MODELLING URBAN TRAFFIC AIR POLLUTION DISPERSION

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KEY WORDS: Modelling, Urban, Pollution, GIS, Three-dimensional

ABSTRACT:

The prime aim of this research is to support decision making, e.g., air quality impact analysis, human health assessment, through spatially modelling traffic-induced air pollution dispersion in urban areas at street level. Based on the information needed in decision making, a framework for a street level air quality decision support system is established, which is composed of basically three parts: an urban base data model, a dispersion model with a spatial database and a 3D GIS environment for visualisation. The database is used to provide input for executing the dispersion model. The dispersion model called OSPM is adapted to determine the pollution level on the basis of traffic, meteorology and street configuration data.The framework for assessing and visualizing pollution levels was implemented for four pilot-study spots in The Hague, The Netherlands. Those spots are representative for the main configuration of roads across the city. NO_2 and PM10 were selected to be modelled pollutants for the reference year of 2006. Parameters considered for the dispersion model were street width and length, building height, wind velocity and direction, ambient air temperature, background pollution, traffic volume, vehicle type and speed.The pollutants concentrations were visualized in planar and non-planar view with buildings represented by cubic volumes. The visualized result has potential to provided valuable information for pollution impact analysis, by including also the vertical dimension of the influenced area and population. Moreover it provides important information to decision makers for air quality assessment and management.

1. INTRODUCTION

Latest since the introduction of European environmental standards for air pollution local authorities are facing the challenge of being responsible for effective counter measures if limit values of air pollution are exceeded. The public is put into the position to request from the local authorities to ensure sufficient environmental living quality for all inhabitants according to European standards. Thus, local authorities as well as the public need 'high-resolution' information on air pollution levels that give not only the pollution levels for few measurement stations within a city (macro-level) but also pollution levels for the individual streets (micro-level). Therefore air pollution models have been introduced, where measurements are commonly used for calibrating the pollution models. In practice, setting up an area-wide air monitoring network is rather expensive and costly to operate and maintain.

One of the dominant sources of air pollution affecting environmental living quality in urban areas is road traffic-induced air pollution (Duclaux et al., 2002; European Environment Agency, 2003; Rebolj and Sturm, 1999). Providing information about traffic air pollution and finding out its distribution is therefore a crucial starting point for planning effective measures to improve air quality. Such information helps decision makers to optimize e.g. urban design.

However, the phenomenon of road traffic air pollution shows considerable variation within a street canyon as a function of distance to the source of pollution, therefore, the levels and consequently the effected number of inhabitants varies. The location of hot spots of high pollution levels that exceed a certain threshold has besides a horizontal also a vertical dimension; the latter is usually neglected. The little attention to the vertical variation is mainly caused by the fact that urban environmental policy standards only demand monitoring and therefore modelling of pollution levels at a specific measurement height (e.g. 3.5 m above ground), ignoring that below this measurement level but also offering no specific information to inhabitants living on upper floors of high rise buildings.

To fill this information gap a variety of micro-scale air dispersion models have been developed in the past years. Such models provide information about the horizontal as well as vertical variation of air pollution levels, including a discrimination of most common pollutants (e.g. C02, NO2, PM10) that have different spatial spreading behaviours. Most dispersion models have a special output formats e.g. tabular outputs, but unfortunately do not integrate the information into a spatial database in conjunction with contextual information of the street canyon which would allow urban planners and decision makers to easily access and interpret the information. Linking up dispersion models with a GIS environment is a mean to resolve this shortcoming. Modelling pollution dispersion with a GIS platform is also a powerful way of making the modelled results user-friendly and easily understandable for local authorities as well as the public (Rebolj and Sturm, 1999).

Several researches have been studied that aimed at linking dispersion models with a GIS system. Gualtieri, et al. (1998) developed a GIS framework to predict urban traffic air pollution. The entire system consists of 3 main components, a GIS databases, sub-models and resulting thematic maps. The sub-models include traffic model, emission and dispersion model.

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Similar, Lim, et al. (2005) developed an integrated decision support system aiming at assessing urban air quality. The system was an innovative framework to link existing air quality tools including a transportation model, an emissions inventory and dispersion model. In Cincinnati, United States, a traffic pollution model and GIS and 3D visualization techniques have been integrated (Wang, 2005), showing various manners to represent pollution levels in planar and non-planar perspective but the approach is only suitable for an area with very few buildings.

