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Impact of road network structure on pollutant emissions: Illustration for a Demand Responsive Transport system

Julie Prud'homme
University of Avignon- UMR ESPACE (CNRS 7300)
74, rue Louis Pasteur
84000 Avignon, France
julie.prud-homme@etd.univ-avignon.fr

Cyrille Genre-Grandpierre
University of Avignon- UMR ESPACE (CNRS 7300)
74, rue Louis Pasteur
84000 Avignon, France
cyrille.genre-grandpierre@univ-avignon.fr

Rémi Prud'homme
TVC-LISP
36, avenue La Bruyère
38100 Grenoble, France
tvc.lisp@gmail.com

Abstract

Transportation activity strongly contributes to pollutant emissions in atmosphere (about 50% of the total CO and NOx) with a lot of direct or indirect effects on public health and greenhouse. Research has largely studied and comprehended the role of transport modes, types of vehicle, driving practices which favour or not energy consumption (speed, acceleration). In this research, we develop a methodology which makes us able to estimate pollutant emissions at the scale of the road section, depending on road network properties. We apply it to a Demand Responsive Transport system and establish several scenarios with different kinds of road networks (scenarios of speeds and connected network shape). Some hot-spots of emission are highlighted in faster road networks.
Keywords: Pollutant emission estimation, road network shape, hot-spot of emissions, Demand Responsive Transport.

1 Introduction

Transportation activity strongly contributes to pollutant emissions in atmosphere (about 50% of the total CO and NOx) with a lot of direct or indirect effects on public health and greenhouse. Research has largely studied and comprehended the role of transport modes, types of vehicle, driving practices which favour or not energy consumption (speed, acceleration). These factors come out onto pollutant emission (*i.e.* ARTEMIS: Assessment and Reliability of Transport Emission Models and Inventory System [3]; COPERT: Computer Program to Calculate Emissions from Road Transport program, [9]). However, the impact of the structure of road networks on pollutant emissions remains minimally explored, although the network is a main component of the transportation system. Since the link between car speed and pollution is now well known, we still do not really know the relation between pollution and network structure, except that pollution increases with longer networks. In fact, more or less twisting routes can result from the network topology or morphology and from the way edges are valuated and oriented in the graph to describe the local flow impedances and the degree of homogeneity of speed. In research, factors that are often considered as prominent are origin-destinations flux, population densities and places or interest location, and generally all what can describe a territory mobility as a whole complex system. Nevertheless, networks are most of time taken into account as a background black box or a space passive support. They are only used to compute origin-destination matrices according to shortest path algorithms. Though, it may be of great interest to handle routes as a relevant level to identify and measure pollutant emission, because it encompasses the vehicle behaviour within the road network structure.

2 Objectives and methodology

In this context, our study aims at identifying the possible effects of road network structure on pollutant emissions.

To identify these different effects, our work lays on a set of different components:

- a transportation demand-supply system including the urban area of Avignon, south-east of France (within a neighbourhood of 20 km around the town centre), where people want to go to the centre at different times during the day;
- a transport service: a Demand Responsive Transport (DRT). This service has the capacity to group passengers in vehicles due to cost, time and travelled distance reduction, while keeping a sufficient quality of service, despite a few acceptable detours and time loss for a few clients. These services are often used by clients who move to important traffic generators (train stations, city centres, airports, etc.) in rather short times and acceptable fairs. They can have a non-negligible effect on transport efficiency and pollution reduction, compared to private car use. This will also allow us to assess the effect of the network structure on the client grouping rate in vehicles;
- a model of pollutant emission, adapted from the MEET project (Methodologies for Estimation of Emissions from Transport) [8]: GREEN-DRT (Geographical Reasoning on Emission Estimations based on road Network shape adapted to Demand Responsive Transport system) [10]. This model takes into account the type of vehicle (size, type of motor and fuel), the speed allowed on the road sections from origin to destination and the averaged ambient temperature.

