Impact of Regulatory Measures on Pollutants Concentration in Urban Street Canyon – A Pilot Study

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Abstract. Many studies show the significance of transport-related air pollution in urban areas and its impact on human health. Implementation of technological improvements, low emission zones (LEZ) and more rigorous exhaust-emission legislations can lead to a decrease in the contribution of road traffic emissions. Query ID="Q2" Text="Please check and confirm if the corresponding author their email i have been correctly identified. Amend if necessary."

Numerical experiments were conducted using the Air Quality Management & Assessment System: ADMS-Urban, which is a comprehensive system for air quality modeling in urbanized areas. The main goal of this study is to assess the impact of regulatory measures on the pollutants' concentration fields in one deep street canyon, located in the central parts of Sofia city. One month period was selected for the modelled traffic scenarios. The year of 2018 was chosen for the base case scenario, and the cases with implemented LEZ were for 2026 and 2030 years.

The main findings of this study show significant reduction of NO_2 concentration when both measures traffic reduction with 20% and restriction on entry into LEZ of most polluting vehicle types are applied. The specific hourly and weekly traffic flow dynamics have to be taken into account for additional drop in pollution at the hot spots along the G. S. Rakovski str., bul. Vasil Levski and bul. Patriarh Evtimiy. This pilot study allows to build the basis of new methodology and demonstrate the use of numerical modelling capabilities in the process of selecting potential measures and giving recommendations for the decision-making institutions.

Keywords: Air pollution · Urban street canyon · Low emission zones effects

1 Introduction

The air pollution ranked 4th among the leading risk factors for premature mortality on a global scale – 6.67 million cases in 2019 (https://www.stateofglobalair.org/health/global). It is associated with both acute adverse health effects (e.g., higher risk of hospital admissions in people with chronic diseases on days when air quality is poor), as

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well as with chronic health impacts, even at low exposure levels (HEI 2020). Long-term exposure to high levels of air pollution in the residential environment has been linked convincingly to higher risk of respiratory (lung cancer, asthma, and susceptibility to infection), metabolic (diabetes mellitus), cardiovascular (hypertension, myocardial infarction, and stroke) and neurodegenerative diseases (dementia), as well as to adverse birth outcomes (preterm birth and low birth weight). Many studies show the significance of transport-related air pollution in urban areas and its impact on human health (Krzyzanowski 2005).

This study aimed to present the first steps in developing the basis of new methodology and demonstrate the use of numerical modelling capabilities in the process of selecting potential measures and giving recommendations for the decision-making institutions. Numerical experiments were conducted using the Air Quality Management & Assessment System: ADMS-Urban (CERC 2020), which is a comprehensive system for air quality modeling in urbanized areas, and it is developed and supported by the private organization Cambridge Environmental Research Consultants (CERC). The main goal of this study is to assess the impact of regulatory measures on the pollutants' concentration fields in one deep street canyon, located in the central parts of Sofia city. One month period was selected for the modelled traffic scenarios. The year of 2018 was chosen for the base case emission scenario, and four cases with implemented low emission zones (LEZ) for 2026 and 2030 years.

2 Methods and Input Data

2.1 Methods

The methodology used in this study includes high resolution air quality dispersion modelling (with 5 m), for limited domain with street canyons, coupled with the numerical results from a regional meteorological model and new developed sector emission inventories for road transportation. Five different emission scenarios were developed - so called "baseline" for the year of 2018 and four with implemented low emission zones for the years of 2026 and 2030 (Burov and Brezov 2022) in the central part of Sofia city.

Two types of data are necessary to run the ADMS-Urban system – meteorological conditions and road emissions. As was discussed in Dimitrova, and Velizarova (2021), the main deficits of the application of local Gaussian type models for air quality studies are coming from two main sources:

- the complex topography requires a more realistic flow field and a lot of additional meteorological variables for adequate air quality modelling, which cannot be provided by single point (like a single meteorological observational site);
- the emissions inventory from transport and domestic heating is the most uncertain part of the air quality modelling and new approaches, methods and tools have to be developed and applied for these sectors to reduce the discrepancy between measurements and modelling results.

