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MODELING REAL-WORLD TRAFFIC POLLUTANT EMISSIONS AND URBAN AIR QUALITY AT HIGH SPATIAL AND TEMPORAL RESOLUTION

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Abstract: Pollutants emitted by road traffic represent a major contributor to the population exposure in urban areas. Current air quality management tools always rely on macroscopic estimates of road traffic emissions. They are representative of statistical traffic conditions adapted to large spatial scales and an average driving profile, but do not characterize local driving patterns in real use. In an attempt to address these shortfalls, our study presents a microscopic estimate of road traffic emissions (AIRMES), and their impact on air quality characterization for a district of the French city of Marseille.

The microscopic emissions model is based on driving profiles in real use, where traffic conditions, driving styles and road signs have a first-order impact. It then describes the polluting emissions at the scale of the vehicles depending on their engine technology. Emissions are scaled up to a district level in accordance with the traffic and vehicle fleet of the area. The microscopic methodology takes into account the variety of real speed profiles of the vehicle fleet, as well as the impact on emissions of road signs and slopes, particularly on one-way lanes. Air quality modeling is performed with PMSS (Parallel Micro Swift Spray, developed by ARIA Technologies). In the main domain, 4.0 km by 4.5 km, emissions are updated every 5 min on all road segments. In an inner domain, 400 m by 800 m, a downscaling process goes to 5 s and 5 m to demonstrate the added value of high resolution emission and dispersion models. Air quality mapping is presented with different resolutions for the main domain (one day , 4 m and 10 min) and for the smaller one (10 cycles of three successive traffic lights , 1 m and 5 s).

Overall, the mapping of air quality shows similar results to those obtained from the aforementioned macroscopic methodology (COPERT, with an hourly update of emissions). But at a finer level, the mapping illustrates the strong influence of real emissions at different air quality hot spots based on the vehicle fleet, the slope and the road signs. The inner domain with higher resolution shows that the fleet and road signs can be explicitly considered in the mapping of air quality. As an example, poorly synchronized traffic lights prevent smooth traffic, which leads to a significant increase in pollutant concentrations.

This study demonstrates the interest of coupling a microscopic emission model with a high spatial and temporal resolution dispersion model to evaluate local air quality. This new tool could be used as a part of a decision support system to optimize road traffic networks and signs.

Key words: *Microscopic traffic emission model, PMSS, Lagrangian particle modelling*

1. INTRODUCTION

The microscopic methodology AIRMES (De Nunzio *et al* 2020) for estimating traffic emissions is used for air quality modeling around a district in the city of Marseille, France. A large modelled domain covers an area of 3.4km wide by 4.5km high and a small one 400m by 800m. The study focuses on the emissions and dispersion of the NOx pollutant. The macroscopic methodology COPERT is compared to the microscopic methodology AIRMES for estimating emissions (part 2). The impact of both methodologies on the dispersion is then highlighted (part 3).

2. CONSTRUCTION OF A MICROSCOPIC EMISSIONS INVENTORY

The establishment of the annual average daily traffic (AADT), the vehicle fleet, and the speed profiles per road segment are required to calculate a traffic-related emissions inventories. The roads of the large domain are described in segments of 42m on average, but their length varies from a few meters to several hundred meters, while those of the small domain are refined to 5m.

2.1. ANNUAL AVERAGE DAILY TRAFFIC AND VEHICLE FLEET

An AADT is assigned to each segment and is distributed among the vehicle categories: passenger cars (PC), light commercial vehicles (LCV), heavy goods vehicles (HGV), buses and 2-wheelers. The vehicle flows are derived from traffic counts by the road network managers, supplemented by a traffic model for segments where the information is not available. An hourly modulation of the AADT is established by AtmoSud, based on annual vehicle flow counts in the city center. A 300m lane in the small domain has a succession of 3 traffic lights, and an additional 5s modulation is added to the traffic density. The average density equals that of June 20, 2019 at 18:00UTC, but there are no vehicles downstream of red lights, and more upstream of red lights than green lights.

A French organization (CITEPA) provides annually 4 national vehicle fleet descriptions (urban, suburban, highway, medium) detailing the use of each type of vehicle (PC, LCV, HGV, buses and 2-wheelers), fuels (gasoline, diesel, electric, LPG), EURO standard, cylinders, etc... An adjustment by AtmoSud to the January 2018 version is used to catalog the vehicles in Marseille, and associates each road segment one of the 4 modified vehicle fleets. A medium load for HGV and LCV is assumed.

2.2. SPEED PROFILE: MACROSCOPIC METHODOLOGY

For each road segment, and for each type of vehicle, different speed profiles are established by AtmoSud according to the slope, sinuosity and level of congestion. Between 3 and 7 average velocities per segment and level of congestion are defined, with a probability for each one. For a low congestion level on a road limited to 50km/h, 15% of the vehicles drive at 10km/h, 45% at 30km/h and 40% at 50km/h.

