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Agent-Based Modeling and Simulation for Urban Air Quality Assessment

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Abstract. Urban pollution poses a pressing environmental challenge, with substantial impacts on public health, particularly in urban areas. This paper presents a original approach that integrates vehicle-specific emission factors, derived from real-time traffic data, into an agent-based transport modeling framework. We introduce an emission calculation tool, augmented by supplementary data from HBEFA, incorporated into the MATSim environment to simulate multi-agent transport dynamics. The comprehensive MATSim scenario, encompassing digital road networks and public transportation systems, is generated through the Eqasim pipeline. This pipeline ensures a dependable pathway from initial data inputs to the completion of transport simulations.

We apply this methodology in the real-world context of Calais, France, modeling pollutants such as NO₂, PM₁₀, and PM_{2.5}. This modeling effort generates emission maps that illustrate the results, offering valuable insights for emission analysis. Furthermore, our approach provides critical information for decision-makers involved in managing and assessing urban air quality, thus contributing to more informed environmental policies and interventions.

Keywords: Multi-agent, Transport, Air quality, Emission, Urban, Simulation

1 Introduction

The use of modeling techniques based on mathematical and numerical techniques to investigate the links between air quality and illnesses and deaths has increased over the past few years [5]. People who live in major metropolitan areas are most affected by air pollution, which is mostly caused by vehicle emissions [11]. A wide range of thousands of different pollutants—e.g., ozone, nitrogen dioxide, sulphur dioxide, particulate matter, carbon monoxide, and volatile organic compound—contribute to air pollution [12]. Their nature and concentrations depend on the region geography and also on the source of the emission. According to a survey by the Statista in 2022, using the car is still the first means of transport used by the French people to go to work. Still, nearly 30% of French people use a sustainable means of transport such as public transport, cycling, or walking.

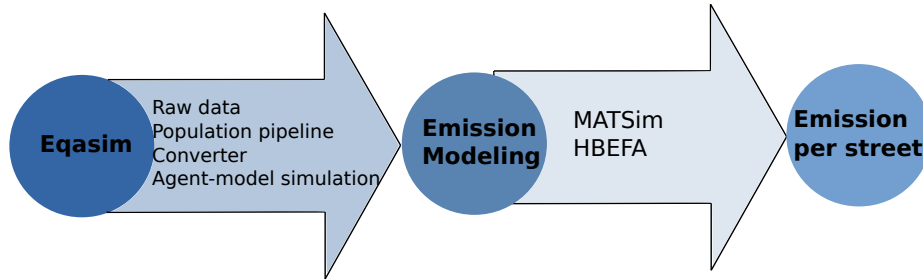


Fig. 1. Pipeline of this study

In order to provide sustainable solutions, transportation policies should take into account changes in travel behavior as well as advancements in emission control technologies [8]. In metropolitan areas, air quality measurement stations are usually sparsely deployed, making the overall or local city air quality assessment very challenging. Fortunately, Air Quality Models (AQMs) allow to identify the sources of air pollutants and are helpful for analyzing different types of air pollution [10].

In recent decades, agent-based models have gained popularity across many scientific disciplines, mostly due to their ability to simulate internal complex systems and interactions. Agent-based models are dependent on a synthetic travel demand with the aim of simulating the behavior of agents on the transport network and knowing about the competition over infrastructure [16]. An agent model is based on two basic blocks, i.e., (1) the synthetic travel demand and the transport supply as input data, and (2) the simulation environment. There are hundreds of studies conducted using the agent-modeling frameworks such as MATSim [6], POLARIS [3], simMobility [4], TRANSIMS [15], or SUMO [13]. Hence, there is a need to create a synthetic travel demand dataset and to enable users to transform the data into a model using agents—e.g., MATSim—and to simulate traveler conduct.

2 Methodology

The aim of this research is to link the multi-agent based model to emission modeling to calculate emission per street and having the emission shape file as shown in fig. 1, this pipeline is described in more detail in the following sections.