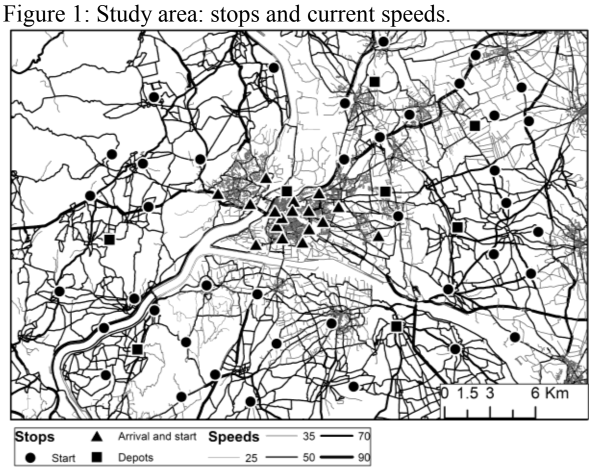
The method we propose consists in changing the current structure of the road network to analyse its effect on pollutant emissions, induced by different topological and functional characteristics and speed changes on road sections.

First, we briefly present the study area and explain the choice of the different tested networks. Next, we introduce the DRT system and the associated transportation demand. Then, the pollutant emission model is detailed. The paper ends on the results of different simulations that are finally discussed.

3 The study area and the simulated networks

The study area corresponds to a neighbourhood of about 20 km around the centre of Avignon (that gathers 85'000 inhabitants). The current road network is composed of 27'700 arcs (edges or road sections). The major roads mainly converge toward the town centre. It involves 12% of the road section which allow a speed over 50 km/h. There are four bridges in the study area which allow to cross the Rhône and the Durance rivers, those having a strong influence on the shortest paths (Figure 1).

Figure 1: Study area: stops and current speeds.



In Table 1, we can see the speed values assigned to the arcs regarding different simulated networks. For example, arcs with a speed of 90 km/h in the *current* network will get a speed of 110 km/h for the *fast* network.

Table 1: Speeds according to scenarios (km.h^{-1})

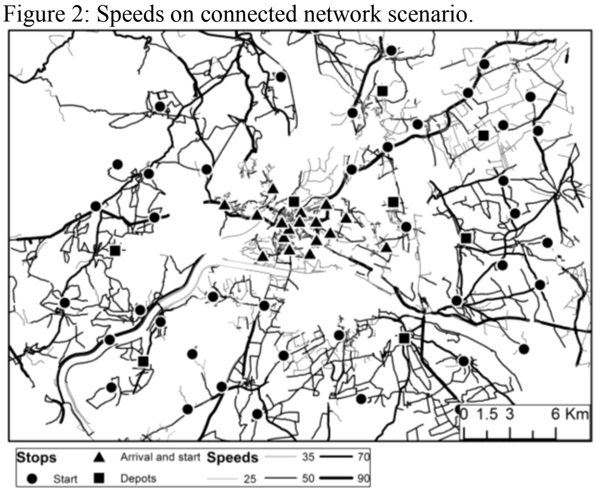
Current	Fast	Slow	Homo-geneous 1	Homo-geneous 2
90	110	80	80	55
70	90	65	75	55
50	60	45	60	55
35	45	35	45	55
25	35	25	30	55

For the *current* network, the speed values correspond to the maximum theoretical values according to the French legislation. The values for the *fast* network are higher and correspond more or less to how the network is really covered. For the *slow* network, the simulated speed decreases, that corresponds to an actual trend of urban planning. This decrease aims at improving safety and competitiveness of non-automobile transportation modes and also at limiting fuel consumption (and so pollutant emission) and noise nuisance. In a chrono-planning perspective, the decrease of speed can also be used as a leverage to improve spatial coherence and balance between places of life.

The *first homogeneous* network simulates the effects of a hierarchy in terms of speed, considering the different types of road, their subsequent shortest paths and pollutant emissions. Indeed, the higher the hierarchy, the stronger the difference of induced shortest paths in time *versus* distance. In other words, travellers tend to maximize the use of speed roads to save time. For the *second homogeneous* network, the speed is limited to 55 km/h on all the road sections. This theoretical speed is chosen because it allows to reach the same global accessibility in the studied area, as well within the *current* network.

At last, we test the effect of connectivity. To do so, we randomly deleted arcs in the graph of the current network from arcs which have a theoretical speed lower than or equal to 50 km/h. That leads to a *connected* network, made of 10'180 arcs, with 11% of the sections allowing a speed exceeding 50 km/h. Let us notice that removing these arcs did not modify the network connexity, which remained identical (Figure 2).

Figure 2: Speeds on connected network scenario.



Based on the *connected* network, we processed four complementary simulations where the arc speeds correspond respectively to the speed assigned to the *current*, *fast*, *slow* and *homogeneous* networks. Connectivity is an important parameter to test, in a context where planners intend to limit the number of roads accessible by car from door to door and to preserve some areas (eco-districts). At the opposite, at small scales, connectivity improvement appears to be a significant leverage to favour non-motorised modes [7].