2.2 Meteorological Input

We overcame the deficits discovered in the previous study by using the output from the Advanced Research version of the regional modeling system Weather Research and Forecasting Model ARW-WRFv. 3.9.1 (Skamarock et al. 2008), which can provide sufficient information for meteorological conditions at the exact location, where in-situ measurements are missing. The WRF model output delivers additional meteorological parameters like planetary boundary layer height, sensible surface heat flux, solar radiation and accumulated rain – variables missing at the measurement sites. These additional parameters significantly improve the description of the meteorological conditions, ensuring better air quality results. Special tool WRF to Met utility (CERC 2016) derived the meteorological conditions in the required format from the grid cell corresponding to the local area for ADMS-Urban run.

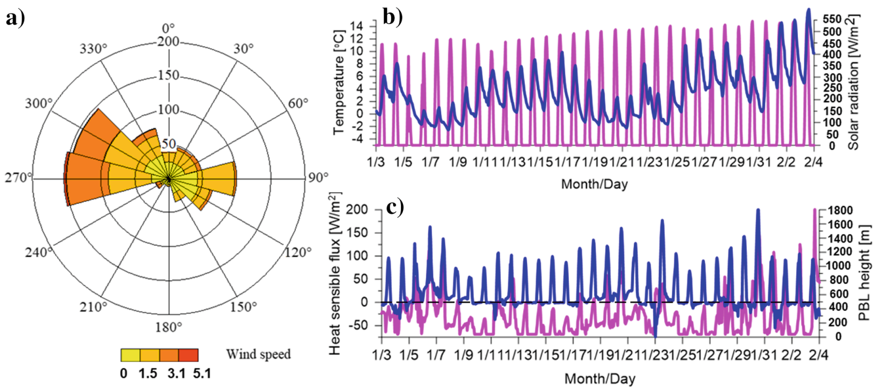

Fig. 1. Wind rouse (a) and time series of temperature (blue line) and solar radiation (pink line) (b) and sensible heat flux (blue line) and PBL height (pink line) (c).

One month of simulations are performed for January 3rd to February 3rd 2020. The period is characterized with dry weather, only several hours with light rain – less than 2 mm per hour (AMS 2020) were registered, and quiescent conditions. The wind speed was less than 4 m/s at 10 m height for the entire period, except several hours during the days 4th, 5th, 23rd, 29th, 30th, 31st January and 3rd February 2020. The maximum velocity during these days does not exceed 7 m/s (Fig. 1 a). Predominant winds for the area are from W and NWW direction with close to 150 occurrences during the one-month period and the highest wind speed, and E with 100 occurrences. These three directions cover more than a half of the cases. The solar radiation is less than 550 W/m^2 for the entire considered period, and the PBL height is less than 500 m for most of the time, indicating stable stratification and low turbulent mixing. For short periods, several hours during the day with higher wind speed, the PBL height increases above 1000 m (6, 7, 28, 30, 31 January and 2, 3 February 2020) indicating more dynamic weather. The negative sensible heat flux corresponds to stable conditions for several days in the beginning and the end of the period as well as 11th and 23rd of January.

2.3 Emissions Input

The methods applied to prepare the traffic emission inventory include a wide array of data gathering and processing as well as rapid traffic, activity and morphology mapping and modeling steps and techniques. The traffic distribution model takes into account the diverse characteristics of the street network and the spatial development of Sofia. The relatively large portion of missing data requires pre-processing (filtering) and phased imputation using a well-trained multivariable regression, preferably with optimally selected parameters. More details on the specific methods and tools that have been applied to the development of the transport emission inventory scenarios can be find in the paper of Burov and Brezov (2022).

