e.g. traffic volume, fleet composition and traffic fluidity) and variation in street canyon morphology (e.g. aspect ratio [AR], the ratio between building height [H] and width [W]; sky view factor [SVF]; lateral aspect ratio [LAR], which is the ratio between street canyon length [L] and building height [H]) [5].

Already in 1988 [6], conducted research on the importance of street canyon morphology on street level pollution by investigating the impact of the AR and LAR on in-canyon ventilation patterns. In general, numerous studies (summarized in Ref. [5]) indicate that once AR $>$ 0.65, the inner-canyon wind flow strongly degrades, as in case of perpendicular air flows, a skimming flow appears. Due to the reduction of natural ventilation in the street canyon, pollutants tend to accumulate in different zones, depending on the in-canyon wind flow (see Fig. 1). It is assumed that in case the street canyon’s axis is oriented perpendicularly to the incoming wind direction, pollutants tend to accumulate at the leeward facade of the street canyon. In case the street canyon’s axis is oriented parallel to the incoming wind direction, pollutants tend to

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* Corresponding author.
E-mail address: Dimitri.voordeckers@uantwerpen.be (D. Voordeckers).

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Nomenclature

AR	aspect ratio
H_{var}	building height variance
LAR	lateral aspect ratio
SVF	sky view factor
TV_{tot}	total daily traffic volume
TV_{av}	average hourly traffic volume
TV_{max}	maximum hourly traffic volume
θ_{dev}	deviation from the main wind direction

accumulate at the downwind area of the street canyon [5]. Fig. 1 illustrates the close relationship between air pollution and the in-canyon aerodynamic effects in case of $AR > 0.65$.

Due to the increasing concerns about urban air quality, the impact of street canyon morphology on in-canyon air quality gained more interest and numerous parameters, not only the impact of the AR [7,8], but also building height variations [9,10], roof shape [11,12] and the presence of trees [13,14] are examples that have been studied recently.

Furthermore, it is understood that in-canyon air quality is the result of a very complex conjunction between numerous parameters, such as in-canyon conditions, background conditions and also physical and chemical mechanisms (summarized in Table 1, section 2.2). The impact physical (e.g. wall heating [15,16]) and chemical dynamics such as photochemical reactions between reactive pollutants, such as nitrogen oxides ($NO_x = NO + NO_2$), volatile organic compounds (VOCs) and secondary pollutants (e.g. ozone, O_3) should not be neglected. Previous studies [17–19] revealed significant negative correlations between O_3 and its precursors (e.g. CO and NO_2), indicating that the increase/decrease of O_3 concentrations may result in decreased/increased concentrations of primary pollutants. Also, the formation of O3 is weakened/amplified with the decrease/increase in ultraviolet radiation relating to aerosols [20]. The phenomena of photochemical reactions in a street canyon configuration were furtherly studied by Refs. [18,21,22].

On a larger scale, research has been conducted on numerous urban morphology indices, such as gross floor area ratio, plan area density and frontal area density [23] to determine and improve the ventilation capacity of a city region. However, studies which focus on street canyon morphology indices are rather scarce. Recently [24], conducted a city-wide analysis on the impact of street canyon morphology and local meteorological conditions on measured particle pollution in 23 street canyons in Shenyang (China). They found significant lower pollution levels in high-rise areas compared to multilayer building areas, which contradicts previous theoretical research [7,8,25,26]. However, the research of [24] did not incorporate traffic volume, which can largely influence the measured concentration levels [27,28].

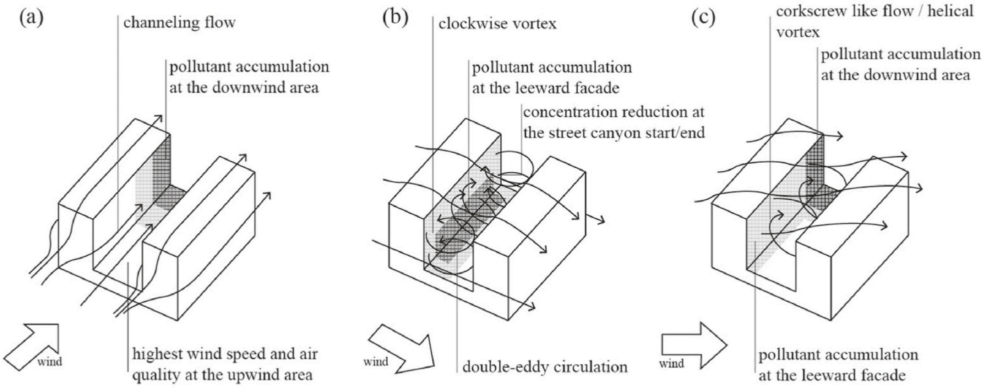


Fig. 1. Estimated flow regimes and pollutant distribution for different orientations of the street canyon ($AR > 0.65$) towards the prevailing wind direction [5].

Table 1
Parameters related to local air quality in street canyons.

category	Parameter	data availability[a]	references[b]
Non-spatial background conditions	meteorological background conditions	yes	[43,44] [45,46]
	urban background pollution	yes	
spatial background conditions	topography/urban terrain	yes	[23,43,47]
	urban density	yes	[23,47]
	mean built volume	yes	[48]
	height variability	yes	[23,49]
	street canyon density	Yes	[23]
	urban porosity	No	[50]
	urban vegetation coverage	Yes	[23]
local meteorological conditions	Temperature	no	[17,24, 51–53]
	relative humidity	no	[24]
	wind speed	no	[18,54]; H [55].
	wind direction	no	[18,54]; H [24,55].
	atmospheric pressure	no	H [24,55].
local (traffic) emissions	traffic volume	yes	[27,28]
	fleet composition	yes	[27,54]
	lane position	no	[5,18]
	traffic fluidity	no	[56,57]
canyon morphology (in-canyon wind flow)	orientation to the main wind direction	yes	H [5,55].
	aspect ratio (AR)	yes	[7,8]
	lateral aspect ratio (LAR)	yes	[5,58]
	sky view factor (SVF)	no	[24]
	building height variance	yes	[9,10]
	roof shape	no	[11,12]
	building permeability	no	K. [59,60];
	presence of trees	yes	[13]; [75]
Physical and chemical dynamics	wall heating	no	[15,16]
	photochemical mechanisms	no	[18,21,22]

[a] data available at street canyon level for the city of Antwerp.
[b] selection of relevant recent publications.