2.1 Eqasim pipeline

The Eqasim pipeline was created by Sebastian Horl and Milos Balac in 2021 [7]. It is based on synpp—i.e., a general Python module to chain different stages in a higher-level pipeline setup—which serves as the pipeline backbone. While it may be applied in a wider range of situations, its main objective is to offer a reliable

foundation for applications such as travel demand synthesis and transport simulation [6]. In order to use many data points and to increase realism in mobility for travel demand models, the Eqasim framework was considerably changed and supplemented with a number of algorithms [14]. For instance, a typical series of steps consists of loading raw census data, cleaning raw census data, loading raw household travel survey data, cleaning survey data, merging census and survey data, and lastly generating a synthetic population from the merged data [7].

The Eqasim pipeline is divided in three parts:

1. Population pipeline: the collected raw data—e.g., household travel survey, population census, enterprise census, commuting flows—are openly available and published by governmental agencies. They are firstly filtered and cleaned.
2. Converter: the synthetic travel demands converts the above data to an appropriate format so that they can be used in an agent-based model, i.e., MATSim in this paper.
3. Agent-based simulation: in this part, there is a need to add the additional data. In particular, we use road network—based on OpenStreetMap data—and General Transit Feed Specification (GTFS), i.e., a public transportation schedule stored in a common format. GTFS has two major component, i.e., GTFS Schedule and GTFS Realtime. In simple text files, GTFS Schedule presents information about routes, timetables, prices, and regional transit features. Moreover, it is regularly updated.

2.2 Emission Modeling

In the Emission Modeling part, in order to use MATSim emission contrib which is an extension in MATSim for air pollution emission in France, it's necessary to collect the *crit'air* data from the site of Ministère de la transition écologique et de la cohésion des territoires.

A tool for calculating exhaust emissions based on the “Handbook on Emission Factors for Road Transport” (HBEFA) is provided by the emission package [9]. HBEFA is a database application that gives emission factors for all applicable road transport vehicle categories—i.e., Passenger car (PC), Heavy-duty Vehicle (HDV), Light Utility Vehicle (LCV), buses, coaches, and motorcycles—for a wide range of traffic scenarios, each is separated into many groups. All regulated and significant non-regulated pollutants, fuel/energy usage, and CO₂ emissions are all included in the emission factors [1]. We use HBEFA 4.2 in this study.

Road type, driving speed, driving dynamics, and vehicle attributes all have an impact on warm emissions. Distance traveled, amount of time spent parked, and vehicle characteristics all affect cold-start emissions differently. Warm and cold-start emissions calculate by using the tool called emission modeling for both vehicle type like passenger cars and heavy goods vehicles. HBEFA provides the emission factors and the other data is provided by survey data and the input data for MATSim traffic demand. The vehicle characteristics such as fuel type, Euro-class are kept by MATSim, when outcome is generated at any time we have

information about each agent’s vehicle, finally we have emission events which follows the MATSim framework containing the generated cold-start and warm emissions. This emission events including the information about the vehicle, the time, the link and the exact mass of pollution emission, then at the end we have emission per street and emission shape file [7]

3 Results of Pilot study

3.1 Study Area

The city of Calais in France is chosen to test the approach. This city in the North of France has 76,402 inhabitants, according to the last census in 2014, which gives a population density of 2,233 inhabitants per square kilometer.



Fig. 2. Map of Calais

An example of generating a synthetic travel demand based on Calais openly available data is taken as the pilot study. One of the output of this step contains the file `trips.csv` that includes the information on the all trips by agents in plain and geolocalized form. There are other outputs like `housholds.csv`, `persons.csv`, and `activities.csv` that contain the information related to this case study.