4 Demand Responsive Transport service

In Europe, DRT is a kind of public transport which combines the advantages of collective transport and individual automobile [4]. It offers more flexibility to clients and includes the objective of grouping passengers and reducing travelled distances and costs. Depending on the kind of DRT, this service can serve different types of urban or rural territories, including place-to-place, door-to-place and door-to-door coverage. In this paper, we use a place-to-place DRT simulator, involving located stops on the network, close to population and downtown places of interest (flow generators). This DRT capacity of client grouping can lead to significant environmental impact, especially in pollutant emission reduction, since the carrier vehicles are close to the demand and group passengers due to allowed detours. Indeed, a DRT journey generates a unique emission peak at starting (usually at the vehicle depot or parking). Thus, a part of the travel occurs in cold conditions which are bad for fuel consumption and pollutant emissions, before a warmer stage where both are reduced.

In this study, we generate random demand under constraints of population and stop location. Indeed, many stops are available to pick-up clients on the whole served area, while only a few stops to drop them are located in the town centre. Each stop is associated to a probability of client origin or destination. The time has also been discretized in many classes assigned to different demand probability regarding person activity schedules. An acceptable time delay has been fixed for all the possible routes and clients, whatever the simulation. Finally, many combinations of time and space are possible for origin-destination couples, but they are constrained by the mobility practice on the studied territory. For optimizing the vehicle assignment and routing, we use an efficient optimisation kernel, which is already exploited by several private or public carriers and taxis in North-Eastern France. For each simulation, we keep the same demand given a number of instances and only the network shape and topology change.

5 The pollutant emission model: an adaptation of methods of pollutant emissions estimation

Pollutant emissions are directly related to cars fuel consumption. Several factors have an impact on the quantity of pollutants emitted by road transports. In DRT systems, vehicle fleet is mainly composed by cars and light-duty vehicles. In this particular case, the major factors to be considered are distance, speed, local temperature, vehicle type and driving rhythm (mainly associated to driver). This leads to a few rules, among which some can be used in our model.

- The more the mileage, the higher the fuel consumption, and so the more important are pollutant emissions.
- It is known that the correlation between speed and pollutant emissions does not progress like a linear function. Mostly, consumption is higher for lowest speed level, decreases around 50-70 km/h and increases again for higher speed level.
- Temperature influences the quality of fuel consumption, especially during the first traveled distance of a journey. Until the engine reaches the temperature for optimal fuel consumption, the combustion remains imperfect and provokes a pollutant over-emission.
- Emission performances vary depending on vehicle types. To characterise a vehicle type, we need to consider several criteria such as (i) vehicle purpose (passenger car, light duty vehicle, lorry, bus, coach), (ii) vehicle size (cylinder), (iii) vehicle age and associated emission control level, based on norms fixed by EU legislation, (iv) type of fuel used (mainly petrol, diesel) leading to different pollution levels.
- The driving rhythm plays a non-negligible role in the quantity of pollutant emitted. A study [2] showed that the density of road sections controlled by traffic lights affects driving patterns and practice. Higher densities cause lower average travel speeds, higher speed oscillation, and increase heavy accelerations and high-power demand.

To estimate the quantity of pollutants emitted by a DRT system and to evaluate the impact of the road network on it, we developed a model adjusted from MEET to DRT systems that integrates the road network dimension. It takes into consideration speed, distance, temperature and vehicle type as described below (equation 1). It is based on a routing system composed of a set of optimized routes that minimizes the traveled distances and the associated cost, including the number of vehicles used according to their depot location. Once we get the routes for the whole vehicles, we apply the following model to each route assigned to a vehicle:

$$E_k = \quad D_{V,t,j} \times e_{V,j,k} \qquad (1)$$

where:

E_k is the quantity of each pollutant k emitted, expressed in gram

$D_{V,t,j}$ is the distance travelled on road type j by the vehicle V

$e_{V,j,k}$ is the emission factor of pollutant k corresponding to the average speed on road type j, for the vehicle V

This model calculates emissions of carbon dioxide (CO2) and main pollutants carbon monoxide (CO), hydrocarbon (HC), oxides of nitrogen (NOx) and particulate matter (PM). It enables to estimate the quantity of each pollutant emitted on each road section and for each DRT route and vehicle. According to our set of networks, it becomes possible to assess the impact of different kinds of network on the quantity and the location of emitted pollutants. Indeed, coupling this model with a GIS allows to quantify the impact of each road network on theoretical driving rhythms. Thanks to the graph, it becomes possible to explore the number of sections, speed breaks, turns which represent as many configurations of speed oscillations. To make the simulations comparable between every network structure, we fixed some parameters:

- an homogeneous light-duty vehicles fleet (10 seats in each vehicle);
- 8 depots where 50 vehicles are available (can be considered as unlimited, according to the simulated demand);
- 17 destination stops available downtown;
- 59 origin stops located on the whole area;
- 500 clients moving at any time, from and to relevant stops, under space and time probability constraints.

