Transport Emissions from Sofia's Streets - Inventory, Scenarios, and Exposure Setting

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Abstract. The present study aims to demonstrate high quality traffic emissions inventory in Sofia city serving as an input for dispersion modeling and simulations through baseline and scenario development juxtaposed to exposure characteristics of the urban environment. The spatial scope of the study is the compact city of Sofia. The baseline year is 2018 and the scenario development is up to 2030 with several reference years in between. The methods applied 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 diverse characteristics of the street network and the spatial development of Sofia. The utilized traffic data is from various sources with poor integrity. In order to obtain a relatively good estimate of the average annual daily traffic for the entire city street and road network, data interpolation and machine learning regression models are tested through QGIS and Python. The relatively large portion of missing data requires pre-processing (filtering) and phased imputation using a well-trained multivariable regression (we found the Random Forest Algorithm to be an excellent choice), preferably with optimally selected parameters. As the latter may differ in the analysis of the main traffic arteries, the primary and the secondary street network, we study each of the clusters separately, allowing given predictions to propagate down the hierarchy. Further on the space-time activity model stems from land use and functional analysis of points of interest with differentiation of the presence of mobility modes and people throughout time. The urban morphology and surface modeling makes use of the Street Canyon Tool from CERC implemented in ArcMap environment as well as the UMEP plugin and other native tools in QGIS. The specific emission scenarios falling under predefined general assumptions are calculated through CERC EMIT and rely on both fleet composition changes and urban plan provisions. The paper raises an array of issues for discussion over the results through the link between emissions generation and exposure settings changing under different conditions as a preliminary step towards spatially and temporally differentiated health impact evaluation. A major conclusion is that the specific configuration of urban street canyons and traffic load in the city impose varying degrees of impacts and risks from the transport sources which need to be addressed by more specific scope and design of measures that can prevent public health in an efficient and equitable manner.

Keywords: Traffic · Inventory · Scenarios

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1 Introduction

Most urban dwellers of cities today in global terms are exposed to dangerous levels of air pollution from a cocktail of sources and chemical species, fine and ultrafine particles. This continues to be one of the major challenges for the urban environment in the light of public health [1].The Sustainable Development Goals address directly the challenge through two goals, three targets and related indicators [2], namely: a) Goal 3 “Ensure healthy lives and promote well-being for all at all ages” with Target 3.4 “By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being” and the Indicator 3.4.1 “Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease”, as well as with Target 3.9 “By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination” and the Indicator 3.9.1 “Mortality rate attributed to household and ambient air pollution”; b) Goal 11 “Make cities and human settlements inclusive, safe, resilient and sustainable” with Target 11.6 “By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management”, and the Indicator 11.6.2 “Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)”. The indicators are monitored in general through various statistical and environmental screening tools, but the more fine resolution picture for every particular city is only available if ambitious scientific methods and applied techniques are in place to link statistics, inventories, models, measurements, surveys, etc. into integrative reliable instruments for support of planning and decisions on the path of achieving the global, national and local goals.

The study of the background levels of emission concentrations has advanced a lot in the last decades but the fine grained picture for many cities isn’t that close to become available in due time because of lack of reliable measurement, inventory and modeling systems in place. Different tiers of inventories as well as physical and health modeling techniques exist that can predict relatively well at a reasonable cost the dispersal and exposure to pollutants [3]. At the base of such approaches is an array of geospatially referenced data sets. These can vary depending on the tools and techniques but it can be said that more comprehensive databases can be much more precise in revealing the patterns and how they are overlaying and interplaying. South-East European cities are the most affected by the air pollution problem in Europe and are among the World hotspots [4, 5]. Many of the Bulgarian cities are at the top of the list of polluted cities in the EU and it is important to say that this is not due to heavy industry as it was in the past but to domestic heating and transportation [6]. Sofia, the capital and biggest city with its almost 1.5 million citizens and visiting commuters and tourists is the most polluted capital in the EU. There are many underlying cumulative reasons both natural and anthropogenic which overlap as various sources and make its situation complicated and challenging for understanding and adequate policy making. The amalgam of building morphology and street network patterns with varying degrees of roughness and porosity of the urban tissue shape the many types of urban street canyons and other situations of poor ventilation. The growing polycentricity, the densification of secondary mixed use centers and parallel contrasting advantaged and disadvantaged new peripheral suburban development which is often called ‘muddy’ with missing public works, altogether add to the factors behind pollution and its distribution in the cityscape. The lagging behind and low quality public rail and road works and maintenance provoke the deepening car dependence and the vicious cycle of growing motorization rate along with many critiques to the development of the public transport and neglected shared and light mobility and access modes of travel.

