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Coupling traffic and emission models: dynamic driving speed for emissions assessment

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Abstract

Emission models can provide an estimation of the environmental impact of road traffic. However, decision makers need to be confident in these assessments in order to implement reduction strategies. The key issue at stake, especially in dense urban zone, is to describe accurately the traffic dynamic and particularly the congestion periods. The proper definition of the link mean speed is the ratio of total travelled distance and total time spent during a given period. This spatial speed description can be easily obtained from a dynamic traffic simulation. However, in operational conditions, it is often deduced from observed speeds on loop detectors or speed limit, which inevitably implies a bias on related emissions to be quantified. For this study we focused on vehicle trajectories in the morning peak for a typical weekday in a 3km^2 urban network. These detailed traffic data represent a considerable amount of data, but allows us to operate any spatiotemporal aggregation used for emission assessment sake. The emission calculations were made at link level each 6 minutes, combining the various traffic indicators and either the Copert emission factors database or Phem model. The related fuel consumption and NOx emissions are compared.

Keys-words: road traffic emissions, emission models comparison, dynamic traffic variable, driving speed.

1 Introduction

Road traffic emissions are known to make large contribution to air pollution in urban areas. In 2013, the transport sector is the largest contributor to Nitrogen Oxides emissions (NO_x), accounting for 46% of total EU emissions (European commission, 2015). Exposure to NOx pollutants concentrations has been

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demonstrated to have detrimental impacts on human health (Shaughnessy & al. 2015), while CO_2 road traffic emissions highly contribute to global warming. Therefore, in the last few years, many efforts have been made to quantify the contribution of greenhouse gas emissions and other pollutants from transportation. Various emission models can provide an estimation of the environmental impact of road traffic, which can range from very local (*e.g.* for some road traffic facilities assessment) to global investigations (*e.g.* for inventories elaborations). A detailed review of the vehicle emission models can be found in (Smit & al. 2010) (Franco & al. 2013), while (Fallah Shorshani & al. 2015) provides a review of the complete modeling chain (traffic, emission, dispersion and stormwater).

However, decision makers need to be confident in these assessments in order to implement reduction strategies. Therefore the inaccuracies and inconsistencies associated to emission estimations cannot be minimized. The urban scale concentrates the main current research efforts, because urban road traffic causes the vehicle kinematics that generate the higher emissions and are the most difficult to take into account, namely rapid speed variations and congestions (Ma & al. 2015)(Ahn & al. 2009), (De Vlieger & al. 2000) (Zhang & al. 2011) (Qu & al., 2015).

2 Objectives

Classical methods for assessing road traffic emissions are based on an aggregated kinematic characterisation of the vehicles flow. Thus, emission model, such as Copert (Gkatzoflias, 2012) needs mean speed and total distance travelled for a given time period to estimate the related emissions. On the contrary, instantaneous models, such as Phem (Zallinger, 2009) provide dynamic emission estimation directly from the vehicle trajectories, taking into account the whole traffic dynamic.

Microscopic traffic models, being good providers of traffic data adapted to emission models, are now considered as relevant for emission estimations (Vieira da Rocha & al. 2013). These models are especially used to provide modal emission models for testing local development scenarios (Xu & al. 2016)(Erdman & al.2016). The sensitivity studies that explored the impact of car-following calibration on emissions (Vieira da Rocha & al.2015)(Lu & al. 2016) give some insights to use them wisely in that purpose. The main benefit of traffic dynamic modelling, especially in dense urban zone, is to describe accurately the vehicles kinematics and particularly the congestion periods. In parallel, it can help evaluating the bias introduced when using aggregated traffic representations at different temporal and spatial scales.

The main objectives of this work are (i) to compare road traffic emission models (Phem and Copert) applied to a large network and (ii) to test innovative ways to transfer information from the traffic model to a « mean-speed » emission model (Copert).

The section 2 presents the simulation framework and the tested models. The section 3 compares the emission estimations.

3 Material

Traffic simulation

The network under study is a 3-km^2 zone covering part of the cities of Le Perreux-sur-Marne and Neuilly-Plaisance, in the Parisian area. The traffic network, displayed in Figure 1, has been selected during the Trafipollu research project, for its high range of traffic conditions. For this study we focused on the morning peak hour for a typical weekday.