This research aims at providing spatial information of the horizontal and vertical variation of air pollution that has the potential to support informed urban decision making, advocating for the importance of non-planar (3D) information compared to the conventional planar (2D) presentation of pollution levels which are still the standard of urban environmental policies. Main focus within this paper is to discuss the incorporation of the outputs of the pollution dispersion model with a spatial database and illustrate an initial visualisation in 3D GIS environment.

2. METHODOLOGY

The prime aim of this research is to support decision making in urban areas, by providing information on horizontal and vertical variation levels of (traffic caused) air pollution that allows an assessment how different inhabitants are affected. The objective is achieved via integrating the output of a dispersion model into a spatial database that contains urban base data that subsequently permits visualisation of the vertical dimension of air pollution levels (see Figure 1).
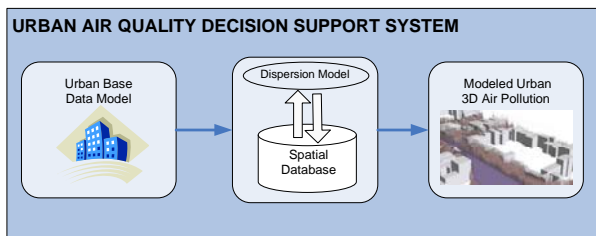

Figure 1: Conceptual scheme of system design

The work flow starts with analysing the context of decision making about traffic-induced air pollution dispersion using the centre of The Hague municipality, The Netherlands as case study. Several interviews with transport and planning experts of the environment, transportation infrastructure and city planning department were conducted during September to November of 2007. Also the urban base data were acquired from the municipal database. Further meteorological information was obtained from the Royal Dutch Meteorological Institute (KNMI).

According to the current environmental conditions in The Hague, nitrogen dioxide (NO_2) and particle matter 10 (PM10) show critical levels in the study area (centre of The Hague) where in part of the area the annual average $40\mu g/m^3$ for both pollutants are exceeded (European Commission, 1999). In order to assess the influenced area and affected population, the spatial scale was confined to the street level.

A micro-scale dispersion model was consequently needed to work out pollutants levels, namely NO_2 and PM10, the tabular results of the dispersion model were subsequently linked with the spatial database. A 3D GIS environment was used to visualize pollutants levels in non-planar view and was than compared with planar pollution maps (see Figure 1).

2.1 Employed Dispersion Model

The employed dispersion model for this research is OSPM (Operational Street Pollution Model). OSPM is a practical street pollution model that is developed by the Department of Atmospheric Environment, National Environmental Research Institute, Denmark. It is able to incorporate the street canyon wind flow where the wind vortex occurs and thus the wind at street level is opposite to the flow above the roof level(Berkowicz,2000). Figuer 2 illustrates the general condition of wind flow in a street canyon. The flow condition causes that pollutants emitted from the traffic in the street are having higher concentrations on the leeward side of buildings adjacent to the road; whereas buildings on the windward side are exposed to the background pollution and pollution generated by the air recirculation within the canyon. OSPM predicts that the concentration on the windward side of the street is lower than on the leeward side.
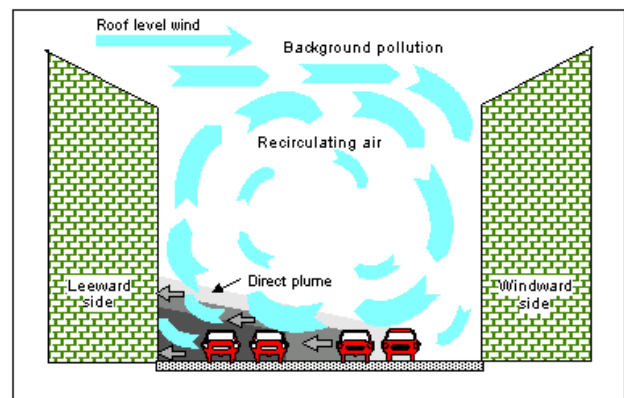

Figure 2: Wind flow in street canyon (Berkowicz 2000)

Another important feature of OSPM is its capability to model turbulences which are composed of two parts: ambient turbulence depending upon the wind velocity and traffic-induced turbulence dominating in the case of low wind velocity (<1 m/s) (Tang and Wang,2007). The computation of concentration is a sum of the direct contribution from the traffic and re-circulated pollution from the air circulation. A plume dispersion model is employed to calculate the direct contribution, whereby the wind direction at the street level is contrary to the roof level wind (Kukkonen et al., 2000; Tang and Wang, 2007). The model assumes a linear dispersion of pollutants and homogenous traffic emissions across the street canyon. A box model is adopted to compute the recirculating contribution, whereby the pollution exchange with the background is taken into account: the incoming flux is equal to the traffic emission while the out-going flux is dominated by the turbulence at the top of the street.