2.3. SPEED PROFILE: MICROSCOPIC AIRMES METHODOLOGY

To accurately describe the accelerations along the roads, each road segment is described by approximately 50 points and is labelled with the following characteristics: high congestion level, presence of a traffic light, priority or non-priority intersection, high or low curvature. Experience has led to the definition these categories: for high congestion levels, the velocity remains low and neither the road signs nor the curvature of the road have a significant impact. Several sub-classes within each category have been defined: a vehicle can stop at the traffic light (red light sub-class) or not (green light); on a road with priority at an intersection, a vehicle can accelerate, decelerate or have an unchanged velocity.

In real use, traffic conditions, road signs and driving behaviors have a first-order impact on vehicle accelerations. The present project follows the *Geco air* project led by IFPEN with the support of ADEME. By the deployment of a smartphone crowdsensing application, the project collected the GNSS (Global Navigation Satellite System) signal at 1 Hz of the position, speed and acceleration of vehicles, with the license plate giving access to the vehicle characteristics. By June 2019, the database covers 5.9 10^7km in France and is used to characterize the speed profiles in real conditions. The speed profiles are adjusted to Gaussian statistics for every subclass of each category, and for each vehicle type. The probability of occurrence of each subclass is deduced from the database, and for example, the probability of stopping at a traffic light is 40%. The physical consistency of the statistics is checked by taking into account the maximum accelerations achievable by the different types of vehicles (IFPEN database).

Gaussian statistics are used to randomly generate, on average, 20 speed profiles per road segment, respecting the maximum speed of the road, a possible stopping point, and keeping the statistical weighting of each subclass of a given category. The profiles are established by scanning the segment from one end to the other (De Nunzio *et al* 2021). Another method consisting of adjusting the speed profiles to polynomial functions shows poorer results in comparison to the measurements and has been abandoned. The establishment of statistics for each segment category allows an independent approach of the *Geco air* application. This assumption is verified by learning from the 2 10^6speed profiles of the Lyon and Paris regions only. The randomly generated profiles are then compared to those measured in the considered district of Marseille (33700km by June 16, 2019). The predicted profiles preserve the variability of speed profiles in real conditions. Figure 1 (left) shows examples of measured and predicted speed profiles for a road segment with a stop. The median of the absolute error is 2.1km/h between the measured and predicted speed profiles. Averaged on all segment categories, the absolute error is 10%.

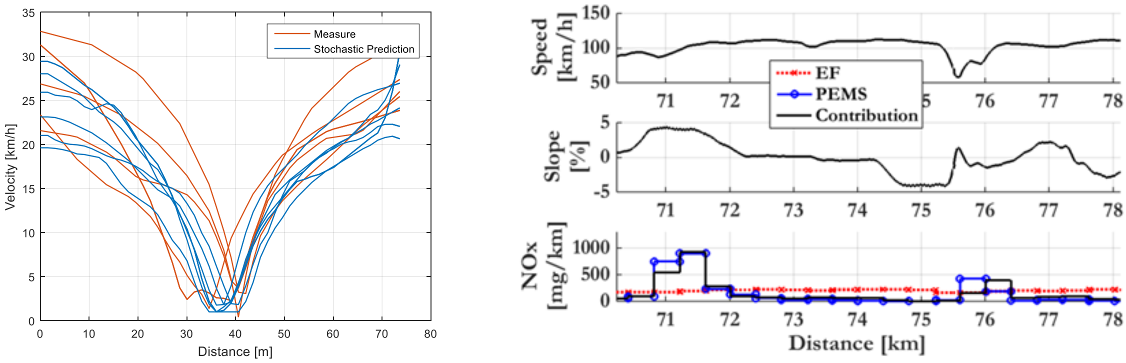

Figure 1: Measured and predicted speed profiles on a road with a stop (left). Highway PEMS measurements (blue), and comparison with the microscopic (black) and macroscopic modeling (Emission Factor, red).

2.4. EMISSION: MACROSCOPIC USING COPERT METHODOLOGY

Emissions of NO_X are calculated by multiplying the flow of each type of vehicle (AADT) by an emission factor, which in turn depends on the vehicle fleet, and is a function of the speed profile. The COPERT methodology assumes two-way streets and not one-way streets. The over-emission during uphill driving is compensated by an equivalent under-emission during downhill driving, except for HGV where an over emission is estimated base on the slope and medium load. In addition, for both microscopic and macroscopic methodologies, cold emissions are based on COPERT Beta factor and are an assumed 3% proportion of the total emission rate of each road segment in the city of Marseille. This factor presents the fraction of mileage driven with a cold engine or with the catalyst operating below light-off temperature corrected for newer technology vehicles. The NO_X emissions evolve temporally with an hourly update.