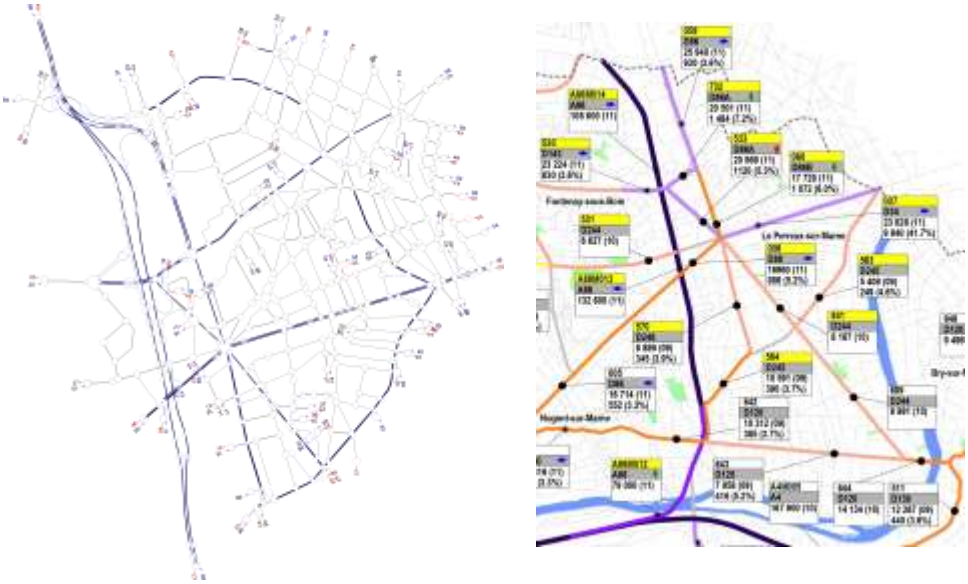

Figure 1: Network of the traffic microsimulation (left) ; traffic experimental data (right) - Trafipollu project

The traffic microsimulation has been implemented within the Symuvia platform, which gives access to the position, speed and acceleration of each vehicle on the network with a 1s-resolution. Vehicles routing choices are governed by a dynamic traffic assignment model, which guides each vehicle on the network on the route that minimizes its travel time towards its initially affected destination.

Vehicles movements at the microscopic scale are governed by a set of rules, including car-following modeling (Leclercq & al., 2007), lane-changes (Laval & al., 2008) and specific movements at intersections. The platform also copes with the cohabitation on the network of vehicle with different kinematics, including passenger cars, buses and heavy-duty vehicles. This detailed traffic data represents a considerable amount of data, but allows us to operate any spatiotemporal aggregation used for emission assessment sake.

All vehicles second-by-second trajectories during the morning peak are extracted from the traffic microsimulation. These speed profiles are either: (i) directly formatted to correspond to Phem model input data, which are 1s-speed time series, or (ii) used to produce aggregated traffic variables, characterizing road segments for each 6min period, in order to correspond to Copert model input data. These aggregated data are composed of a mean speed and a distance travelled, for each road segment and time period.

Various speed definitions are compared for qualifying the vehicles kinematics on each road segments, which correspond to an increasing level of detail that aim to reduce the associated potential errors:

1. The operational (or default) definition describes the speed as the speed limit $\mathbf{V_{limit}}$, which is the first available information. Associating the road segments to $\mathbf{V_{limit}}$ instead of the actual vehicles speeds might however result in high errors.
2. The speed experimented at one specific location on the road segment $\mathbf{V_{loop}}$ corresponds to the local insight that can be obtained through electromagnetic loops. Associating the road segment to $\mathbf{V_{loop}}$ amounts to assuming that vehicle speeds are homogeneous along the segment.
3. The speed characterizing the vehicles kinematics on the whole road segment $\mathbf{V_{spatial}}$ can be determined thanks to the Edie's definition (Edie, 1963), in which the spatial speed is the ratio between the total travelled distance and the total spent time. This speed definition is the more accurate and compatible with the emission estimations, but it relies unfortunately on data not available on a real network.