For the selected case study (Antwerp, see Section 2.1), studies on street canyon morphology and its relationship with air quality are rather scarce. To the knowledge of the authors, only two main studies on the topic of street canyons were conducted by Refs. [23,29]. [29] made mappings of the aspect ratios of different neighborhoods in the city of Antwerp but did not perform a city-wide analysis and did not correlate their results with air quality measurements. The study of [23] was performed as a preliminary study for our research paper, in which numerous spatial indicators were analyzed on a city-wide scale for Antwerp and Gdansk in order to delimit air quality managements zones. Within the study of [23]; a simplified street canyon mapping was used to calculate street canyon density, but no data on traffic volume or NO2 values was incorporated. The study already points out the high amount of street canyons in Antwerp, however, no further detailed analysis on these street canyons (e.g. link to air quality and other spatial and non-spatial parameters) was performed.

In general, air quality in street canyons is studied by three approaches: wind or water tunnel studies, model simulations, and field measurements [5]. So far, air pollution dispersion and dilution in street canyons has been mainly investigated by model simulations (CFD models) and in most cases, idealized models have been used. Therefore, the impact of the surrounding built-up area is neglected or reduced to a very simplistic representation. A study by Ref. [30] suggests that, even when idealized, the topography and urban terrain of the surrounding environment influences the turbulent structure of the incoming wind near the street canyon, and therefore affects the pollution dispersion process. To tackle the shortcomings of modelled simulations, field measurements can be used to validate the theoretical models. However, a clear lack of experimental data and field measurements for validation purposes is present [5]. Especially on a city-wide scale, studies on the aforementioned parameters (e.g. AR, LAR, building height variation) and their effect on in-canyon air quality are rather scarce, probably due to the lack of monitoring stations, geospatial data and measuring equipment.

In conclusion, a twofold problem statements is present: (1) the lack of sufficient data of field research to support theoretical assumptions and (2) the lack of city-wide analysis on street canyon morphology and its relation to in-canyon air quality. These knowledge gaps obstruct the possibility to formulate clear and applicable policy guidelines, which are highly demanded due to the recent developments concerning urban air quality and public health. In our research, we aim to address the two parts of the problem statement simultaneously.

Passive nitrogen dioxide (NO_2) samplers enable the collection of spatially distributed data in cost-efficient manner [31], while retaining sufficient data quality [32,33]. Very recently, the scale at which these NO_2 passive samplers are used, has greatly expanded, through citizen science projects involving up to 20.0000 participants, which monitor the air quality outside their house [34]. The monitoring effort typically lasts only a few weeks, but statistical model approach to reliably transform the data from multi-week averages to annual averaged values [34]. The resulting large-scale datasets reveal the granular structure of air quality with unprecedented detail and provide a new data resource to analyze the drivers of urban air pollution. Here, we explore this new data resource to investigate the relationship between measured NO_2 values, traffic volume and canyon morphology on a city-wide scale. Hereby we aim to acknowledge or refute preliminary theoretical findings and use this city-wide analysis to develop more profound insights on air quality in street canyons, which are useful for further research and spatial policy making.

2. Method

2.1. Case study

The city of Antwerp (51.22°N, 4.40°E; Belgium) is located on the Scheldt Estuary, and hosts one of the largest ports in Europe. The city has a population of over 520,000 residents and covers an area of 204.5 km^2 (average population density of 2542.78 persons km^{-2}). The Antwerp region experiences dominant south-west (SW) winds, with an average annual wind speed 4 m/s [35]. Antwerp has a regional background NO_2 pollution of 15 $\mu g/m^3$ and urban background NO_2 values of 22 $\mu g/m^3$ [36]. A study by Ref. [37] proclaimed Antwerp as one of the cities with the highest loss of life expectancy due to air pollution in Europe (similar levels were found in Paris, London, Milan, Stuttgart and Frankfurt).

A number of city-wide air quality studies have already been conducted [29,38], supporting the development of detailed air quality models (the ATMO-street model chain) for NO_2, PM2.5, PM10, and black carbon (BC) concentrations. The ATMO-street model points out specific zones such as the ring road and numerous street canyons as problematic areas where yearly pollution concentration levels (NO_2) are extremely higher than the European standards of 40 $\mu g/m^3$ (up to 70 $\mu g/m^3$ near the ring road [38]).

In 2018, a large-scale citizen-science measuring campaign ('CurieuzeNeuzen') was set up by the University of Antwerp and the Flanders Environment Agency (VMM) [39,40]. The project engaged 20.000 citizens across the entire Flemish region to measure NO_2 concentrations in front of their house using a low-cost sampler design (average 1.5 sampling sites km^{-2}). The monitoring effort lasted 4 weeks, and a statistical model was developed to reliably transform passive sampler NO_2 data from 4-week averages to annual averaged values [34]. Overall, the citizen-science project resulted in an extremely large and spatially detailed dataset of yearly averaged NO_2 values, which gave clear insight into spatial patterns and local 'hot-spots' of NO_2 pollution [41]. The data was used to directly quantify the exceedance of legal thresholds, to estimate static and dynamic population exposure, and to critically assess and improve the performance of air quality models [42].

In the city of Antwerp (the largest city of Flanders with the highest abundance of street canyons), a total of $N = 1009$ samplers were installed, providing an average sampling density of 5 sites per km^2 (Fig. 2). Here, we will use this urban subset of the larger dataset to investigate the relation between NO_2 values and key street canyon characteristics, in order to gain a more profound insight on how urban street canyons affect air quality.