The mixture of sources leads to high concentration of air pollution and numerous exceedances of the limits throughout the last decade that provoked debates on where to start from in resolving the issue, which sources of pollution to blame for, to regulate and invest into them to comply, hopefully following the results of reliable and focused research. Various modeling [7] and apportionment measurement [8] studies have shown different picture of the contribution from the domestic heating, transportation and other sources depending on the methods, data and spatial scope applied. Several generations of official inventories of the traffic emissions fall in the first tier as they do not step on the basis of actual transport model and rely on very rough estimates [9]. Bias is unavoidable when there are many data and knowledge gaps and lack of cross validation or shared baselines used. The question remains open in terms of more comprehensive studies and verification investigating the changing pollution patterns in the city space. This piece of research which is linked to other experiments and future steps in development provides first insights in an integrated approach and methods starting from steps of provision of a baseline towards more in-depth modeling, verification and evaluation of impacts.

2 Research Framework, Materials and Methods

The more general aim of the research is the link between air pollution, health and urban development while here in the focus is the improved inventory of transport emissions with the help of rapid traffic modeling, the elaboration of scenarios for the fleet in the context of implementation of measures and spatial development, and the exposure setting relying on estimates from a model of activities in Sofia city. Further on the research framework includes measurements; numerical experiments in the field of dispersion modeling; epidemiological survey and longer term spatial development scenarios with their health related aspects.

One of the biggest challenges at the base is the quality of the underlying traffic and fleet data. It comes from various sources with poor access to the more complete sets, no integrity and many methodological mismatches in the data gathering approaches. It is a typical practice led fragmentation stemming from the sectorized institutional silos. The scarce public access to traffic count data and the lack of actual municipal level transport model are the results from this fragmentation. There are rich data sets made available through the open data access from a municipal enterprise [10]. With the help of own data gathering and various processing steps for matching of diverse geometry, attribute data and methods the research tries to bridge the available resources. Thus the need for time and cost efficient approach is pressing and the answer is through performing the most steps by using public accessible data and open source software which has the ambition to demonstrate a pathway which out beats the public spending boulevard to the urban knowledge arena for the air pollution discourse and contemporary choices.

2.1 Materials and Methods for Rapid Traffic Modeling and Emission Inventory

As key input for traffic modeling we use data for key boulevards and junctions, various types of streets in Sofia from several sources at our disposal: measurements provided by the municipality and its planning enterprise from single days in 2017 and 2018 for almost 40 junctions, car count geolocation sample along the street network for the entire 2018 and 2019 (part of the street network) [11, 12], previous and next traffic count campaigns from consultancies [13, 14] covering sets of primary or secondary streets, and the Open Transport Model [15]. For the visualization and analysis of the available data we use both QGIS tools and Python modules.

Several additional factors are considered, including space syntax (choice and integration) performed with depthMapX, functions distribution (points but also buildings and areas of interest) and population density with coefficients of the motorized share of users' and dwellers' mobility mode. After applying properly tuned heat maps in order to 'smear' the point data across the grid, we select an optimal set of features based on correlation. The data is then conveniently normalized, calibrated and clustered in preparation for the ML techniques we resort on in the following stages of our work.

2.2 Materials and Methods for Fleet Inventory and Scenario Development

The fleet baseline inventory steps on one dimensional fleet stratification available as input data, distributed by general vehicle typology, type of fuel, engine size, EURO category, year of production and availability of filters [16, 17]. This available data is then juxtaposed through an Analytical Hierarchical Process to the CERC EMIT most complete and differentiated database with the help of Excel for intermediate calculations. Thus the matching is performed with minimum expected deviation due to the association and uncertain distribution for some sub-categories. The NAEI2014 Urban 2014 version 2 is used as the closest possible database to the emission performance of the fleet in Sofia and Bulgaria at the baseline year 2018. We are assuming that the older fleet in Sofia corresponds to that previous year in the database. It consists of almost 550 sub-categories based on multi-dimensional stratification including the fuel types (Zero Emissions Vehicle, Petrol, Diesel and LPG), Vehicle types (Passenger vehicles, LGV N1 (I, II, III), HGV (rigid, artic) (diesel), Bus, Coach (diesel), Moped and Motorcycle (petrol)), engine volume and vehicle weight types (2.5 tonnes ($<$1400 cc, 1400–2000 cc, 2.5 tonnes), 3.5–7.5 tonnes, 7.5–12 tonnes, 12–14 tonnes), EURO standard types (Pre-Euro 1, Euro 1, 2, 3, 4, 5, 6, Hybrid), cleaning technology types (incl. Particle Trap, Failed Catalyst).