6 The geographical information workflow

The workflow lays on four complementary tools that interoperate together. Under a global script package developed within Common-LISP environment, the workflow

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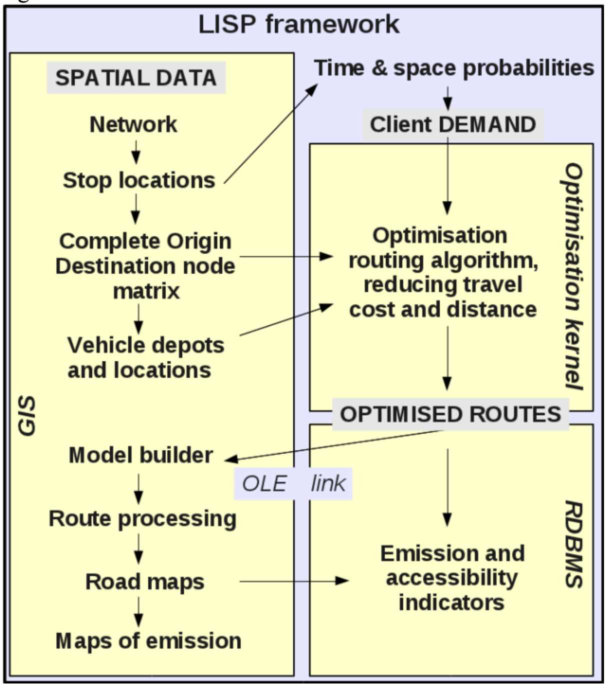
requires to use a GIS (©ArcGIS) connected to a RDBMS (©Access) and an optimisation kernel dedicated to this kind of DRTs (©Galeopsys).

Although we shall not describe this workflow structure in details in this article, the figure 3 depicts the different levels and steps where the information is handled and the functions processed. The GIS software allows building the origin-destination matrix, to manage the routes and to map the results. The RDBMS is used to build topological and functional relations between network including stops, cross-roads, sections, clients and routes, for building relevant aggregated indicators. The LISP environment is used as an umbrella covering the whole process and providing rapid and efficient data transfers.

Figure 3: Simulations workflow



7 Results

In this section, we present and discuss some results from the simulated scenarios (Table 2). First, an important variation of pollutant emission depends on the tested networks. Indeed, the amount of emissions varies from 4'267'016 g (case of the *slow* network) to 7'672'819 g for the *connected* network (*i.e.* a ratio of 1.8).

Consistently with the emission model we applied, the speed plays a crucial role. The faster the shortest paths produced by the routes on the network, the higher the pollution. However, the role of the speed is ambivalent. Indeed, since speed contributes to pollution, it allows in the same time to increase the opportunity to group passengers in the same vehicles (for a given level of service) and so to decrease the travelled mileage. For example, whereas the system needs 102 circuits to pick-up 500 clients on the *slow* network, it needs only 97 for the *fast* network. Although, even if 5 vehicles stayed at the depot, this gain is not sufficient compared to the speed effect on pollution emission.

Obviously, another advantage of the speed is to improve accessibility. So the global node accessibility for persons using their personal car (computed by the mean transportation duration from a node *i* to all the nodes of the Origin-Destination matrix) varies (about) from 4 minutes for the *fast* network to 13 minutes for the *slow* network (and 31 minutes for the *connect* network!). These interesting results lead to the following question: what is the 'acceptable' balance between pollution increase and good accessibility? Since a significant speed increase seems to disagree with current urban planning policies, a *homogeneous* network is set as a good compromise, because the number of circuits and the total mileage are the lowest. On the one hand, that contributes to the economic system reliability, due to an efficient nodal accessibility (better than the actual situation). On the other hand, pollutant emission is only 14% superior to the minimum reached with a *slow* network and only 6% superior of the one from the *current* network. Indeed, a *homogeneous* network allows a good accessibility and, according to its low hierarchy in terms of speed between the arcs, it does not favour shortest time detours on sections assigned of high speeds. These results are confirmed by those obtained with the *second* theoretical *homogeneous* network which leads to the lower mileage and rather low pollutant emissions (only 4% more than the *slow* network).