The receptor on the leeward side receives pollution contribution originating from the traffic emissions within the zone (the recirculating pollution and a part of the emission from outside of the vortex area). The receptor on the windward side mainly receives pollution from the air recirculation. If the whole street

is not occupied by the vortex, the traffic emission from outside of the recirculation zone contributes as well. In the case of zero wind velocity or the wind direction is parallel to the street, concentrations on both sides of the street are close to equal.

2.2 Input Data

The OSPM dispersion model requires three main input data sets, which were organised into a road, building and meteorology database(see Figure 3).The model uses the traffic data to extract pollution levels for different pollutants, while the street and building configuration in combination with the meteorology are used to model the dispersion within the street canyon. The tabular output of the model delivers air pollution values of selected pollutants at defined receptor points along buildings facades. The receptor points can be defined in vertical dimension with user-specific spacing, e.g. in intervals of 1m vertical steps along building facades.
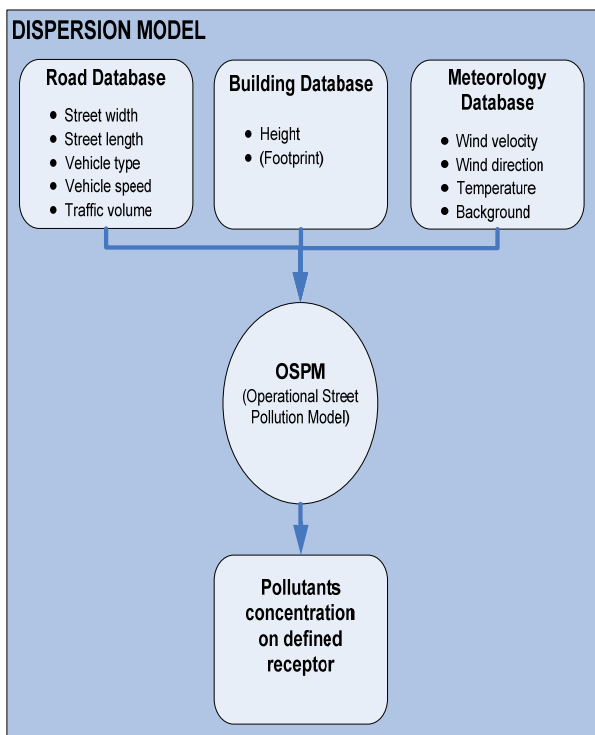

Figure 3: Components of the Dispersion Model

Road Database

The road database is divided into two categories, namely street geometry and traffic flow. The former includes street width and segment length; the latter comprises vehicle type, speed and traffic volume. Road width and length was extracted using the building footprints. Vehicle type is categorized into light, middle and heavy. Their definition is provided in Table 1. Vehicle speed represents hourly average speed along a road segment. Traffic volume presents hourly number of vehicle of each vehicle type.

The raw traffic data that includes hourly traffic volume, vehicle type and speed was provided by The Hague Municipality (reference year is 2006).

Light	private cars and small lorries with 4-wheel	
Middle	lorries, trucks with 2 axles and 4 back wheels, buses	
Heavy	trucks with 3 axles or more, trucks with trailer and tractors with semi-trailer.	

Table 1: Vehicle type categories

Building Database

Building database includes building height and footprint. The building height (of a single building and average height of buildings along the street) is needed for executing OSPM. The footprint was used in a latter step to establish cubic buildings in GIS to present vertical pollution variation. Also building footprint and height was obtained from The Hague Municipality.

Meteorology database

The required meteorology data for OSPM are hourly wind velocity and direction and ambient temperature. Hourly background pollution of NO, NO_2, O_3 and PM10 were also required.

The wind velocity and direction for 2006 was obtained from the website of Rotterdam meteorology station, the Netherlands. The station is named as Zestienhoven and the observation height is 10m. Both cities, Rotterdam and The Hague are located very close and have the same general meteorological condition, thus as no data could be obtained for The Hague the conditions of Rotterdam were used. Temperature data was extracted from the database of the Atmospheric Science Data Center, sponsored by NASA. Due to data availability, the latest data was for period of July 1983 - June 1993. The background concentration of relevant pollutants of 2006, namely NO, NO2, O3 and PM10, was extracted from the archives of National Institute for Public Health and the Environment, the Netherlands.