The rich subdivision of the fleet types allows for detailed elaboration of various scenarios for the years 2022, 2026 and 2030. The predefined general assumptions are reflected into the fleet composition changes, especially the shifts in the ratio of EURO standard and cleaning technology types. They are considered to be dependent on the natural substitution rate of the fleet, which is relatively slow for Bulgaria and Sofia, and the substitution is driven by the urban plan provisions and regulations, especially the introduction of low emission zones. Media publications about the intentions of Sofia Municipality shaped the business as usual scenario, which includes an internal ring and an external ring with a temporary, seasonal ban on entering the LEZ with vehicles from the ecological classes 1 and 2 [18]. Additional proposals from consultancies [19] and non-governmental organizations [20] are also considered, compared and constructed as scenarios through time.

2.3 Materials and Methods for Urban Morphology Modeling

The urban morphology and surface modeling makes use of the Street Canyon Tool from CERC that is implemented in ArcMap environment. The basic parameters for definition of the canyons are used, whereas the building distance tolerance (proportion) is 0.3, the building distance tolerance (meters) is 14 m, the precision mode is for EMIT, the target minimum proportion of road with buildings is 0.4 and the maximum distance to the nearest building is 50 m. Additional maps for analytical purposes are produced with the help of the UMEP plugin and other QGIS tools which include digital surface model, sky view factor and other visualization oriented layers and properties settings.

2.4 Materials and Methods for Activities Modeling

In building the model of activities, which is space-time differentiated, a series of assumptions were made for the spatial load of people and share of mobility modes based on land use types, the surface area and the built-up gross floor area (GFA), the concentration and significance of points of interest and functions [21] and their share in the GFA, statutory and regulatory norms of the area dedicated to the number of residents and users (employees and visitors) [22, 23], as well as own analysis and assessment of the objects functional hierarchies based on registers, statistics and observations. The temporal aspects are addressed by differentiation of the presence of people and their mobility modes throughout time of the day, week and season in the different groups of functions and land uses. The groups relate to housing (housing stock), labor activities (economy and economic base, science and innovation), recreation (culture, recreation and tourism, green system and sports), services (social infrastructure, administrative and office buildings and services) and communication (transport and communication infrastructure).

3 Results

3.1 Rapid Traffic Modeling, Fleet and Emission Inventory, Scenarios and Urban Street Canyons

The results from the search of factors and algorithms that can support a reliable rapid traffic modeling with the use of available data with poor integrity have led to many experiments and intermediate results (Fig. 1a). Up to this point for the case of Sofia we have reached a satisfactory solution which seems to be promising for answering similar tasks elsewhere when trying to overcome data related obstacles.

Comparing various machine learning (ML) algorithms for data imputation, we found out that the Random Forest regression outperforms them all in this particular task by a large margin [24, 25]. Some of the most obvious reasons are that: a) it is a collective

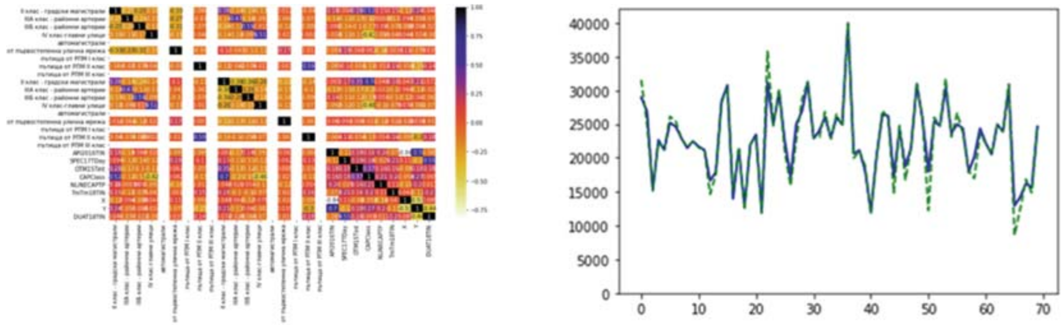

Fig. 1. a) The correlation matrix of features used in the model, filtering out a part of the street network (in this case, parts of the inter-city primary boulevards and streets; b) Comparison between measured and predicted values for the test data.