Table 2: Simulations results

Network	Pollutant Emissions (g)	Standard deviation of pollutant emissions at the scale of the arc	Sum travel duration by car (minutes)	Sum travel distance by car (km)	Mean speed of the travel by car (km / h)	Nodal accessibility by car (minutes)	Homogeneity index	Number of DRT circuits
Current	4 624 092	1 502	12 012	12 088	58	12	88	96
Speed	5 625 954	1 935	9 877	12 172	71	4	155	97
Slow	4 267 016	1 430	13 299	12 055	52	13	118	102
Homogeneous	4 902 521	1 487	10 830	11 822	63	11	124	95
Connect	7 672 819	4 750	31 176	29 013	55	31	72	111

Other findings concern the connectivity. As expected, the *connected* network, with an actual speed and a low connectivity, generates a lot of pollution, because it implies large detours with a low grouping rate in vehicles. Moreover, the *connected* network has been tested with the speeds of all other networks. The results confirm that the higher the hierarchy between arcs in terms of speed, the higher the absolute values of speed, the higher the emissions.

To test the reliability of our results, we simulated different spatiotemporal configurations of demand involving 500

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clients. For the whole cases and indicators, the differences and orders remain similar and allow generalising the analysis. Moreover, the results are the same for 1000 clients. However, a demand growth does not necessarily induce a mileage increase, whatever the network. Indeed, when the demand is denser, it becomes possible, even with the *slow* network, to group people in vehicles. Doubling the demand multiplies the pollutant emissions by 1.8, whereas the number of circuits is only multiplied by 1.3 due to the grouping ability of the optimisation kernel.

We noticed that a *homogeneous* network sets as a good compromise between individual accessibility, pollutant emissions and client grouping rate in vehicles. Those networks are also more homogeneous in the sense they are composed of quite similar types of road sections along circuits. The more homogeneous the section speed, the rarer vehicle braking or acceleration, the lower emission. Due to a lack of technical references on the effects of driving rhythms on pollutant emissions, our model does not integrate yet this parameter of great interest [1]. However, we propose to assess the route homogeneity of the different simulated networks, to make relative the results obtained with the pollutant emission model. To do so, we computed an index of route homogeneity **H** that takes into account the topological structure of the optimized routes:

$$H_n = \frac{Nch_j \;\; L_j}{j} \qquad (2)$$

where:

n is the label of the network

Nch_j is the number of speed changes along the network routes j (acceleration or braking)

L_j is the length of the routes j (kilometres)