2.2. Parameter selection

The in-canyon air quality is defined by numerous parameters and is a complex combination of background conditions, in-canyon conditions and morphological and meteorological aspects which cause temporal (e.

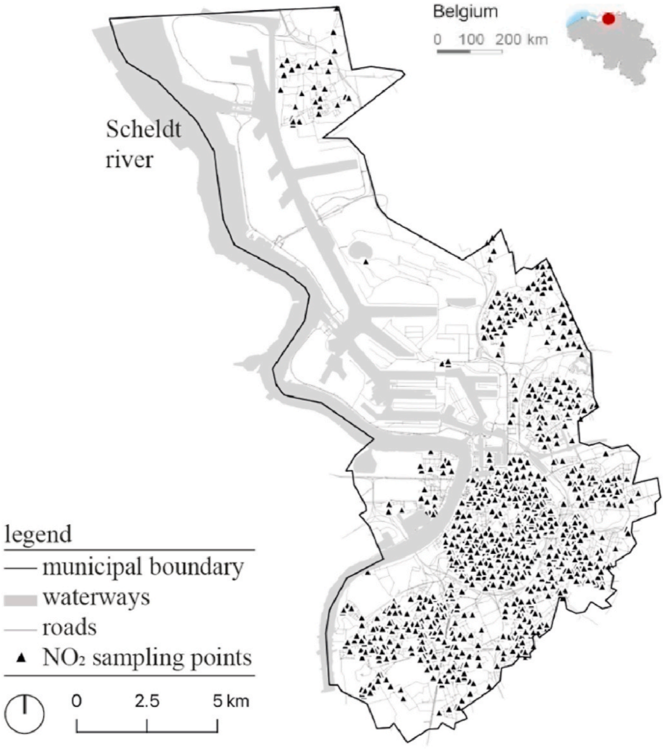


Fig. 2. Location of the study area and NO_2 sampling points within the citizen science campaign.

g. meteorological conditions) and spatial (e.g. street canyon morphology) variability [5]. conducted a broad literature research to compile a set of parameters with a proven impact on local air quality in street canyons (summarized in Table 1). The general impact of spatial and non-spatial background conditions on the air quality has already been investigated widely [23]. On a local scale [24], already investigated the influence of local meteorological conditions (e.g. temperature, relative humidity and atmospheric pressure) on in-canyon levels of particulate matter.

For the case of Antwerp, we aimed to conduct further research on the relationship between local spatial condition (canyon morphology) and traffic volume, parameters which were less emphasized by Ref. [24]. Also, for the case of Antwerp, meteorological conditions were not monitored at the street level during the citizen science campaign. Based on the available data, we selected the following local parameters in order to investigate their relationship to the measured NO_2 values of the citizen science campaign: (1) traffic volume, (2) deviation from the main wind direction, (3) AR, (4) LAR, (5) building height variance and (6) the presence of trees.

2.3. Data collection

Data on traffic volumes (the total daily traffic volume (TV_{tot}), the average hourly traffic volume (TV_{av}), the maximum hourly traffic volume (TV_{max})) was derived from the Strategic Traffic Model for the transport region of Antwerp (version 4.2.1), made available by the Department of Mobility and Public Works of the Flemish Government in cooperation with Arcadis Belgium. The Strategic Traffic Model includes traffic volumes on an hourly basis (number of vehicles per hour), which are validated by traffic counts. The geospatial datasets (3D GRBgis) were retrieved from the Databank Ondergrond Vlaanderen (DOV) database [73], which we used to develop a street canyon dataset (see Section 2.4). Additional data layers (e.g. location of trees) were retrieved from the Opendata Geoportal of the city of Antwerp [61]. We also transferred the data of the measured NO_2 values of the “Curieuzeneuzen” campaign to a geospatial layer, in order to link them with the aforementioned geospatial layers (e.g. traffic volumes or the 3D GRBgis).

2.4. Geospatial processing in GIS

Geospatial analysis was conducted in QGis (QGIS.org, released 2018. QGIS Geographic Information System. Open Source Geospatial Foundation Project. version 3.4.4- madeira. https://qgis.org), a software program for mapping and analysis in urban planning. Firstly, the geospatial data of the road axis and 3D building configuration (GRB) was imported. In order to develop a street canyon dataset, every 5 m segment of road axis that was delimited by a continuous facade on both sides, was flagged as a potential street canyon (see Fig. 3). In total, 46.102 segments (~491 km or 29.5% of the total road length) were designated as a potential street canyon (Fig. 4a), only based on the fact that these streets are delimited by facades on both sides of the road (maximum width of 60 m) and not by their AR. Next, adjacent 5 m segments were merged to continuous street canyons and following parameters were calculated for every segment: AR, LAR and building height variation. In QGis, an angle of orientation was automatically assigned to every street canyon segment. The deviation between this street orientation angle and the main wind direction (SW or 225°) was calculated ranging from 0° (parallel) to 90° (perpendicular). The aforementioned process results in a street canyon data set with multiple morphological parameters (e.g. AR, LAR, building height variation and deviation of the street axis from the main wind direction).

Secondly (Fig. 4b), the number of trees in every street canyon was determined by an automatic count of every tree from the tree data layer of the vegetation inventory from the Opendata Geoportal of the city of Antwerp [61]. The number of trees is thereafter divided by the street canyon length, in order to calculate the number of trees per meter of street canyon.

Thirdly, the street canyon dataset was interlinked with the Strategic Traffic Model (Fig. 4c) and the NO_2 sampling points (Fig. 4d). However, data on traffic volume and NO_2 were not available for every street canyon section. In total, we found 321 data points with complete data on street canyon morphology, tree density, traffic volume and NO_2 values (Fig. 4e).