The specific emission scenarios falling under predefined general assumptions are calculated through Atmospheric EMissions Inventory Toolkit – EMIT (CERC 2015) and relys on both fleet composition changes and urban plan provisions. EMIT provides annually averaged value of the emissions of different pollutants for each segment based on source activity data – traffic flow, type of vehicle, engine size and fuel, speed and source length of the road etc. The temporal allocation is made on the basis of daily, weekly, and monthly profiles, provided by Builtjes et al. (2003). The database, in the public domain, divides the vehicles according to the type - cars; light commercial vehicles (<3.5t); heavy commercial vehicles (>3.5t); buses; motorcycles, etc. It further divides the vehicles by engine size and fuel - petrol, diesel, methane, LPG (liquid petroleum gas), electricity. A final classification concerns vehicle technology – Euro 0; Euro 1; Euro 2; Euro 3; Euro 4, Euro 5 and Euro 6. The last classification is essential as it provides a lot of information such as year of registration, fuel consumption, engine wear, conditions and pollutant emissions. The lower classes (Euro 0; Euro 1) provide emissions greater than a new vehicle and the expected pollution is higher.

Baseline 2018 scenario uses the distribution of vehicles based on comparison and combination of data from Sofia Directorate of the Internal Affairs, Sofia Municipality Public Transport Directorate and other sources. The simulated potential measures cover restriction on entry into LEZ for Euro 0, Euro 1 and Euro 2 classes, when the nitrogen dioxide NO_2 concentration is in the range of 100 $\mu g\ m^{-3}$ to 150 $\mu g\ m^{-3}$; for Euro 0, Euro 1, Euro 2 and Euro 3 classes, when NO_2 concentration exceeds 150 $\mu g\ m^{-3}$; if the NO_2 concentration exceeds 150 $\mu g\ m^{-3}$ for three days the vehicles from Euro 0 to Euro 4 are banned from entering the LEZ, only electric vehicles from Euro 5 and Euro 6 classes can enter.

The four specific cases with implemented LEZ for 2026 and 2030 years represent restriction on entry into this zone for vehicles of different categories:

- Case 2026 with unaffected traffic (the same as for baseline 2018 scenario)
- Case 2026 with reduced traffic of 20%
- Case 2030 with unaffected traffic (the same as for baseline 2018 scenario)
- Case 2030 with reduced traffic of 20%

More details on different segments of the roads and the necessary input data are shown in chapter 3.2. ADMS-Urban model set-up.

3 Models Set-Up and Flows

3.1 Weather Research and Forecasting Model Set-Up

ARW-WRF is a state-of-the-art atmospheric modelling system, designed for a broad range of applications. Three nested domains based on a Lambert projection (Fig. 2 a) were used with resolution of 9 km – domain 1 (D1), 3 km – domain 2 (D2) and the innermost domain 3 (D3) with 1 km (Fig. 2 b). The model was implemented with 50 pressure-based terrain-following vertical levels from the surface to 50 hPa. The initial and boundary conditions were derived from the 0.25° NCEP Final Operational Model Global Tropospheric Analyses datasets (https://rda.ucar.edu/datasets/ds083.3/) available every 6 h. Data assimilation (fdda model option) was used for the outermost domain D1 for all vertical levels. We did not apply data assimilation for the intermediate domain D2 and the innermost domain D3 (Sofia Valley).

The selected case study covered 31 days (3rd January –3rd February 2020) with an additional 24 h of spin-up. The WRF physics package included the new version of the Radiative Transfer Model parametrization (Iacono et al. 2008) for longwave and shortwave irradiance to compute radiation at every 5 min; the Noah land surface model (Chen and Dudhia 2001); and the Kain-Fritsch cumulus parametrization, for D1 only (Kain 2004). The same domain has been tested with different planetary boundary layer (PBL) and moisture schemes for several previous studies and have been validated (Egova et al. 2017; Vladimirov et al. 2018; Dimitrova et al. 2019; Kirova et al. 2021). Based on our experience, Shin-Hong PBL scheme (Shin and Hong 2015) with revised MM5 surface layer scheme (Jimenez et al. 2012) and the National Severe Storms Laboratory (NSSL) moisture parametrizations developed by Mansell et al. (2010) have been selected in this study.