iterative method, which gives it a lot of flexibility, especially when dealing with mutli-dimensional unorganized noisy data as in our case; b) it is much less prone to overfitting that is a major concern for such problems; c) it is much less sensitive to scale, e.g., it does not require data pre-processing. The overall result is accuracy reaching up to 95–96% in certain phases of prediction, or around 90% using the cross-validation score for the standard 'r2' (r square) parameter (Fig. 1b). The standard deviation is also pretty decent: up to 3–4% for the most 'well-behaved' data, but these estimates quite expectedly get worse as we attempt to predict a bunch of values using only a handful of measurements (10% or less). To address this issue we use the old Roman 'divide et impera' principle starting with the major traffic arteries where we have most of our measurements and the missing values can be predicted with great accuracy as already pointed out. Then, we use the Random Forest regression model to update some of the features that are highly correlated with the traffic data for the next phase which focuses on medium size streets still bearing a lot of traffic, especially during rush hour. Finally, after another round of updates we handle small streets and far from the city center districts. The advantage of this approach is that we allow the ML algorithm to be trained for a specific task giving more weight to different features for different phases of the data imputation (this may easily be seen using the SelectKBest function in Python) avoiding both over- and under-fitting.

For the last phase we combine interpolation and regression techniques as the data is too scarce. Besides, small streets cover a wide range of districts with different dynamics, so additional clustering has been used. Here the reliable predictors naturally differ from those applicable to large boulevards, having more to do with population density for example. Although the accuracy in this phase drops significantly to 70–80%, these predictions are still sufficiently useful and may further be calibrated with the aid of additional data. Moreover this part of the city network accounts for less overall traffic.

The modeled traffic in the points of the crossings is then returned to the street network vertices via interpolation and is halved where the street line represents one direction. The ratio of motorcycles, light and heavy vehicles is estimated by point data from historical counts and is interpolated class by class which is especially relevant for the heavy traffic on the primary transit roads and boulevards versus the minor roads. The additional input data for the elevation, width, canyon height, surface and gradient needed for EMIT is produced in QGIS thanks to available attributes, layers from publicly accessible open or free data and own editing. The calculations in EMIT are returned to QGIS via shp and dbf files (Fig. 2).

Fig. 2. Amount of PM10 emissions along the: a) primary network (lines and g/km2/s); b) the secondary one (cells and t/y)

These emission and fleet inventory results are supplemented by more detailed description of the urban street canyons in the case study for "G. S. Rakovski" Street which is a more in-depth example representing focused, interrelated methodological steps with additional high resolution meteorological and dispersion modeling showing rich results at various receptor levels and in the light of part of the developed scenarios [26].

What the bigger picture shows is that transit and congested boulevards, denser networks of service streets in the center, at some of the secondary centers and most populous districts have the highest share of emissions and they have to be targeted by complementary measures to diminish the generation, concentration and dispersion of the emissions towards vulnerable areas and population groups. The urban street canyon phenomena is spreading beyond the central part of the city towards some of the most populated and visited areas in the city and it is a strong determining, structural factor for higher concentration of polluters and exposure to them if activities take place in and around.

3.2 Activities Modeling and Exposure Setting

The activity modeling results provide the opportunity for estimation and visualization of the concentration of people indoor and outdoor in comparison to traffic, transport emissions generation, air pollution dispersion, as well as to geo- and urban morphology, land cover and land use in typical peak hours, day and night time, working and weekend days, occupation and vacation times of the year, along with specific episodes of pollution. The typical day and night time location of people are visualized by heat maps with 500 m radius based on the points of activities (Fig. 3a and b).

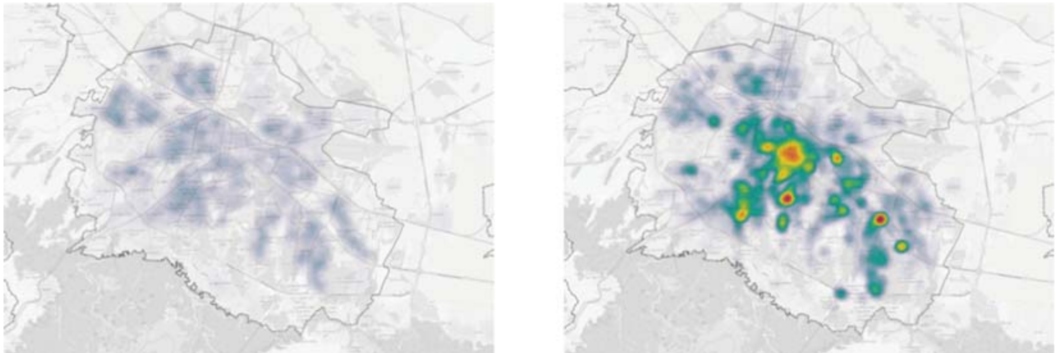

Fig. 3. Modeled activity concentration heat maps with radius 500 m: a) residents; b) users

It is important to comment that the daily activities of the city host bigger and more concentrated number of employees and visitors from the city, its suburbs, towns and cities from the functional urban area, the whole country and beyond. Different coefficients may apply for the simultaneous presence of people indoor, outdoor and in or around the various means of transportation and mobility modes.