2.5. Statistical methods

All data connected to the data points were extracted from QGis using the ‘GroupStats’ plugin. Subsequently, the data was imported in the IBM SPSS statistics (IBM Corp., Released 2020, IBM SPSS Statistics for Macintosh, Version 27.0. Armonk, NY) and a pairwise Pearson correlation and multiple regression analysis was conducted for the selected parameters (NO_2, traffic volume, deviation from the main wind direction, AR, LAR, building height variation and the number of trees per linear meter). Next, a principal component analysis (PCA) was carried out in order to furtherly investigate which factors produce NO_2 variations. Based on the found predictors (AR and TV_{max}) for NO_2 variations, a distribution plot was made (Fig. 6). This distribution plot gives a clear insight in the relationship between AR and TV_{max} and hereby supports the detection of a number of typical street canyon typologies and their threshold values for AR and TV_{max} (see Section 4.4).

3. Results

3.1. Pairwise pearson correlations and multiple linear regression

Table 2 shows the pairwise Pearson correlation coefficients (r) between the investigated parameters. It is self-evident that the highest correlations were found between the total daily traffic volume (TV_{tot}), the average hourly traffic volume (TV_{av}) and the maximum hourly traffic volume (TV_{max}) with significant r-values close to 1. Also, these

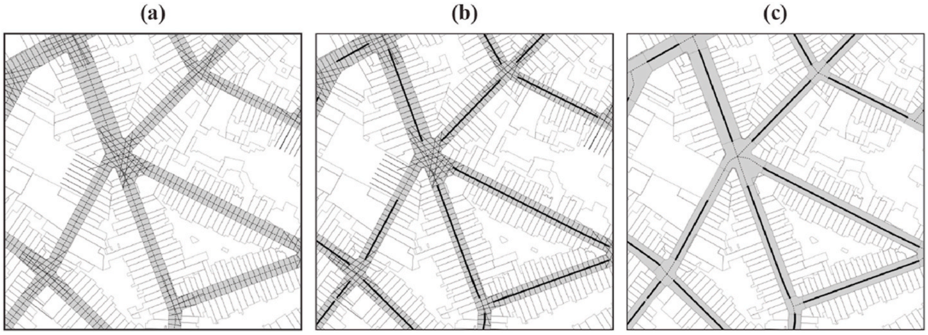


Fig. 3. GIS processing of street canyons with (a) the dividing of the streets in 5 m sections, (b) the selection of 5 m segments delimited by facades on both sides and (c) the merging of adjacent 5 m segments to street canyons.

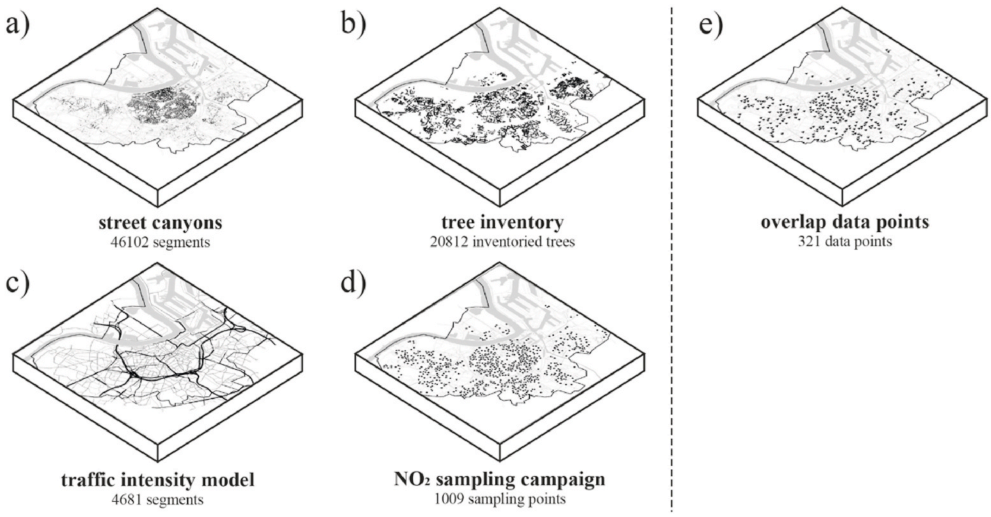


Fig. 4. Overview of data layers used in the geospatial analysis with (a) all street canyon segments, (b) data from the tree inventory, (c) data from the Strategic Traffic Model, (d) the NO_2 data from the sampling campaign and (e) the overlapping data points.

Table 2
Pairwise Pearson correlation coefficient (r) between pair of the total daily traffic volume (TV_{tot}), the average hourly traffic volume (TV_{av}), the maximum hourly traffic volume (TV_{max}), the aspect ratio (AR), lateral aspect ratio (LAR), deviation from the main wind direction (θ_{dev}), building height variance (H_{var}), the number of trees per linear meter (T/m) and the measure NO2 values (NO_2_year). $^{**}p < 0.01$

	TV_{tot}	TV_{av}	TV_{max}	AR	LAR	θ_{dev}	H_{var}	T/m	NO_2_year
TV_{tot}	1								
TV_{av}	1.000**	1							
TV_{max}	0.987**	0.982**	1						
AR	−0.201**	−0.201**	−0.183**	1					
LAR	−0.044	−0.44	−0.059	−0.065	1				
θ_{dev}	0.018	0.018	0.027	0.033	0.097	1			
H_{var}	0.030	0.030	0.027	0.233**	−0.056	−0.033	1		
T/m	0.055	0.055	0.063	−0.360**	0.070	−0.026	−0.076	1	
NO_2_year	0.361**	0.361**	0.380**	0.328**	−0.027	0.018	0.051	−0.053	1

traffic-related parameters (TV_{tot}, TV_{av}, and TV_{max}) had significant negative correlations ($r \approx -0.2$) with the aspect ratio. This indicates that when AR decreases (e.g. streets get wider), traffic intensity tends to increase and vice versa. Another significant negative correlation ($r = -0.360$) was found between AR and the number of trees per linear meter (T/m) indicating that when AR decreases, the number of trees is likely to increase (due to the available space). A positive correlation of $r = 0.233$ was found between AR and the building height variance (H_{var}), indicating that in street canyons with higher ARs the variation in building heights tends to increase. Most importantly, the total daily traffic volume ($r = 0.361$), average hourly traffic volume ($r = 0.361$), maximum hourly traffic volume ($r = 0.380$) and the aspect ratio ($r = 0.328$) had significant positive correlations with the measured NO_2 values. On the other hand, no significant correlations were detected between the NO_2 values and the lateral aspect ratio ($r = -0.027$), deviation from the main wind direction ($r = 0.018$), building height variance ($r = 0.051$) and the number of trees per linear meter ($r = -0.053$). This indicates that the measured NO_2 values are mostly determined by traffic volumes and the aspect ratio of the street canyon, but their r-values (r ranging from 0.328 to 0.380) also imply the substantial impact of other unexplained parameters (e.g. relative humidity, local wind direction and wind speed or background conditions).