3.2 ADMS-Urban System Set-Up

ADMS-Urban (CERC 2020) is a practical short-range dispersion model for modeling a wide range of buoyant and passive releases to the atmosphere. The model is being used across the world for air quality management and assessment studies of complex situations in urban areas, and in proximity to motorways, roads and large industrial areas (Stocker et al. 2012; Hood et al. 2018; Biggart et al. 2020; Dimitrova and Velizarova 2021).

The coordinate system used in this study is WGS 84 UTM zone 34N (epsg:32634) with grid resolution of 5 m (Fig. 2 c) and 28 vertical levels. The area consists of 44 streets and boulevards (included full or partly) divided in 160 road segments, which are located in the center of Sofia city (Fig. 1 c). Most of them (27 streets or 61%) represent a typical street canyon structure with aspect ratios $H/W > 0.65$, where H is the average height of the buildings, W – canyon width. Those segments are described, within the model, as road sources, with the emission height adjusted to account for the range of heights of vehicle emissions, and the horizontal turbulence describes the additional traffic-produced turbulence (CERC 2020).

In order to describe the road sources more accurately, the Advanced Street Canyon module option in network mode was used. This module can model the channeling of flow along a street, can represent asymmetric canyons and the effect of pavements within the canyon, and can calculate the effect of a street canyon on the surrounding area. The complex terrain option applies 3D flow and turbulence field to the dispersion model, which modifies the plume trajectory and its dispersion, in order to account for the disturbances in the air flow, originating from the topography of the area. Dry and wet deposition processes are included.

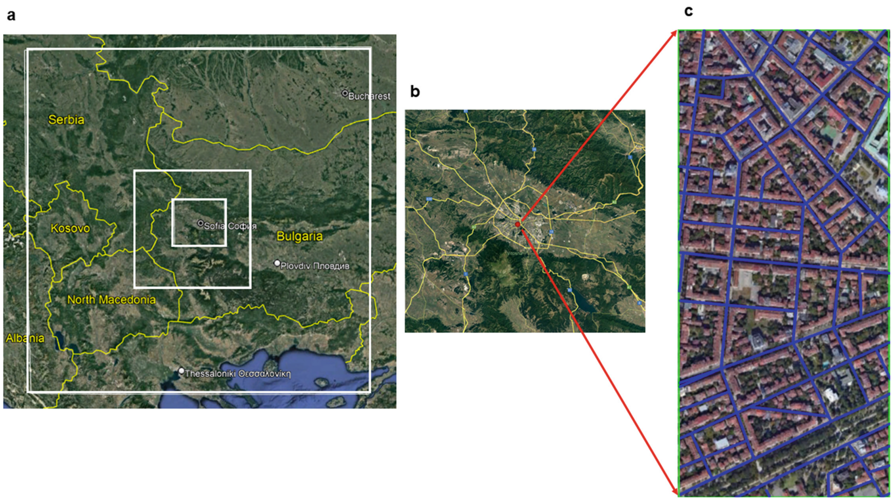

Fig. 2. Area of simulations with the WRF model – all domains (a) and the innermost domain D3 with 1 km (b); domain used for the ADMS-Urban model with 5 m grid and all simulated roads included.