2.3 Linking the results of the dispersion module with a spatial database

The air pollution at a certain height in front of the buildings facades is obtained with OSPM using as input vehicular emissions, street configuration, meteorological data and urban background concentrations. The pollution level is uniform along the same street axis in front of one joint building facade, which is composed of background and traffic-induced pollution. The output is given in a tabular format for each receptor point showing different pollutants values (for the selected pollutants) at user defined height intervals.

In order to ease the visualization of pollution levels, cubic buildings were generated by extruding the building footprint

with the given height information. The information per receptor point (in tabular format) was linked to evenly distributed points vertically over the building surface with 1m interval. Figure 4a provides an example of such points distribution. The points along the same horizontal axis have the same pollutants level value. Interpolation was undertaken on those points of pollutants level. Natural neighbour method was used to interpolate the points. The interpolated output was projected to a TIN surface with a vertical offset as shown by figure4.b. The vertical offset leaning towards the buildings was chosen in order to ease the later interpolation (Kurakula and Kuffer 2008). TIN surface and interpolation can be in fault if any points have same x- and y-value. Visualization of pollutants levels was achieved both: over the sloped surface and over the street surface.
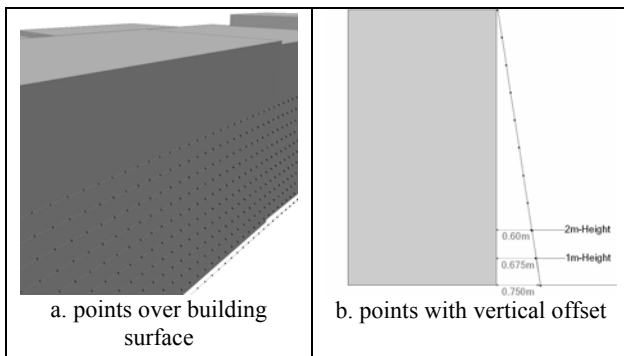

| a. points over building surface | b. points with vertical offset |

Figure 4: Even points to store pollutants concentration

3. RESULTS OF PILOT STUDY

3.1 Study Area

Four pilot-study areas in The Hague, The Netherlands were chosen to test the approach. Those four areas were determined using the following classification of the four major urban road types across the city. Figure 5 illustrates the four road types

- Category 2 is the 'base type' whereby one-story buildings are only on one side of the road;

- Category 3A is defined as 'roads with buildings on both sides', furthermore, the buildings situate at a distance from the road axis of less than 3 times the height of the building;

- Category 3B is a special version of 3A, a typical 'street canyon', where there are much higher buildings on the sides of the road, additionally, the buildings situate at a distance from the road axis of less than 1.5 times the height of the buildings;

- Category 4 is a road with 'building on one side' but where the buildings are situated at a distance from the road axis of less than 3 times the height of the buildings.

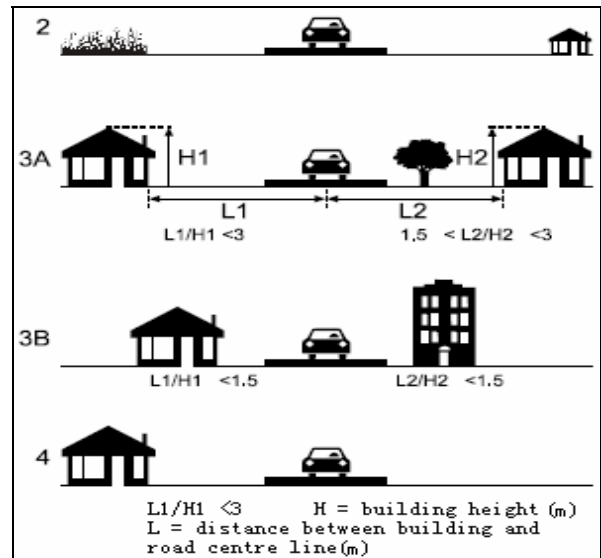Thus, each pilot study area represented a good example of one road type. The model was run for each road type.

Figure 5: Road type categories (Barelds, 2007)

The profile of the four pilot-study areas is provided by the table below.