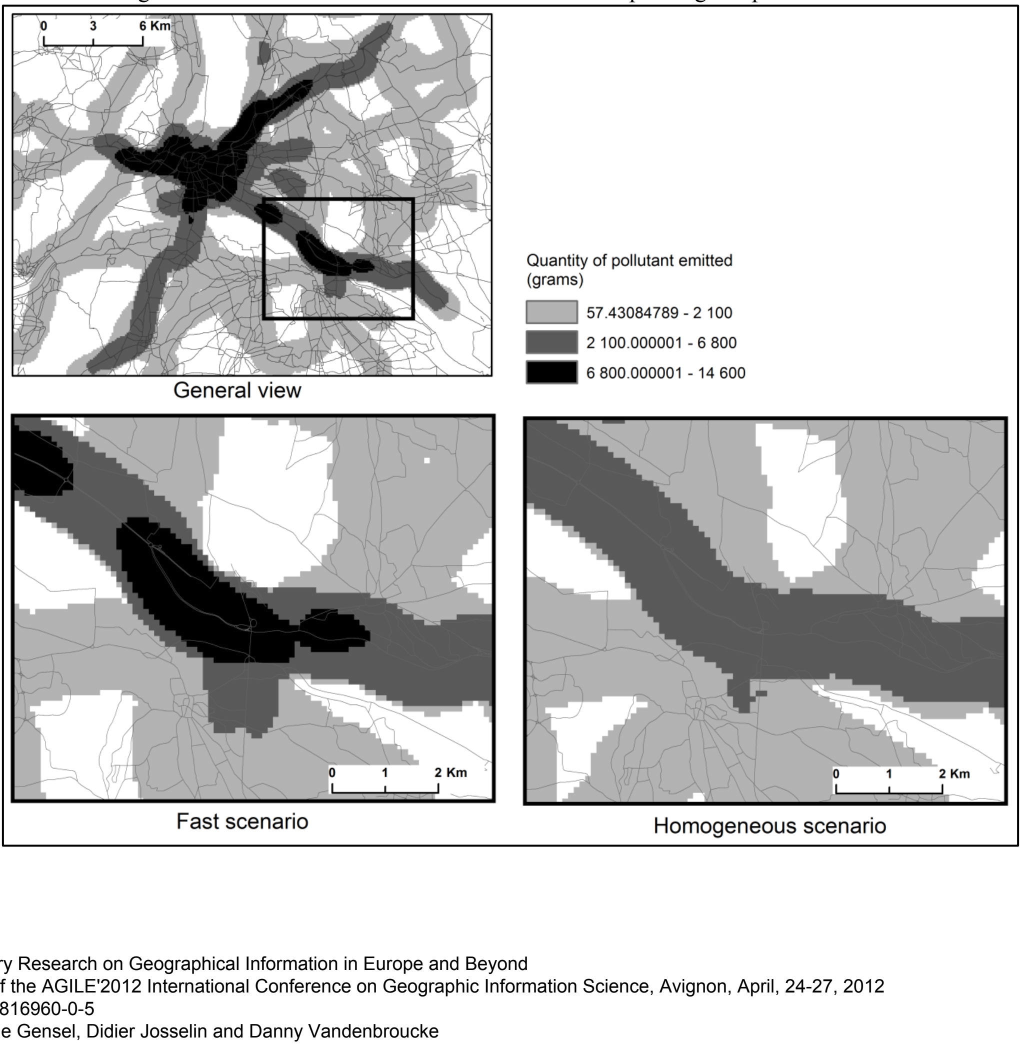
j is the number of routes computed for the network n

For instance, considering 1000 clients, H varies from 200 for the *fast* network to 90 for the *homogeneous* network (respectively 156 and 151 for the *slow* and *current* networks). Once again, these large differences show that *homogenous* networks seem suitable to minimise pollutant emission while preserving a rather good accessibility. Such differences are also visible at a local scale.

Figure 4 depicts pollutant emissions location on the *homogeneous* and the *fast* networks.

Pollutant tends to be more concentrated when the speed hierarchy between arcs is high, especially in areas close to downtown. In this case, the 'betweeness centrality', [6] that is to say the probability for an arc to be integrated in a lot of shortest paths, is concentrated on sections allowing the highest speeds. In contrast with more *homogeneous* networks, an important number of arcs are involved in shortest paths, leading to less hot spots of pollution, and so less public health problems. Indeed, in order to save time, it is not profitable to allow detours by reaching road sections of high speed.

Figure 4: Pollutant emissions : local concentration depending on speed scenarios.



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8 Conclusions

The objective of our work was to study the possible effects of the structure of the road network on pollutant emissions. For a given transportation demand, a given transportation mode (DRT), and a given pollutant emission model, we simulated changes in the topology and in the functionalities of the road network. Also, we examined their effects on pollutant emissions and on the efficiency of the transportation supply.

Using a workflow, integrating a GIS, a RDBMS and a model dedicated to the optimisation of DRT transportation supply, we emphasised the role of the network structure both on pollutant emissions and on the level of accessibility provided. Hence, the network structure should no longer be considered as a black box but rather as a key variable in order to optimise the transportation system and its externalities. Indeed, we highlighted that the current type of network (i.e. with a high hierarchy in terms of speed between the roads), is not optimal either for pollutant emissions or for accessibility. This finding is consistent with other works which pointed out the undesirable externalities of hierarchical networks on automobile dependency [5] or on the fragmentation of urban areas [7].

In contrast, more homogeneous and connected networks appear more suitable to limit pollutant emissions, but also to keep an acceptable level of accessibility.

To confirm and complete our results within further works, we intend to integrate directly in the model the effects of acceleration and deceleration along routes on pollutant emissions. With relevant parameters, this question will be quite easy to solve as our model allows to know the details of the route composition.

Then, to corroborate our results, we shall test the model in other territorial contexts, where the transportation demand is different, in particular in rural areas where DRT are often used.

At last, using a real multicriteria analysis, it seems promising to improve the externalities assessment of the different types of network, regarding the level of pollution, of private car accessibility, and DRT accessibility they induce.

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