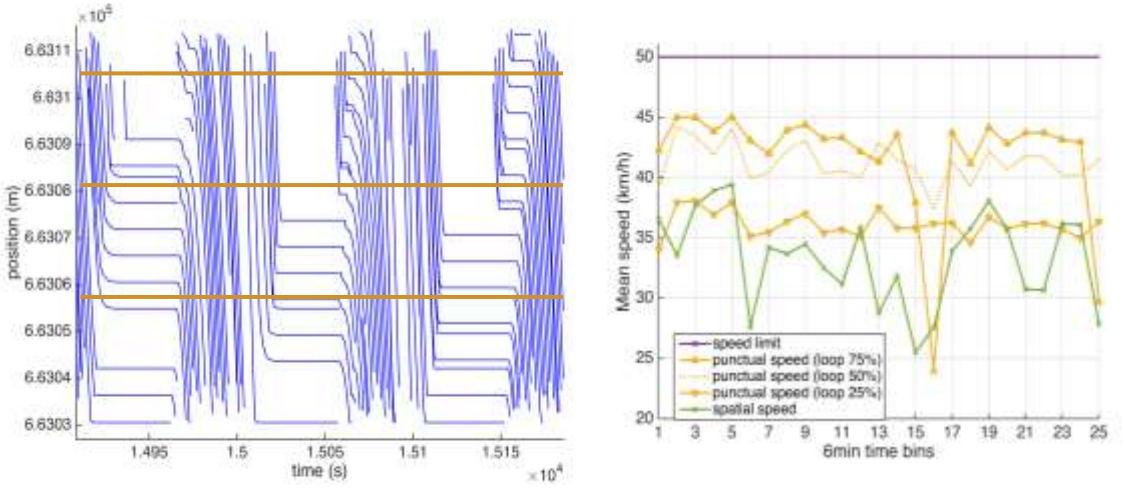

Figure 2: Traffic data: vehicle trajectories (left) – a link mean speed through 5 definitions (right)

These three speed definitions can differ significantly, in particular under congestion, as shown in Figure 2. As expected, the speed limit V_{limit} overestimates the actual speeds. Punctual loops often also result in speed overestimations, which is a long date acknowledged bias. Additionally, the dispersion between the speeds provided by each loop is significant. The resulting emission errors are estimated in the section 3.

Emission modelling

The two investigated emission model types are the modal model and the aggregated model, the implemented models being Phem and Copert IV, respectively. Only hot exhaust emissions are considered. The emission calculations were made at link level, combining the various traffic indicators to the two emission databases. The emissions have been estimated according to the Ifsttar French urban vehicle fleet for the year 2015.

COPERT

Copert IV has been widely used in most European Countries for elaborating the national emission inventories, but it is also extensively used for network emission modeling (Borge et al., 2012, Samaras et al., 2014). However, its use at spatial scales lower than the driving cycles is subject to questions, since the speed distribution might differ and lose representativeness over too small samples or specific traffic conditions (*e.g.* in the vicinity of intersections)(André & al. 2009). Different speed definitions are investigated in section 3.

As any aggregated emission model, Copert IV needs mean driving speed *v (*in km/h) and total distance d (in km) travelled for a given time period to predict the related exhaust emissions. The total emission e (in g) is derived from the unitary emission factors f (expressed in g.km^{-1}), according to formula (1). Unitary emission factors consist of speed continuous functions constructed over driving cycles of about 6mn-length, which are representative of encountered traffic conditions. They are defined for each pollutant k and each vehicle technology *l.*

$$e^{k,l} = d^{l}.\boldsymbol{f}^{k,l}(v^{l}) \qquad (1)$$

We will here consider the simplified formula including the repartition of vehicles over the various technologies for each category (passenger cars, light commercials vehicles, heavy duty vehicles and urban buses). The unitary emission function of a specific category is obtained by operating a weighted average of the vehicle technologies that compose the category. Indeed, even with the finest traffic information, the technology of the vehicle is not individually defined and the emission calculation is generally made at global fleet scale.

$$E^{k,c} = D^{c}.\boldsymbol{F}^{k,c}(V^{c}) \qquad (2)$$

with $\boldsymbol{F}^{k,c}$ the unitary emission factor (g/km) of pollutant k of one of the four categories.