3.2 Results from the simulation

3652 agents have been entered into the simulation. Figure 3 shows that 1429 agents—i.e., 39.13% of all the agents—traveled by car while 1116 agents—i.e., 30.59% of all the agents—traveled in walk mode. Figure 4 shows Euclidean

distances covered by the main modes of transport. For example, 33.71% of agents travelled between 0 and 10000 m by car.

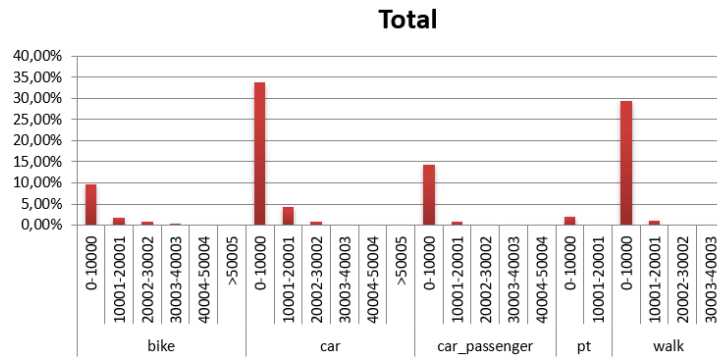


Fig. 3. Distribution of travel distances by modes

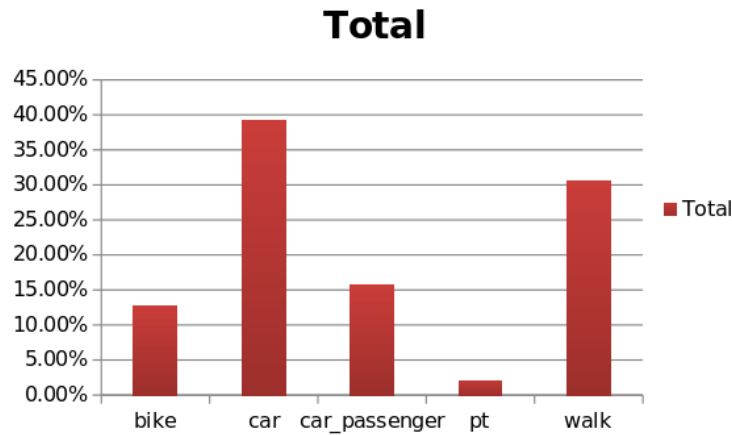


Fig. 4. Covered distance-main mode percentage

Then, after applying the eqasim pipeline for the city of Calais, the emission modeling is applied for pollutants like NO₂ (Nitrogen dioxide), PM₁₀ (Particulate Matter 10 micrometer), or PM_{2.5} (Particulate Matter 2.5 micrometer) in order to create the emission events. The emission model is calculated using exhaust emissions of each vehicle on each link. Figure 5 illustrates the hourly simulated emission (in g/km) for the city of Calais for three important pollutants. The graphs were obtained from simulations, but the produced data are

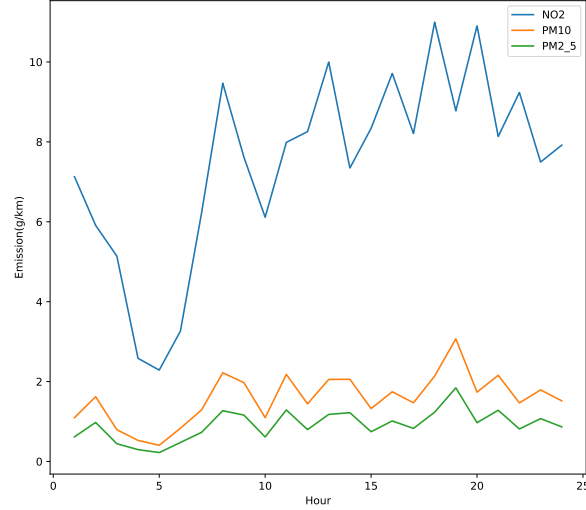


Fig. 5. Hourly Simulated Emissions (g/km)