4 Results and Discussion

Model verification was made using monthly mean concentration values of NO_2 at the measurement site G. S. Rakovski str. №193. The measurements were made at 2.5 m height. Greenpeace volunteers, with help from the organization Deutsche Umwelthilfe, have installed and assembled small diffusion tubes containing a chemical substance (triethanolamine), which is absorbing the measuring component (NO_2). After measuring 31 days, the tubes were sent to the Passam AG Laboratory in Switzerland to provide results (LANUV 2015). Full description of the analyses is available in the report of non-profit civil society organization "For the Earth" (2020). Figure 3a shows the monthly mean concentration of NO_2 at the measurement site with location marked on the map (Fig. 3b) near the crossroad between bul. Vasil Levski and G. S. Rakovski str. Numerical simulations were performed for the same period as for the small diffusion tube collection – from 3rd January to 3rd February.

The obtained modelled values of NO_2 for the baseline and the four different scenarios are presented in Table 1. The concentration for the baseline scenario corresponds to the

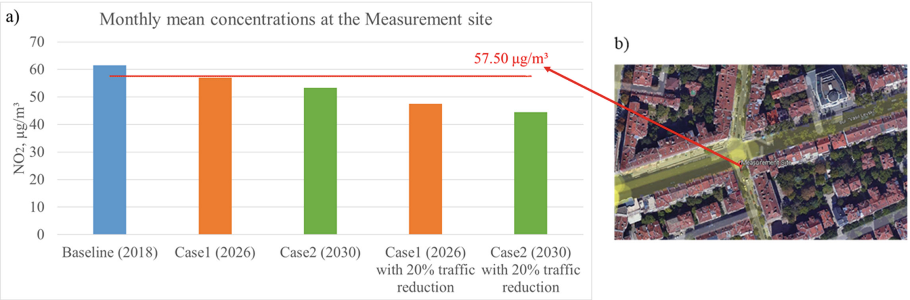

Fig. 3. Monthly mean concentration at the measurement site G. S. Rakovski str. №193 (at 2.5 m height) (a) and location of the site (b).

Table 1. Description of different cases used in simulations.

Scenario	NO_2 µg/m^3
Case 2018 Baseline	61.52
Case 2026 - unaffected traffic	56.99
Case 2026 - 20% reduced traffic	53.39
Case 2030 - unaffected traffic	47.49
Case 2030 – 20%reduced traffic	44.49

real emission inventory and show 61.52 µg/m^3 or slight overestimation of the measured value of 57.50 µg/m^3.

The impact of regulatory measures on the pollutants' concentration fields in a deep street canyon can be seen in Table 1. The monthly mean concentration decreases for both years (2026 and 2030), with more considerable reduction of 14 to 17 µg/m^3 for the cases with 20% traffic reduction compared to the cases with unaffected traffic, where the reduction is approximately between 4 to 8 µg/m^3 for each case, respectively.

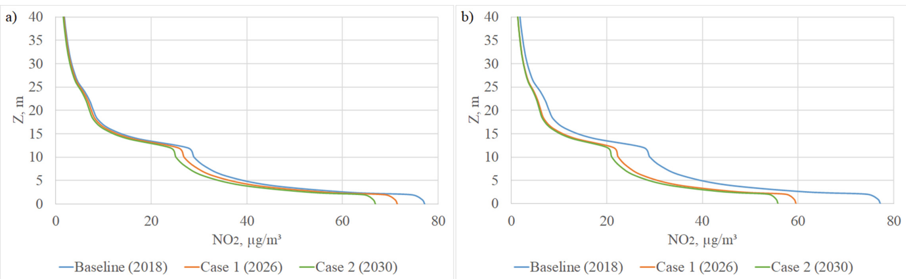

Fig. 4. Monthly mean vertical profiles of NO_2 concentration at the measurement site without traffic reduction for Case 1 (2026) and Case 2 (2030) (a) and with 20% traffic reduction for Case 1 (2026) and Case 2 (2030) (b).