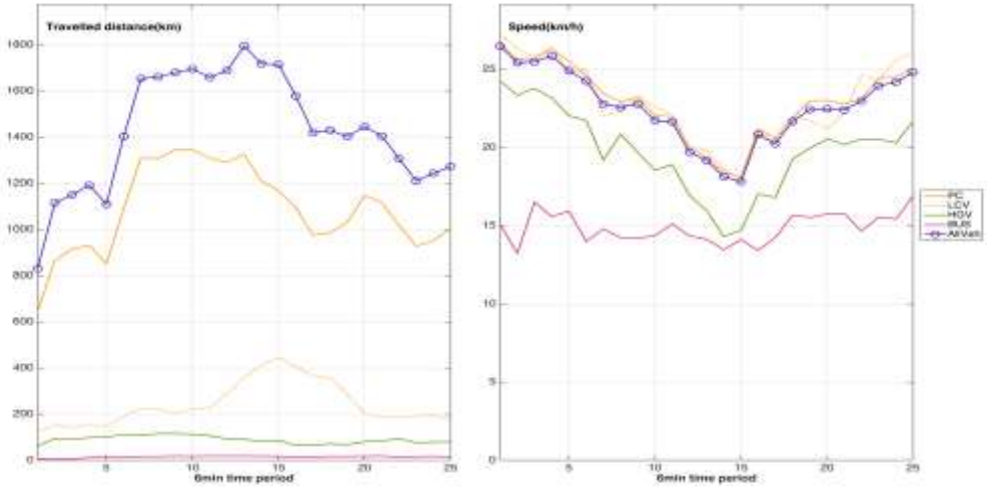

Figure 3 Macroscopic traffic variable experimented each 6min during the morning peak

The emission factors $\boldsymbol{F}^{k,c}$ (in g/km) are defined for the French urban fleet in 2015, in function of the mean speed, over 10km/h, as described by Copert methodology. Though, at link scale, some of the 6mn mean speeds are assigned to a value lower than 10km/h. As emissions are definitely not insignificant at that speed range, the Copert emission curves were extended maintaining the emission factor value at that of 10km/h (straight extension).

PHEM

Phem (Passenger Car and Heavy Duty Emission Model) calculates the fuel consumption and emissions of vehicles based on the vehicle longitudinal dynamics and on engine emission maps, with a 1s time resolution. The model provides an estimate of the engine power of a vehicle at each time step (1s), based on its speed time series and road gradient. The engine speed is estimated based on the transmission ratios and a gearshift model.

Phem has been coupled with dynamic traffic platforms at several occasions, in order to test the impact on emissions of road traffic strategies that modify the vehicle kinematics behavior (Erdman & al. 2016). However, the inadequacy between its required high traffic data resolution and the available dynamic traffic model outputs, which are much less refined, is sometimes matter of questions.

4 Results

This section is devoted to the analysis of the emissions calculations. We will first observe the results with Copert and the impact of the speed definition on emissions assessment. The shape of the Copert emission curves motivates this first study. Indeed, a consequence of this particular shape is that the potential error on emissions is maximum around 35km/h for NOx emissions (respectively around 23km/h for fuel consumption), which is a common mean speed in a city center. Thus, relative error on emissions due to a bias on mean speed is expected to be significant at speed range corresponding to urban scale.

Here, the emissions were calculated at link scale every 6mn thanks to the corresponding traffic variables: distance travelled and mean speed for each vehicle category c. The emission for link-period (j,i) is defined for each pollutant *k* by the following formula :

$$E_{i,j}^{k,c} = D_{i,j}^{c}.\boldsymbol{F}^{k,c}\left(V_{i,j}^{c}\right) \tag{3}$$

where $V_{i,j}^{c}$ is deduced from traffic microsimulation from spatial or punctual virtual sensors. Summing on all the links, we can then observe the impact of speed definition on the emissions over the network.