consistent with the cumulative data declared in 2022 in the Plan Climat Air Energie Territorial (PCAET) of the Communauté d’agglomération du Grand Calais Terres & Mers (GCTM) [2]. The overall exhaust emissions from the main emitters (industry, heating, cars, ferries, and agriculture) of three pollutants can be noted: NO₂ (2,413 tons), PM_{2.5} (209 tons) and PM₁₀ (845 tons). The contribution of road transport alone represents 25%, 30%, and 25% for these three pollutants, respectively. Emissions due to transport in 2018 are therefore estimated at 723 tons for NO₂, 62.7 tons for PM_{2.5}, and 211 tons for PM₁₀. We consider that the 10,000 vehicles, both residents and passing vehicles, covered around 75 million kilometers in this area. Thus, we can estimate the emissions produced per km travelled on the city internal road network, i.e., 9.64 g/km for No₂, 0.83 g/km for PM_{2.5}, and 2.8 g/km for PM₁₀. Figure 5 shows the evolution these three pollutants—i.e., No₂, PM_{2.5}, as well as PM₁₀—for which cumulative data are available.

In fig. 6, hourly simulated emission for PM_{2.5} shows that the peak at 7 pm and Minimum in PM_{2.5} is reached at 5 am.

Once the full simulation has been run, using certain classes defined in eqasim-java to analyze and compute emissions based on MATSim results—i.e., the java class RunExportEmissionsNetwork—we obtain a shapefile of the emissions network. Then, using Simunto tools and services for working with MATSim, we visualize the emissions map shown in fig. 7 for PM_{2.5} at 5:30 pm.

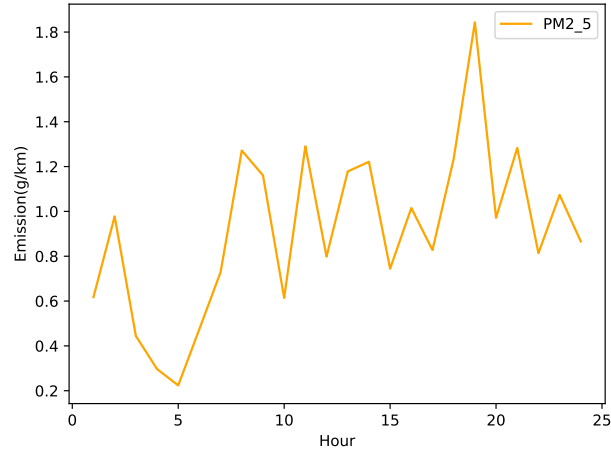


Fig. 6. Hourly Simulated Emission (PM2.5)



Fig. 7. Emission map of Calais for PM2.5

4 Conclusion

In this paper, we applied the eqasim pipeline to derive urban air quality maps of the city of Calais, in Northern France. This pipeline follows several steps—from raw data to final agent-based simulation—using open-source data only. Our work shows that anyone can gather the data and run the code to produce a synthetic travel demand, and then run the simulation by using some extra data, i.e., crit'air, OpenStreetMap, and city public transport schedule data. Then, in Emission modeling part, we followed the approach that links MATSim with the emission factors and traffic situations of HBEFA (Handbook on Emission Fac-

tors for Road Transport) for having the emission events including the absolute emitted mass for some pollutants such as NO₂, PM₁₀, and PM_{2.5} by air pollutant and the information about the vehicle, the time and the link. After applying all the steps until having the emission events for these pollutants, we used one of the class in eqasim-java to create the emission map for Calais. In Simunto via—i.e., the software that allows to work with MATSim—we can visualize the simulation in this environment. In order to visualize the emissions calculated by MATSim Emission contribution, we used emission plugin in this software and importing the emission events file and then for each pollutant we have different emission maps. For instance, for PM_{2.5} we obtained the hourly simulated emission that showed the peak of pollution at 7 pm. As future work, we plan to use the pollution dispersion models to calculate the air pollutant concentration per street.

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