The monthly mean vertical profiles (all data for the period are averaged at the given level) of the NO_2 concentration at the measurement site for the baseline and the four emission scenarios are presented on Fig. 4. For the cases with 20% traffic reduction (Fig. 4b) the concentration is considerably lower than the baseline (2018) and the two cases with unaffected traffic (Fig. 4a). The differences between the baseline and the two cases for 2026 at the ground-level are approximately 5 $\mu g/m^3$ with the unaffected traffic and 17 $\mu g/m^3$ with 20% traffic reduction. For the cases of 2030 the decrease is approximately 10 $\mu g/m^3$ with the unaffected traffic and 20 $\mu g/m^3$ with 20% traffic reduction. A slight increase of the concentration at approximately 12 m height might be due to the formation of recirculation zone inside the street canyon. G. S. Rakovski str. is a typical narrow street canyon with averaged ratio of 2.21 that is favorable for vortex formation inside the street (Oke et al. 2017).

Hourly monthly mean profiles of NO_2 concentration averaged over the entire domain (Fig. 5) can represent the general traffic dynamics for the central part of Sofia city. Different scenarios for 2026 (Fig. 5a) and 2030 (Fig. 5b) are compared with the baseline scenario. The NO_2 concentration for the cases with 20% traffic reduction are lower than the concentration for the baseline and the two cases with the unaffected traffic. There are also two strongly pronounced peaks in the concentration at 8 a.m. and between 5 p.m. to 6 p.m., which corresponds to the rush hours related to travel to and from work.

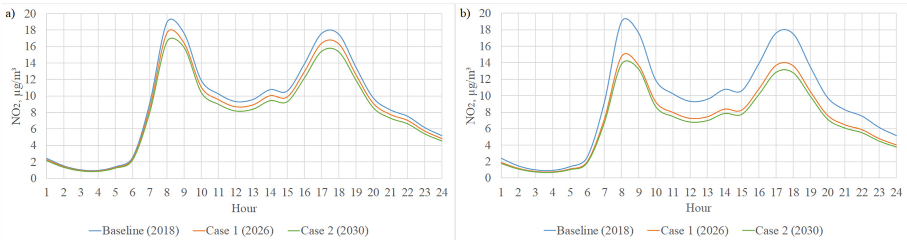

Fig. 5. Hourly monthly mean profiles of NO_2 concentration averaged over the entire domain with unaffected traffic for Case 1 (2026) and Case 2 (2030) (a) and with 20% traffic reduction for Case 1 (2026) and Case 2 (2030) (b).

Comparison between the hourly monthly mean profiles of NO_2 concentration averaged over the entire domain by weekday for the baseline (2018) and differences between the baseline (2018) and Case 1 (2026) as an example is shown in Fig. 6. The concentrations are lowest during the weekend, which significantly affects the concentration (two times less at the rush hours) and are highest at 8 a.m. for Fridays and between 5 p.m. and 6 p.m. for Wednesdays (Fig. 6a). The difference in concentration is almost 3 times greater using emissions with 20% traffic reduction (Fig. 6c) than the unaffected traffic cases (Fig. 6b). The values are 1.9 $\mu g/m^3$ with unaffected traffic and about 6.5 $\mu g/m^3$ with 20% traffic reduction for Wednesdays, where the greatest differences occur.