Subsequently, a stepwise multiple linear regression was performed in SPSS with the measured NO_2 values (NO_2_year) as dependent variable and the maximum hourly traffic volume (TV_{max}), the aspect ratio (AR), lateral aspect ratio (LAR), deviation from the main wind direction (θ_{dev}), building height variance (H_{var}) and the number of trees per linear meter (T/m) as independent variables. The results of the stepwise multiple regression analysis are summarized in Table 3. When using the stepping method criteria for probability of $F \leq 50$ to enter variables and probability of $F \geq 100$ to remove variables, only TV_{max} and AR were selected as suitable predictors. The stepwise multiple regression analysis showed a positive R-squared value (R^2) of 0.145 for the predictor TV_{max} and a R^2 value of 0.309 when combining predictors TV_{max} and AR. When using all independent variables as predictors, the R-squared value only increased by 0.009 (up to $R^2 = 0.318$), which indicates the smaller contribution of the independent variables T/m, H_{var}, LAR and θ_{dev} in explaining the variance in the measured NO_2 values. The results of the stepwise multiple regression indicate that the AR and TV_{max} are useful predictors for NO_2 values in street canyons, explaining part of the variance. But that substantial unexplained variance is present, thus warranting the inclusion of other parameters in the regression model (e.g. relative humidity,

Table 3
Results of the stepwise multiple regression analysis with the measured NO_2 values (NO_2_year) as dependent variable and with the maximum hourly traffic volume (TV_{max}), the aspect ratio (AR), lateral aspect ratio (LAR), deviation from the main wind direction (θ_{dev}), building height variance (H_{var}) and the number of trees per linear meter (T/m) as independent variables.

Model	R	R^2	ΔR^2	F	sig.
TV_{max}	0.380	0.145	0.145	53.964	0.000
TV_{max}, AR	0.556	0.309	0.164	71.000	0.000
TV_{max}, AR, T/m	0.560	0.315	0.006	48.306	0.000
TV_{max}, AR, T/m, H_{var}	0.563	0.317	0.002	36.730	0.000
TV_{max}, AR, T/m, H_{var}, LAR	0.564	0.318	0.001	29.348	0.000
TV_{max}, AR, T/m, H_{var}, LAR, θ_{dev}	0.564	0.318	0.000	24.394	0.000

local wind direction and wind speed as indicated by Refs. [24,62,63] for the unexplainable.

3.2. Principal component analysis (PCA)

Additional to the stepwise multiple regression analysis a principal component analysis (PCA) was carried out in order to furtherly investigate which factors produce NO_2 variations. All parameters (the total daily traffic volume (TV_{tot}), the average hourly traffic volume (TV_{av}), the maximum hourly traffic volume (TV_{max}), the aspect ratio (AR), lateral aspect ratio (LAR), deviation from the main wind direction (θ_{dev}), building height variance (H_{var}), the number of trees per linear meter (T/m) and the measure NO_2 values (NO_{2}_year)) are included in the PCA. The results of the PCA are summarized in Fig. 5. A total of 9 components were classified according to their influence and visualized in Fig. 5a. The loadings for the first 3 components (PC1, PC2 and PC3) are shown in Fig. 5b and c. The loadings represent the weight of each variable when calculating the principal component [63]. PC1 and PC2 are the main components, which explain together over 53.6% of the variability in the data.

PC1 explains 35.6% of the variability in the data the component loadings (Fig. 5b) show that this component can easily be deduced to traffic intensity, with loadings close to 1 for TV_{tot}, TV_{av} and TV_{max} (0.989, 0.989 and 0.987 respectively). For this component, a negative loading of -0.204 is present for the AR. This can be explained by significant negative correlations between TV and AR mentioned in section 4.1. The second component (PC2) is strongly determined by the AR (with a component loading of 0.843, see Fig. 5b). Also, the building height variance (H_{var}) and the number of trees per linear meter (T/m) have larger loadings (0.416 and -0.629 respectively). Therefore, it can be concluded that the second component is closely related to the canyon morphology. The third component had increased loadings for LAR and θ_{dev} (0.679 and 0.754 respectively), which possibly indicates the potential impact of wind-related parameters (e.g. wind speed and direction). The loadings of components 4 to 9 have not been furtherly investigated, since these components only explain a small part of the variability of the data (variance explained <10%).

3.3. Distribution of NO2 values

The foregoing statistical analysis (especially the multiple linear regression) indicated TV_{max} and AR as valid indicators for the variance in the measured NO_2 values. By plotting the distribution of the NO_2 values based on the AR and TV_{max}, the relationship between these three parameters is investigated more profoundly. The distribution is represented in Fig. 6. For the purpose of this research, all street canyon segments were classified into deep (AR > 1.5), regular deep (AR = 1.0–1.5), regular wide (AR = 0.65–1.0) and wide (AR < 0.65) and categorized into 20 classes according to maximum hourly traffic volume (TV_{max} in steps of 40 vehicles per hour). Of the 321 data points in the dataset, 96 (or 29,9%) had an annual NO_2 concentration that exceeded the WHO air quality guideline value (WHO, 2018) and EU legal threshold of 40 μg/m^3 [64].