2.5. EMISSION: MICROSCOPIC AIRMES METHODOLOGY

The engine is modeled (De Nunzio *et al* 2021), including injection and post-treatment, and the vehicle dynamics depend on the type of engine (here, gasoline or diesel), the injection system (direct or indirect), and the emission control system (ECS). The engine speed and torque are estimated from the speed profile, the slope, and the general specifications of both the vehicle and engine. From then the fluid characteristics (intake and exhaust gases and recirculation of burnt gases) are estimated and pollutant emissions deducted according to the efficiency of the ECS on each pollutant. The microscopic emission model has been validated on a large number of vehicles by comparison with experimental data (PEMS-type) acquired either in laboratory conditions or on the road. Figure 1 (right) shows an example of a significant improvement compared to the macroscopic modelling with the consideration of accelerations and slope.

Emissions are scaled up to the district level in accordance with the traffic (AADT). The GIS data in the GNSS database is updated every 5min, and for the large domain, emissions evolve temporally with an update every 5min. The contribution of LCVs to emissions varies a lot in the large domain. PCs contribute sometimes similarly of the sum of the contributions of LCVs and HGVs, with a similar contribution of LCVs and HGVs to emissions. But LCVs can also contribute as much to emissions as PCs. For the small domain, the emissions update is 5s and 10 cycles of alternating traffic lights are modeled, for a total duration of 13min and 20s. The NO_X emission estimate from the measured speed profiles is used as a reference and compared to the one using the predicted speed profiles, and the one obtained by the COPERT methodology. For road segments with a traffic light (respectively a road segment with priority at an intersection), the mean absolute error is 9mg/km, i.e. a relative absolute error of 2%, for the microscopic method (respectively 13mg/km and 2%). These errors are to be compared with 126mg/km, and 23%, for the macroscopic method (respectively 299mg/km and 56%). The overall mean absolute error is 98mg/km for the AIRMES method and 218mg/km for the COPERT methodology.

3. MODELING OF DISPERSION ON THE EUROMED DISTRICT

The estimated emissions are used to model the air quality with a resolution of 4m in the large domain (respectively 1m for the small domain). The topography resulting from a Digital Terrain Model is extrapolated from 25m to the chosen resolution. The buildings are described by a 3D shape file. The station *5 avenues* from AtmoSud is chosen as an hourly measurement of the background pollution, assuming it out of the direct influence of the sources explicitly modeled. The air quality is modeled for June 20, 2019, as that day shows a low level of background pollution in SO_2 (tracing a non-modeled nearby marine activity) and due to the proximity of the day mean to the 2019 annual mean for NO_2 at the *5 avenues* station (25.2µg/m^3 for 26µg/m^3).

3 nested WRF simulations are performed daily by AtmoSud for weather forecast. The air quality model is PMSS (Parallel Micro Swift-Spray model, Trini Castelli *et al* 2018) and it is fed with meteorological data by the finer scale WRF simulation, and by the 16 vertical profiles surrounding the large domain. PMSS is based on the joint implementation of two 3D models. One is a 3D micro-scale meteorology model calculating wind, turbulence and temperature fields in non-stationary conditions, taking into account buildings and topography, and respecting the basic rules of fluid mechanics such as mass conservation. The other a 3D Lagrangian Particle Dispersion Model (LPDM) allowing for the simulation of pollutant dispersion using a large number of pseudo-particles each representing a part of the emitted mass.

3.1. LARGE AREA AND EVALUATION WITH NO_2 TUBES

AtmoSud regularly deploys NO_2 tubes to estimate the annual average concentration, and 45 of them are spread over the large domain. Both the emissions and the PMSS model consider NO_X pollutant. The *Place Verneuil* station from AtmoSud measures NO_2 and NO_X hourly concentrations in the modeled area. The ratio of the observed concentrations is applied to the NO_X modeled concentration to estimate NO_2 concentration. The annual mean limit value for NO_2 concentration is 40µg/m^3. The AIRMES methodology indicates an increase in the NO_2 exceedance area for the modelled day, with an area increasing from 0.864km^2 to 0.890km^2, i.e. 3% more. It should be noted that buildings are excluded from that calculation. Figure 2 shows the observed (annual average) and modeled (daily average) NO_2 concentrations. The comparison remains qualitative but the slope of the linear regression, the correlation coefficient and the standard deviation indicate that the AIRMES methodology is slightly closer to the observations than the COPERT methodology. The proportion of modelled values at +/-5µg/m^3 from the observations goes from 71.1% for the AIRMES methodology to 60% for the COPERT methodology.