The historical core is the major center, vast in terms of territory with higher concentration of people. There are several strongly concentrated secondary centers in between more populous and more often more prosperous neighborhoods, which like the major center attract employees and visitors from the whole city and beyond. Tertiary centers are merged in the high density Socialist housing estates, additionally filled in and built up in the recent decades and also inhabited by smaller businesses, often concentrated at the entry points from important intermodality transport hubs and junctions. These preliminary results need further spatial-temporal differentiation for more in-depth exposure setting evaluation.

4 Discussion

The attempt to construct and develop an integrative air pollution methodology is a challenging endeavor and the experience from the undertaken steps in this research points to the need for more supportive policies behind – scientific, environmental, health and urban related. Nevertheless, the approach provides first fruitful results which can be improved in many ways for the sake of truth and utmost possible proximity to real life flows and impacts from transport emissions. The rapid traffic modeling and emission inventory can become more and more precise through classical four-step transport modeling combined with activity based, machine learning, artificial intelligence, real-time, agent based, etc. approaches developed by the public sector and academic, business and civic partners. The access to data and information is a constraint at the doorstep, so platforms for shared basic models, aggregated information from population (incl. Health status), businesses (incl. Number of employees) and polluters (incl. Vehicle, heating types) registers at the appropriate scale is a must for excellence in this practical political-ecological field. Data warehouses, fleet censuses, and free spatial extents query above the confidential or personal information minimums can be truly beneficial for acceleration of the experiments and policy tests. In following version of this traffic model, additional ML techniques are envisaged to be used in order to fine tune the various data sources, minimize the noise and fill the gaps.

The fleet scenario development can be improved by more specific econometrical studies taking into account the market and regulative environment and changes into it, the pace of the culture of transition to alternatives beyond the conventional travel modes, especially the everyday car use and the uptake of various more suitable vehicle types and energy sources. National, regional and local real emission factors and surveys for the non-exhaust emissions in relation to the vehicle weight, the road and atmospheric conditions can be very helpful for the calibration and strong validation of models and simulations. Registration and degree of everyday and yearly use and maintenance of vehicles may differ, including in cumulative terms from area to area in and around the cities, so monitoring vehicle cohorts can have high added value to research but also to the proper design and scope of regulative measures.

The urban morphology modeling is a prelude to the fine resolution dispersion modeling in ADMS-Urban but also a long term environmental factor which needs to be addressed by strategic and operational urban planning and design, public works and public space management with the vision to avoid excessive exposure, to prevent diseases and to promote active mobility and healthy lifestyles. The activities modeling is very helpful for the understanding of the general exposure picture and the more detailed subdivision temporal and presence types would allow for much more relevant studies of the exposure dose and effect, the particular risks at different sites associated with vulnerable demographic, lifestyle, professional and health status groups. Altogether with improved navigation for air pollution measurements (outdoor and indoor), epidemiological surveys and cohort studies this can reveal the sub-city patterns of the burden of the diseases linked with air pollution and can better inform planning, policy and decision making. These modeling experiments are preliminary steps towards spatially and temporally differentiated health impact evaluation methodology at the urban level to be further developed in the next phase of the research for the case of Sofia.

5 Conclusions

The overlaying of transport, emission, activity and morphology modeling helps us to better understand the link between emissions generation and exposure settings, degree of risks changing under different conditions (geo and urban morphology, vast artificial surface and canyons, arteries and public life). Morphology, traffic load and activities impose varying degrees of impacts and health risks from the transport sources all year round in established and emerging hot spots in Sofia, some of which are the result of weak planning and design, but also poor urban political culture when defending the public interest in the light of environmental risks, epidemiology and urban hygiene. The answers to these scientific and practical challenges lie in the common efforts to produce more holistic urban development models, which can be tested and evaluated by numerous criteria, which can inspire more specific scope and design of multilayered measures to prevent public health in efficient and equitable manner.

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