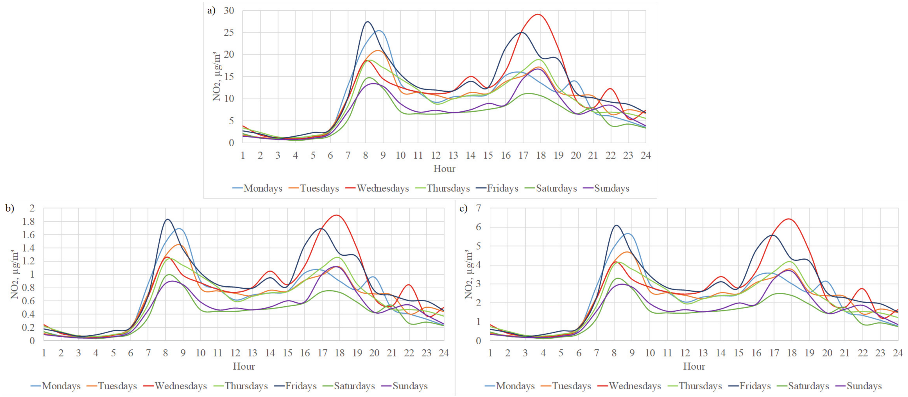

Fig. 6. Hourly monthly mean profiles of NO_2 concentration averaged over the entire domain by weekday for the baseline (2018) (a), differences between the hourly monthly mean profiles of NO_2 concentration by weekday for the baseline (2018) and Case 1 (2026) without traffic reduction (b) and with 20% traffic reduction (c).

Monthly mean horizontal surface concentration field of NO_2 for the baseline and differences between concentration for the baseline and both cases (2026 and 2030) without and with 20% traffic reduction are shown in Fig. 7. The highest concentrations of NO_2 are along G. S. Rakovski str., bul. Vasil Levski and bul. Patriarh Evtimy and range from 50 $\mu g/m^3$ to 200 $\mu g/m^3$, except at the crossroads, where the values exceeded 200 $\mu g/m^3$ (Fig. 7a). Wind from NWW and E directions covers more than a half of the cases, and the wind is approximately perpendicular to the middle part of G. S. Rakovski str., between bul. V. Levski and W.Gladstone str.. The heavy traffic on V. Levski and Patriarh Evimiy boulevards and the predominant wind direction are most likely the reason for the very high concentration.

The greatest differences for all of the considered cases are located along the same roads and crossroads. For unaffected traffic the differences in the concentration values between baseline and 2026 emission scenario reach 10 $\mu g/m^3$ (Fig. 7b), for the 2030 emission scenario reach approximately 25 $\mu g/m^3$ at the crossroads and along the segment between Racho Dimchev str. And Graf Ignatiev str. (Fig. 7c). The differences between the baseline and the scenarios with 20% traffic reduction reach values between 15 (for 2026) to 35 $\mu g/m^3$ along the roads and above 60 $\mu g/m^3$ at the two crossroads. We can also conclude that the measures with additional traffic reduction affects more significantly the pollution reduction inside the street canyon.