Fig. 6 indicates that in general, unrelated to the AR, the number of street canyons with increased pollution (>40 μg/m^3) shifts when TV_{max} surpasses 300 vehicles per hour. In total, 106 of all 321 data points (33%) have a TV_{max} > 300 vehicles/hour, and 57 (or 53.7%) of these data points exceeds the EU legal threshold. By excluding wide street canyons (AR < 0.65), the percentage of points with NO_2 values > 40 μg/m^3 increases further to 70% (38 out of 54 data points with TV_{max} > 300 vehicles/hour and AR > 0.65). Therefore, TV_{max} = 300 vehicles/hour can be set as a threshold value for street canyons with AR > 0.65.

3.4. Street canyon typologies

Based on the distribution of the NO_2 values (Fig. 6), a number of street canyon types can be derived based on their AR and TV_{max} (summarized in Fig. 7). The aim of this categorization is to link specific street canyon types to measured NO_2 values. This can be helpful to predict in which street canyon types NO_2 values are likely to surpass the EU legal threshold of 40 μg/m^3. For the case of Antwerp, wide street canyons (type 1) seem less likely to surpass the threshold of 40 μg/m^3, even in case of high traffic volume (18.2% of all wide street canyons exceeds the threshold NO_2 value). In total 148 of the 321 measuring points were classified as a wide street canyon, representing a high portion (46.1%) of all data points.

For regular wide, regular deep and deep street canyons (all street canyons with AR > 0.65) a distinction has to be made based on traffic intensity, whereas the aforementioned threshold value of TV_{max} = 300 vehicles/hour (see Section 4.3) is used. For street canyons with an AR > 0.65 and a TV_{max} < 300 vehicles/hour (types 2–4), a low chance of exceeding the NO_2 value of 40 μg/m^3 can be expected. In Antwerp, the average NO_2 value for these types ranges from 34.68 μg/m^3 to 37.7 μg/m^3. Also, for regular wide, regular deep and deep street canyons with TVmax <300 vehicle/hour, respectively 19.4%, 31.8% and 17.6% of the measuring points exceeded the NO_2 value of 40 μg/m^3.

On the other hand, once TV_{max} > 300 vehicles/hour and AR > 0.65, the chance of NO_2 values surpassing the 40 μg/m^3 increases drastically, whereas for regular wide street canyons and for regular deep street canyons respectively 72.7% and 71.4% of the data points exceeded the threshold value. For regular wide and regular deep street canyons in Antwerp with TV_{max} > 300 vehicles/hour, an average yearly NO_2 value of respectively 44.77 μg/m^3 and 45.46 μg/m^3 was measured.

4. Discussion

Previous results indicate that the aspect ratio (AR) and the maximum hourly traffic volume (TV_{max}) are the most suitable indicators for in-canyon NO_2 values, and other spatial indicators (lateral aspect ratio (LAR), deviation from the main wind direction (θ_{dev}), building height

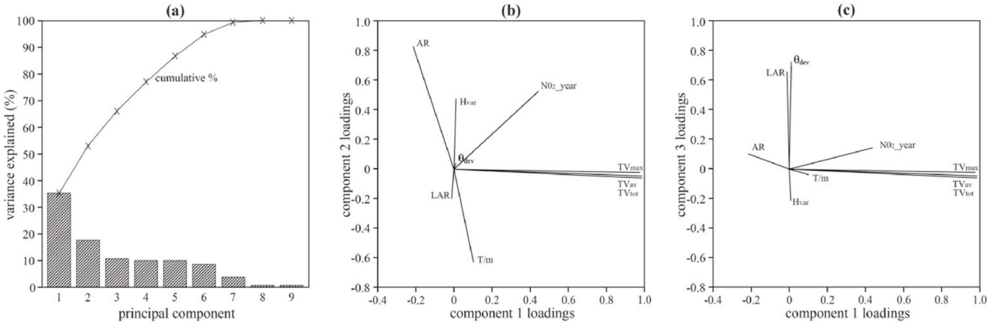


Fig. 5. Result of the principal component analysis (PCA) with (a) the Pareto chart, (b) the component loadings for component 1 (PC1) and 2 (PC2) and (c) the component loadings for component 1 and 3.

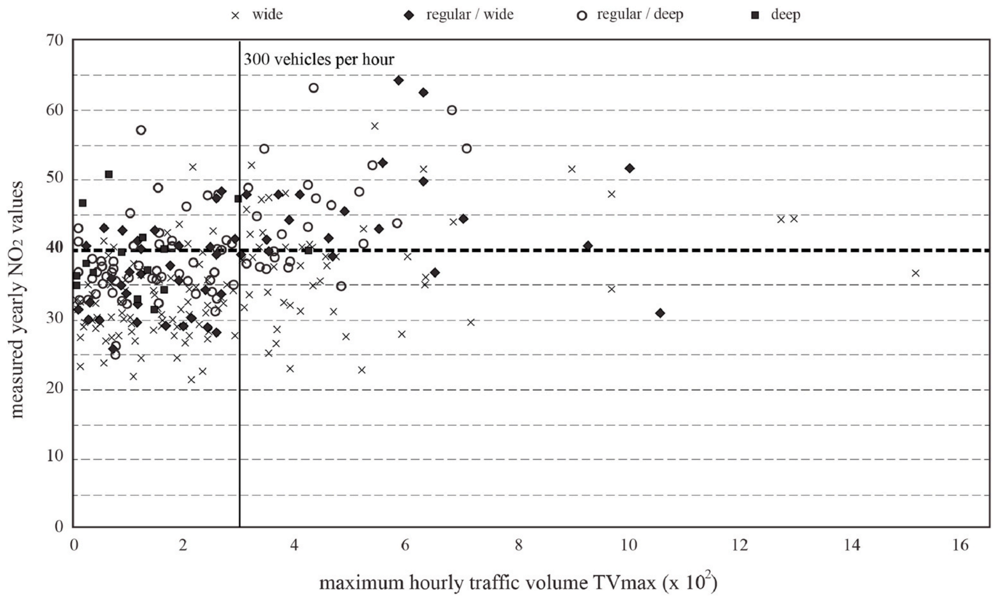


Fig. 6. Distribution of the measured NO2 values based on the aspect ratio (AR) and the maximum hourly traffic volume (TV_{max}).