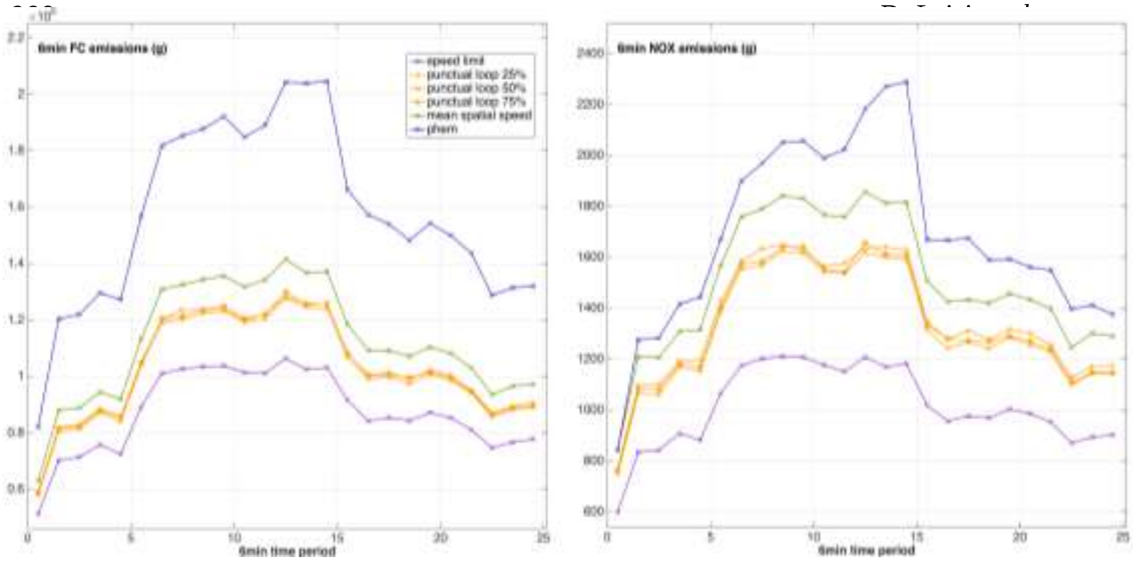

Figure 4: 6min fuel consumption (left) and NOx emissions (right) over the network during the morning peak for the various speed definitions

The figure 4 represents the network emissions for each 6min period, obtained with Copert and the various speed definitions. Degraded speed definitions (speed limit and punctual loops) lead globally to underestimate the emissions. The discrepancies between the calculated emissions are also depending on time, with a maximum gap occurring at the more congested period. The first observation is that, at network scale, the position of the virtual loop does not have a significant impact on the emission levels. We will then focus on the virtual loop positioned in the middle of the link (50% loop). The relative error compared to spatial mean speed has been quantified for each 6min period: for FC, this global error is varying between -3 and -5% with a loop detector (respectively -3 and -5% for NOx) and between -11 à -15% with speed limit (respectively -15 and -21% for NOx).

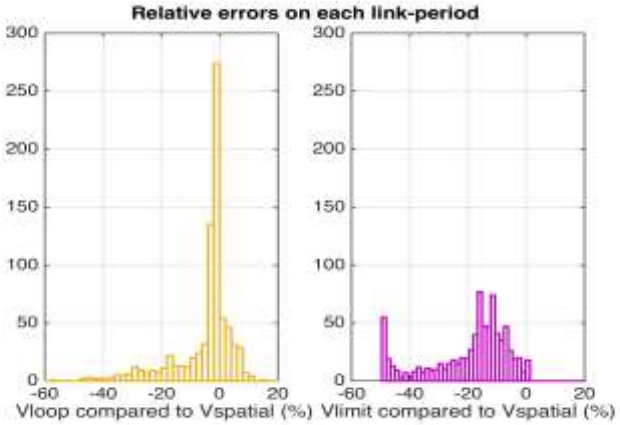

Figure 5: Distribution of relative errors on fuel consumption on links associated to a degraded definition of speed: Vloop (left); Vlimit (right).

The spatial analysis represented in figure 5 shows that the mean relative error for fuel consumption can be ranged from -60% to +20% locally, when using punctual loop definition. Yet, with speed limit definition, the fuel consumption is always underestimated, even locally and the relative error can reach -50%.