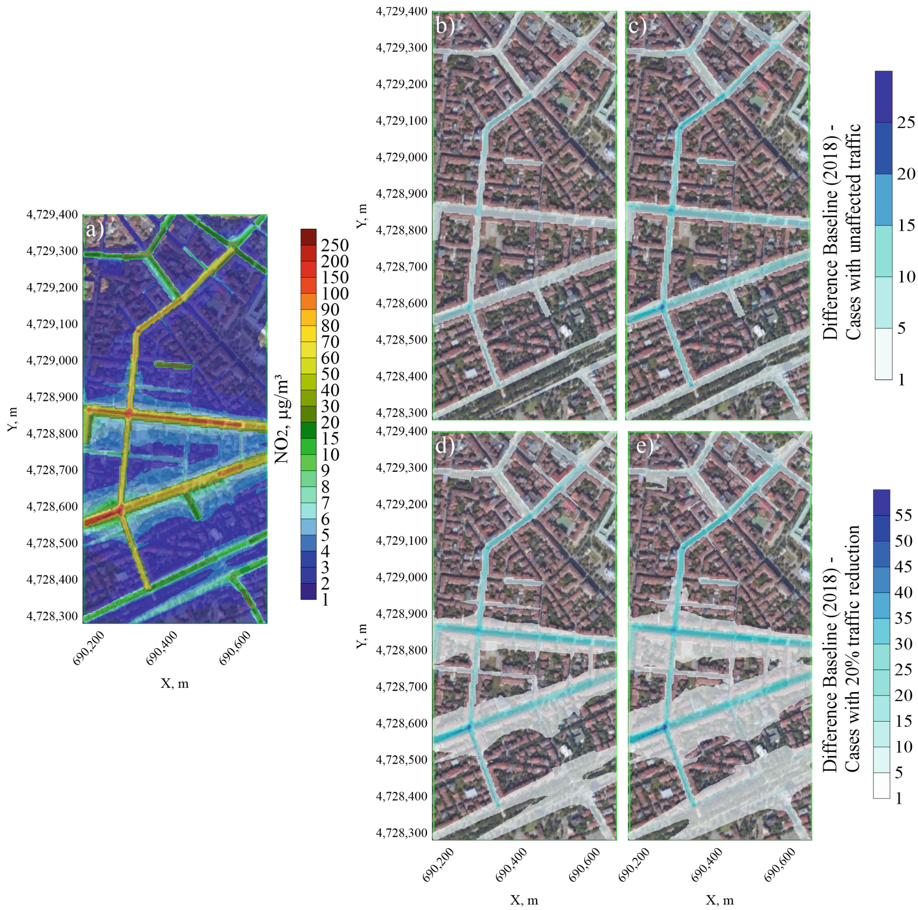

Fig. 7. Monthly mean horizontal surface concentration field of NO_2 for the baseline (2018) (a), differences between the monthly mean concentration field of NO_2 for the baseline (2018) and Case 1 (2026) with unaffected traffic (b) and with 20% traffic reduction (d) and the baseline (2018) and Case 2 (2030) with unaffected traffic (c) and with 20% traffic reduction (e).

5 Conclusions

This work is a pilot study and presents the first steps in developing the basis of new methodology. The results show the numerical modelling capabilities in the process of selecting potential measures and giving recommendations for the decision-making institutions. Some general conclusions are difficult to be made based on only one month of simulations, but the main findings in this study are summarized below.

- Model verification shows slight overestimation by the model of monthly mean concentration values of NO_2 by approximately 7% at the measurement site, located at G. S. Rakovski str. №193 (at 2.5 m height).

- Additional traffic reduction with 20% leads to two times lower pollution compared to the cases only with restriction on entry into LEZ of most polluting vehicle types.
- Two prominent peaks in the NO_2 concentration around 8 a.m. and 5 to 6 p.m. correspond to the rush hours related to travel to and back from the offices.
- The hourly dynamics of different days of the week is different, with the lowest traffic during the weekend, which significantly affects concentration (two times less at the rush hours).
- The greatest effect from the LEZ implementation in the simulated domain occurs along the G. S. Rakovski str., bul. Vasil Levski and bul. Patriarh Evtimiy, and this effect is most prominent at the crossroads between those roads.
- In spite of the described measures, expected concentrations remain high at this locations, more than 150 $\mu g/m^3$ and require further investigation and probably application of more strict measures.

Presented study demonstrates the promising abilities of the new methodology, which includes high resolution air quality dispersion modelling (with 5 m) for limited domain with street canyons, coupled with the numerical results from a regional meteorological model and new developed sector emission inventories for road transportation. It is a useful tool that allows for simulation of different scenarios for future emission reduction and can help authorities with decision making. Some deficits of the study also have to be pointed. The lack of ground air quality data to assess the air quality at street level makes more extensive model verification a difficult task. Data from AQS Pavlovo is used to estimate the ratio between NO_2/NO_x which is very high – 0.67, and it can be a possible reason for the average monthly value overestimation by the model of 4 $\mu g/m^3$. Measurements at more traffic sites are needed to estimate the real traffic structure and ratio between NO_2/NO_x. More simulations are necessary to cover the entire 2020 year in order to compare the modelling results with the annual limit values for the protection of human health of 40 $\mu g/m^3$. And finally, the extended modelling domain, covering Sofia municipality, will ensure more reliable results for air quality related to the road traffic in the entire highly urbanized area. All these points will be investigated in our future studies.

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