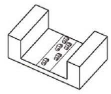
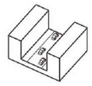
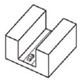
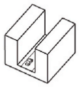
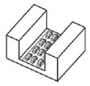
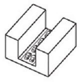
type	isometric representation	type	AR	threshold TV_{max}	average yearly NO_2 values	percentage of NO_2 values higher than 40 ug/m3	N	% of total data points
1		wide	< 0.65	/	33.98 ug/m3	18.2 %	148	46.1%
2		reg wide	0.65 - 1.0	< 300	34.68 ug/m3	19.4 %	36	11.2%
3		reg deep	1.0 - 1.5	< 300	37.7 ug/m3	31.8 %	66	20.5%
4		deep	> 1.5	< 300	36.38 ug/m3	17.6 %	17	5.3%
5		reg wide	0.65 - 1.0	> 300	44.77ug/m3	72.7 %	22	6.8%
6		reg deep	1.0 - 1.5	> 300	45.46 ug/m3	71.4 %	28	8.7%

Fig. 7. Street canyon categorization based on the aspect ratio (AR), the threshold values for the maximum hourly traffic volume (TV_{max}), the average yearly NO_2 values, the percentage of street canyons with measured NO_2 values surpassing the critical NO_2 value of 40 μg/m^3, the number of data points according to the type (N) and the ratio between the data points according to the type and the total data points (321).

variance (H_{var}), the number of trees per linear meter (T/m)) contribute marginally the variance in NO_2 values. The significant correlation between TV_{max} and NO_2_year is self-evident. The influence of the AR was expected based on early pioneering work on in-canyon flow regimes by Refs. [6,65,66] and [67]. These studies also indicated the threshold value of AR ≈ 0.65 (when skimming flow appears in the street canyon under perpendicular wind conditions). However, our research is, to our own knowledge, the first field research to affirm these theoretical assumptions on a city-wide scale.

The R^2 of 0.309 for the model with TV_{max} and AR of the multiple linear regression (and also the R^2 of 0.318 for the model combining all indicators) indicates that other unexplained variables still have a large impact on the measured NO_2 values. Based on previous studies, the residual variance in NO_2 values can be explained by meteorological conditions [17] and photochemical mechanisms [17,21,22]. The study of [17] showed for example that meteorological conditions explained more than 70% of the variance of daily average pollutant concentrations over China and that NO_2 values had significant negative correlations with O_3 as a result of photochemical mechanisms. Although explaining a high percentage of the variability in air pollutant concentrations, meteorological conditions and photochemical mechanisms are mainly determined by real-world atmospheric conditions. Meanwhile, the indicated parameters (TV_{max} and AR) of our study are directly influenceable by human interventions and are therefore more suitable for, for example, formulating guidelines for urban planning and spatial policy making. Nevertheless, these findings indicate that in order to develop thorough insights on NO_2 values in street canyons, it is essential to monitor meteorological conditions and secondary pollutants such as O_3 (in order to evaluate the impact of photochemical mechanisms).

In contradiction to many theoretical studies, no significant correlations were found between the parameters LAR, θ_{dev}, H_{var}, the number of trees per linear meter (T/m)) and the measured NO_2 values. The deviating results for the morphological parameters LAR, θ_{dev} and H_{var} can be explained by the complexity of the surrounding urban fabric. Most studies regarding LAR, θ_{dev} and H_{var} (e.g. Refs. [68–70] use simplified and idealized models, which do not represent realistic urban environments. Therefore, it is plausible that their results are less distinguished in real-world environments. Is it also possible that these parameters cause temporal variations in NO_2 values, which were not detected during our study. Regarding the deviation from the main wind direction (θ_{dev}), no significant correlation with the in-canyon NO_2 values was found, largely contradicting the expectations based on previous studies (e.g. Refs. [18,55,69] and [24]. This can be explained by the fact that in our study, the deviation from the main wind direction (θ_{dev}) was determined by calculating the deviation between the orientation of the street axis and the main (SW) wind direction and not by on-site monitoring of local wind directions. On one hand, it is known that in urban environments, wind directions can rapidly change due to the presence of buildings and obstacles [71]. On the other hand, it is also possible that the wind direction during the sampling period did not equal the main yearly wind direction. In general, the deviation from the main wind direction (as calculated in our study) seems less suitable to predict NO_2 values and wind directions should be monitored on a more local scale. This also holds repercussions for urban planning and policy making, since our study shows that it is not advisable to determine problematic street canyons based on their orientation towards the main wind direction.

Also, the theoretical assumption that trees affect the in-canyon air quality (as indicated by Ref. [13] and [75]) is not acknowledged by our analysis, whereas an insignificant (negative) correlation was found between the number of trees and the measured NO_2 values. However, this finding is also in agreement with previous work by Ref. [42]. The insignificant negative correlation can partially be explained by the correlation (negative significant; $r = -0.360$) between AR and the number of trees per linear meter (T/m) indicating that trees are more likely to occur in wide street canyons, which generally have lower NO_2 values. Another potential explanation is that the impact of trees on NO2 values is largely dependent on a high number of variables which are inherent characteristics of vegetation such as the tree planting density, tree crown porosity, leaf area density or LAD, trunk height and density [5]. This variability was not taken into account in our study but can potentially impact the correlation with the measured NO_2 values.