Street name	Year of data	Surface area	L/H	Road type
Conjuction of Javastraat, Frederikstraat	2006	90 by 90m	≈1	3b
Koningskade	2006	90 by 260m	n/a	2
Conjunction of Prinsegracht, Brouwersgracht	2006	200 by 300m	≈2.5	3a
Neherkade	2006	80 by 150m	≈1	4

Table 2: Profile of pilot-study areas

3.2 Results

In The Hague measurements as well as the planar pollution models are commonly done at the standard measurement height of 3.5m for NO_2, and 3.2m for PM10. The modelled values for the standard measurement height are given in Table 3. A visualisation of the observation height is displayed in Figure 6, showing the building plinth (measured height) shaded in red beneath the pollution surface. In Table 3 it is clearly visible that for NO_2 the limit values for all four pilot areas are exceeded while for PM10 all four areas have values below the limit values. The horizontal variations of the modelled values at the standard measurement height are very tiny and in one case (for PM10, at conjunction Prinsegracht and Brouwersgracht) no variation is given by the model output.

Street name	NO$_2$ (µg/m^3)		PM10 (µg/m^3)	
	Limit value	Modelled Value	Limit value	Modelled value
Conjuction of Javastraat, Frederikstraat		60.45 - 60.50		33.72-33.73
Koningskade	40	60.58-60.63	40	33.72-33.73
Conjunction of Prinsegracht, Brouwersgracht		60.37-60.54		33.73
Neherkade		60.90-60.99		33.72-33.73

Table 3: Modelled result (annual average) for NO$_2$ at 3.5m and PM10 at 3.2m
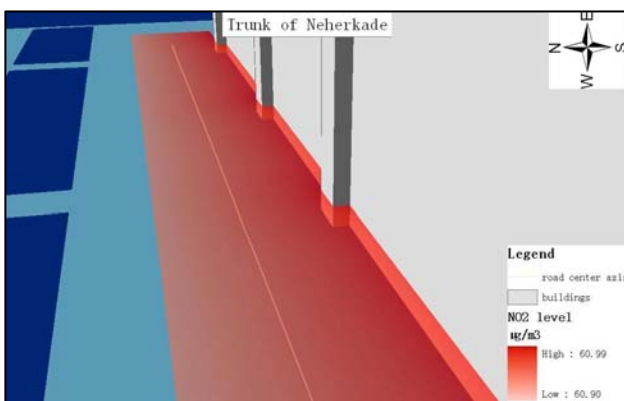
Figure 6: Observation height of NO$_2$

Figure7 shows an example of delineating hot spots of pollution concentration, even though the horizontal variation is not very pronounced. The selected colour ramp gives an easily interpretable output of where the highest pollution levels occur. Such information can be valuable to indicate where measures to improve the air quality are most needed, e.g. improvement of the air circulation.
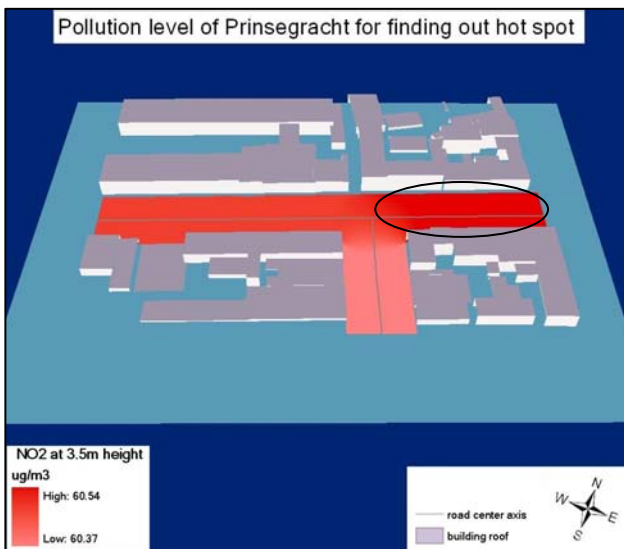

Figure 7: Pollution hot spot

Providing a non-planar view, pollution variations along vertical dimension are visible. The 3D visualisation of vertical pollution levels is achieved by projecting the interpolated pollution in raster format onto the sloped building facade. As can be seen in Figure 8, pollution levels are higher close to the building plinth. While upper floors of the buildings are affected by lower pollution levels, but still in the example given in Figure 8. The limit values are also exceeded for the upper floors.