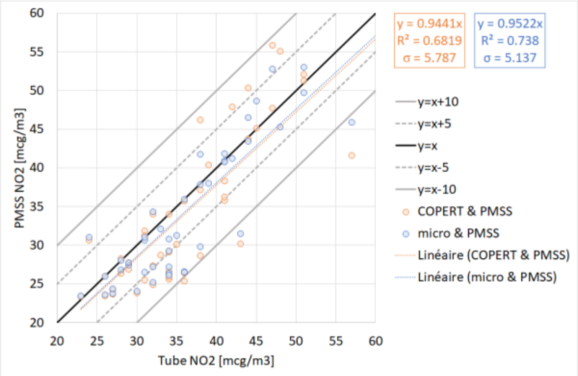

Figure 2: Observed annual mean NO2 concentrations (x-axis) function of the daily average modelled by PMSS (y-axis) and by estimated AIRMES (blue) or COPERT (orange) traffic emissions

3.2. SMALL DOMAIN

Modelling the small domain allows a highlighting of the contributions to the air quality made by driving behaviors and road signs. Figures 3A and 3B present the average NO_X concentration from the COPERT and AIRMES emissions. In agreement with the figure, the realistic speed profiles explain the over-emissions of the AIRMES methodology near the 3 traffic lights, whereas the negative slope in a one-way lane explains the under-emissions of the AIRMES methodology near the top of the figures.

For the 3 traffic lights, a sequence is repeated with a 80s period: acceleration, green lights, deceleration, red lights. When the 3 traffic lights are synchronized, the color changes follow each other, and follow the direction of the lane, here from North to South. In Table 1 and figure 3, a synchronous chronicle is shown along with an asynchronous example, and the latter presents a clear increase in concentration. Both waves are at a constant traffic volume (no increase in traffic over time). The maximum velocity remains 50km/h, but the speed profiles are strongly constrained by the road signs: regardless of the driving style, the velocity is 0 at red lights. On average, vehicles take longer to pass traffic lights in the asynchronized wave, where some have to accelerate twice to pass. For the synchronized wave, the lights are optimized to reduce the accelerations and decelerations so the concentrations are less localized.

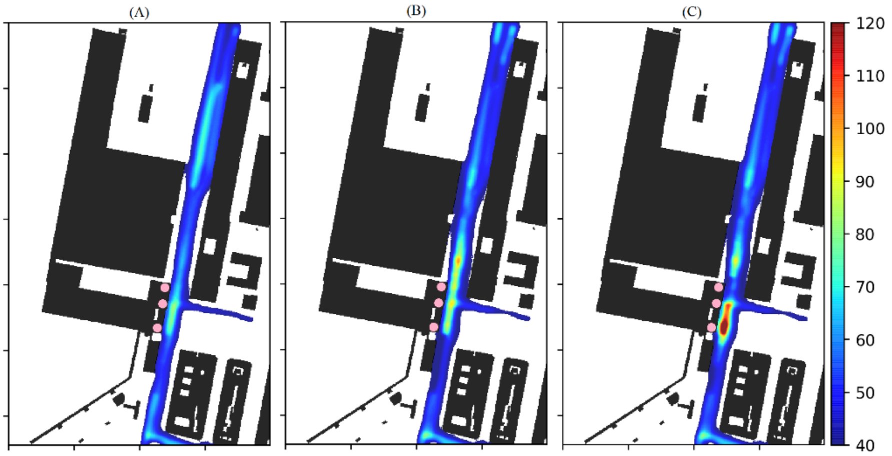

Figure 3: Average NO_X concentrations (in µg/m^3) for COPERT (A, max at 83µg/m^3), AIRMES emissions for a synchronized wave (B, max at 101µg/m^3) and asynchronized wave (C, max at 153µg/m^3), with traffic lights in pink.

Table 1: synchronous and asynchronous chronicles of traffic lights color changes

Time (s)	0		10		20		30		40		50		60		70	
Light 1																
Light 2																
Light 3																
	Synchronized wave															
	Acceleration				Green light				Deceleration				Red light			
	Asynchronized wave															
Light 1																
Light 2																
Light 3																

4. CONCLUSION

The microscopic methodology AIRMES captures the high sensitivity of pollutant emissions to traffic conditions, slopes, road signs and driving style, and significantly reduces errors in estimating emissions compared to the COPERT methodology. Hot spots for air quality (asynchronized wave, significant contributions from LCVs or diesel engines) are explained by coupling the microscopic methodology to a high-resolution atmospheric dispersion model. This work can be quickly and inexpensively deployed in other areas, thus opening the prospect of a digital decision-support platform for urban air quality management.

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