In accordance to the study by Ref. [24]; NO_2 values in regular deep (AR = 1.0–1.5) and regular wide (AR = 0.65–1.0) street canyons can be higher than those in deep street canyons (AR > 1.5), which seemingly contradicts previous theoretical research of [7,8,26] and [25]. However, for our study, it is clear that most deep street canyons have lower traffic intensities (average TV_{max} in deep street canyons is 188 vehicles per hour for Antwerp), which partially explains the lower NO_2 values when compared with regular deep and regular wide street canyons with TV_{max} > 300. This indicates that traffic volume and AR are not independent, as illustrated by the pairwise Pearson correlation ($r = -0.183$ for correlation between TV_{max} and AR) and the PCA (negative loading for AR of −0.204 for the first traffic related component).

Lastly, our study is the first study that clearly manages to delimit a number of street canyon typologies based on a critical combination of their AR, TV_{max} and NO_2 values. The typologies can offer a large contribution for urban planning and spatial policy making and hereby narrow the gap between the theoretical and practical work on air quality in urban environments. Two main rules of thumb for urban planning can be formulated based on these typologies: (1) street canyons with AR < 0.65 are less likely to have increased NO_2 values (>40 $\mu g/m^3$) even in case of high traffic intensities (>300 vehicles per hour). Therefore, on large artery roads with high traffic volumes, AR = 0.65 can be set as a threshold value. (2) Once AR > 0.65, NO_2 values rapidly increase once TV_{max} surpasses 300 vehicles per hour. Therefore, measures should be taken to (if necessary) limit traffic volume in street canyons with AR > 0.65, and 300 vehicles per hour during rush hour (TV_{max}) could be set as a clear threshold value.

5. Limitations and variabilities

In any study regarding air quality in urban environments, a high number of variabilities and uncertainties should be kept in mind, which is an inherent characteristic of real-world atmospheric conditions [72]. These variabilities are clearly indicated by the r values that were found in Section 4.1. Besides these variabilities, a number of limitations are related to the collected data. The yearly averaged NO_2 values from the 'CurieuzeNeuzen' campaign were measured by using passive low-cost NO_2 samplers which were attached to the facades of buildings. In the delivered GIS data, all data from the samplers were transferred to points on the central road axis, opposite to the facade. This made it impossible to detect on which side of the road the NO_2 was measured. However, preliminary studies indicate that large differences in pollution levels can occur on both sides of the street canyon, especially when oriented perpendicular to the main wind direction [7,8,26]. Therefore, some irregularities on the measured NO_2 values should be kept in mind. Also, data from the Strategic Traffic Model was available for 4681 street canyon segments, but the data on very narrow street canyons (AR > 1.5) was very scarce. However, it can be assumed that, due to spatial limitations (limited street width), traffic volumes in these street canyons are fairly low.

Also, no meteorological conditions nor photochemical reactions (e.g. by measuring O_3 concentrations) were measured during the 'CurieuzeNeuzen' campaign. The monitoring of these conditions could potentially have explained more of the variabilities in the measured NO_2 values, as indicated by the prior studies of [17,24]. Also, only NO_2 concentrations were measured. Other pollutants (e.g. particulate matter) should have been measured in order to elaborate more on urban air quality in general. It is plausible that other correlations will be found for different air pollutants, and that indicators such as the number of trees become more valid. However, monitoring these variables (local meteorological conditions, photochemical reactions and other air pollutants) for all 321 street canyons would have been challenging and practically unfeasible.

Lastly, it is plausible that the threshold values suggested in this paper may hold for some cities, but may also shift depending on the size, morphology, traffic intensity and background pollution of specific urban areas. Therefore, a generalization of the street canyon types should be considered carefully. Despite these shortcomings, insights were found, which are of general interest for the field of urban planning and air quality. Especially for the city of Antwerp, this study may result in a more profound insight on the street canyon morphology and typology on scale of the entire city.

6. Conclusion

The relation between city-wide NO_2 values as measured in the 'CuriezeNeuzen' campaign [39,40] and 8 street canyon parameters (total daily traffic volume, the average hourly traffic volume, the maximum hourly traffic volume, the aspect ratio, the lateral aspect ratio, the deviation from the main wind direction, the building height variance and the number of trees per linear meter) was investigated for 321 NO_2 measuring points in Antwerp. The total daily traffic volume ($r = 0.361$), average hourly traffic volume ($r = 0.361$), maximum hourly traffic volume ($r = 0.380$) and the AR ($r = 0.328$) had significant positive correlations with the measured NO_2 values ($p < 0.01$). These finding correspond with recent finding in prior research of [7,8,27] and [28]. No significant correlations were found between the other parameters (lateral aspect ratio (LAR), deviation from the main wind direction (θ_{dev}), building height variance (H_{var}), the number of trees per linear meter (T/m)) and the measured NO_2 values.

The r values of TV_{max} (r = 0.380) and the AR (r = 0.328) of the pairwise Pearson correlation and the R^2 ($R^2 = 0.309$ for the model with TV_{max} and AR) of the multiple linear regression indicate that AR and TVmax are suitable predictors for in-canyon NO_2 values. However, other unexplained variables (e.g. local meteorological conditions such as temperature, relative humidity and atmospheric pressure) still have a large impact on the measured NO_2 values.

Wide street canyons (AR > 0.65) seem less likely to surpass the threshold of 40 $\mu g/m^3$, even in case of high traffic volume. This can be explained by the increase in natural ventilation performance once AR < 0.65, which confirms early pioneering work on in-canyon flow regimes by Refs. [6,65,66] and [67]. Hereby, the definition of a street canyon can be delimited to a street flanked by facades on both sides, with an AR > 0.65. Even more, based on our research, it can be concluded that for this every street canyon in Antwerp (AR > 0.65), the threshold value of $TV_{max} = 300$ should be respected in order to avoid NO_2 levels higher than the European limit value of 40 $\mu g/m^3$. The determined threshold value can be of interest not only for Antwerp, but also for other cities with a similar morphology, NO_2 values and traffic intensities in the same order of magnitude (e.g. London and Paris). However, further research should be conducted on the extrapolation of the threshold value for other cities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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