In principle pollution isolines can be generated to be used as warning line indicating where the limit value is exceeded. By doing so, the height *(H)* where pollution exceeds the limit value can be easily identified. Consequently, the polluted surface area on street level and the part of the building facades where the value exceeds the limit can be found out. Number of raster cells below a particular isoline can be extracted, thus

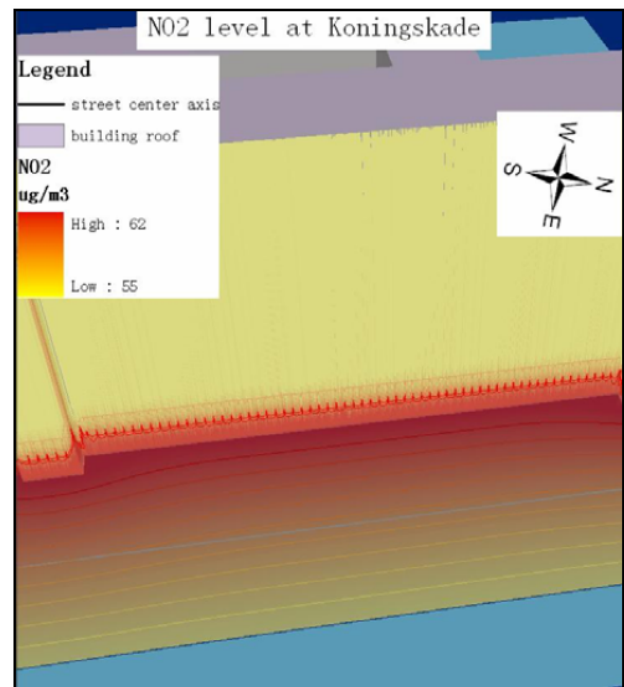$$raster\ cell\ size\ \times\ N = polluted\ area.$$

Figure 8: Pollution isoline

In addition, a warning line that represents where pollution limit value is exceeded can be used to calculate the number of floors affected as well as allow an estimation of the number of influenced inhabitants. Within the selected pilot study areas no such case could be found, since NO$_2$ exceeds everywhere the limit value. A fictive example is presented to demonstrate the implementation of a warning line (see Figure 9). This fictive example uses a much taller building (60m height), typical for Asian mega cities to illustrate the level of vertical pollution variation, in combination with adjusted traffic data of the case study area. The output of OSPM was again linked to the spatial database to allow a visualisation of a warning line at 17m height. In Figure 9 the area below and above the limit value is clearly indicated. Such information could be used in the design of new buildings, e.g. to provide for lower floors and air circulation system that gets fresh air from the upper parts of the buildings, if pollution levels are very critical on lower floors.
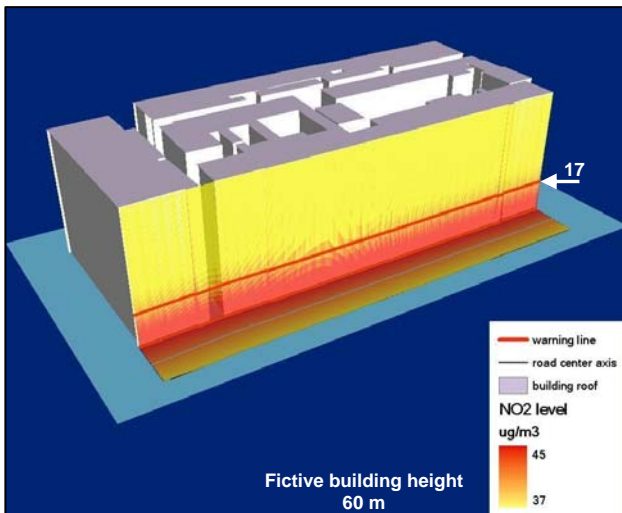
Figure 9: Pollution warning line

4. CONCLUSIONS

With pollution determined by OSPM, pollutants level can be linked with a spatial database and visualised in a 3D GIS environment. The 3D GIS environment enabled to visualize pollution levels in the form of maps, in both planar and non-planar view.

In planar visualization also the cubic building model is displayed to improve its interpretability, hot spots where the highest pollution occurs can be easily detected by representing pollution level using an appropriate colour ramp.

In non-planar view of visualized pollution over the street surface and buildings facades, pollution variation can be observed along the building facades. Pollution isolines can be generated over the street surface and building facades. A warning line can be extracted from the isolines, where the pollution is exceeding the limit value. Such a pollution warning line can help to better assess the critically affected areas. As well as it can be used to estimate the number of influenced inhabitants for (parts of the) building, street or neighbourhood.

The output of such models would be extremely useful for the design of new buildings as well as for the development of an entire area as it provides an easy tool for evaluating different design alternatives, including traffic circulation planning. Bottlenecks of urban micro air circulation where hot spots of pollution levels are expected can be easily detected. Further the level of expected air pollution on different floors can be assessed and design alternatives for air ventilation within high rise buildings proposed.

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ACKNOWLEDGEMENTS