The figure 4 also represents the emissions evaluated thanks to the instantaneous model Phem. The implementation of this emission model being stochastic (see fig.6), the curve printed in figure 4 is the mean emission value over 10 replications. Indeed, the stochastic fleet definition impacts not only the local emission but also the network emissions. The mean global gap reaches 5.3% for fuel consumption, respectively 12.5% for NOx emissions. This modal emission model admits the finest dynamic traffic representation (i.e. speed profiles) as input data. It is then not surprising to achieve higher emissions levels, especially for congestion periods. The gap between Copert emissions (with spatial mean speed) compared to Phem emissions has been quantified: the relative errors reach -33% for fuel consumption (respectively -21% for NOx emissions). We can observe a constant gap between the two models for fuel consumption, independent of the congestion. However, the relative errors are always more important in congested periods than in free-flow conditions.

In other words, the congestion peak is particularly underestimated with an aggregated emission model, which leads us to conclude that this bias is partially due to the use of mean speed, that poorly represents vehicle kinematics in bad traffic conditions.

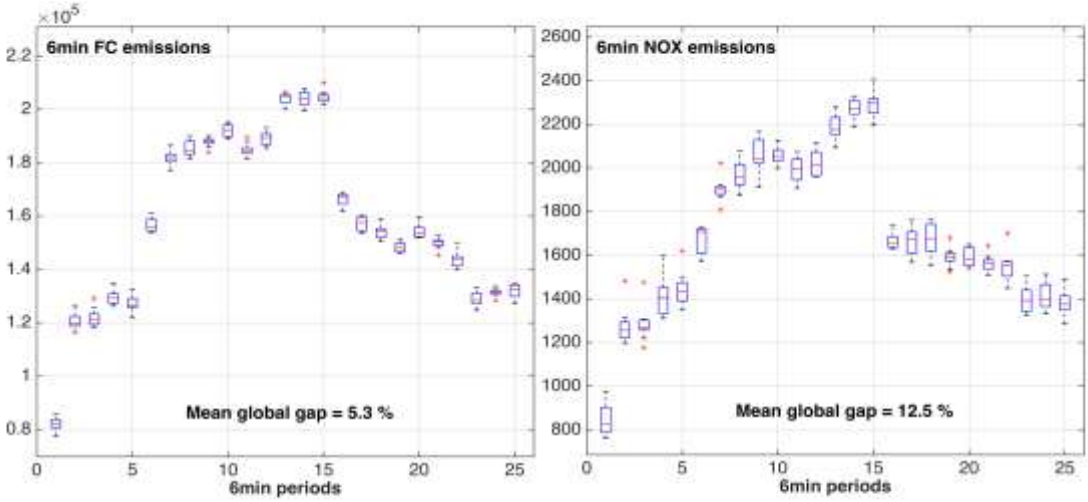

Figure 6: Dynamic network Phem emissions resulting of ten replications.

5 Conclusion

This work proposed a comparison between emissions calculations from a traffic microsimulation, at large urban scale during the morning peak. The testing focused here on looking at the impact of dynamic traffic representations on emissions. This was made in comparing (i) the speed definition as an input data of aggregated emission model and (ii) the emissions evaluated dynamically with a macroscopic traffic variable on one-hand and speed profiles on the other hand.

We confirmed that an accurate representation of vehicles kinematics is needed in order to cope with congestion at urban scale. The use of a degraded speed definition in place of the spatial speed does impact the emissions: the global relative error on fuel consumption (respectively NOx emissions) is -3.8% (-4.3%) with loop detectors and -13.8% (-19.2%) with speed limit. This effect is reinforced in the most congested period and locally.

The use of the finest traffic representation (i.e. trajectories) can also conduct to inaccuracy: the parameter identified is the stochastic way to define the fleet that induces highly variable local emissions.

The differences between the two modeling approaches can be partly explained by the differences between the two databases (hypothesis independent of traffic). However, we think it is possible to work at more coherent results between both models. In order to reach this goal, we will go ahead in working at (i) a better macroscopic traffic indicator compatible with Copert input data and (ii) taking into account more coherently the fleet definition in the two approaches, which is definitively a source of discrepancies.

Acknowledgments

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