DYNAMIC ESTIMATION OF TRAFFIC EMISSIONS IN METROPOLITAN ROAD NETWORKS

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INTRODUCTION

Road traffic is a major source of air pollution, and there is an increasing need for accurate forecasts of vehicles' emissions. At a national scale, aggregate models are in operation (e.g. COPERT 4 (Gkatzoflias, 2007) in Europe, MOBILE 6 (MOBILE, 2000) in the United States). They rely on various statistics on the vehicle operating modes and activity of a large fleet of vehicles, divided in broad classes. A large number of inputs such as mileage per vehicle class, average speed per vehicle class and per road type are combined together. Models of this kind do not directly relate vehicles emissions to traffic dynamics. By contrast, microscopic models estimate emissions by simulating the movement of individual vehicles within a local area, during a particular time period. Because such models entail intensive computations, they are excluded from practice on large metropolitan areas. Current methodologies applied on metropolitan networks rely on average vehicle speed on each link of the network. Static traffic assignment models are used to forecast traffic flow rates and vehicle speed on network links. But since congestion changes with time of day, and because congestion is a major determinant of speed, time-of-day modelling is necessary. Using static models, separate time periods can be considered, but this approach does not capture well the time-continuous reaction of demand to congestion: while congestion levels increase during the day, more and more routes are being used, and at the same time shifts in departure times can be observed. To better handle the time-space dynamics of trips in a network, various dynamic traffic assignment models have been extended to include traffic emission models. Most of them rely on microscopic traffic simulators and for this reason may not be applicable to metropolitan road networks.

This paper presents REALITY, a road activity emission calculation model, together with LADTA, an analytical dynamic traffic assignment model. Together, REALITY and LADTA can help in forecasting fine-grain, time-of-day varying emissions due to traffic.

The paper is organised as follows. Section 1 gives details on the roles of LADTA and REALITY with respect to other packages. The ensemble is targeted for a package dedicated to air quality assessment of transport policy. Section 2 provides a rather simplistic, but fully detailed, example of the kind of analysis that can be performed using LADTA and REALITY. Section 3 gives technical details of the two models, along with some model application results of the Paris area road network. Current limitations and future works are sketched in the conclusion.

1. AIR QUALITY ASSESMENT OF TRANSPORT POLICY

Pollutants emitted by vehicles on the road are either *primary* or *secondary* pollutants. Primary pollutants are those directly produced by vehicles. They include carbon, sulfur and mono-nitrogen oxides (CO_x, SO_x, NO_x). Vehicle speed is the main factor of primary pollutants emissions. *Secondary* pollutants are those resulting from chemical processes in the atmosphere. Ozone (O_3) is an example of a a secondary pollutant. Ozone is a product of chemical reactions activated by the sunlight and involving volatile organic compounds (VOCs).

When concerned with assessing transport policy with respect to air quality, one has to consider not only traffic demand and traffic flow issues, but also emissions from sources other than traffic (e.g. industry, housing), together with the complexity of atmospheric and chemical processes involved in the formation and diffusion of pollutants in the air. The work presented in this paper is part of a larger project whose objective is to improve the way traffic emissions are modelled within the Air Quality Model (AQM) POLYPHEMUS[1] (Mallet et al, 2007). The links between LADTA, REALITY and POLYPHEMUS are illustrated in Figure 1. As stated in the introduction, this paper focuses on LADTA and REALITY (the greyed area in Figure 1).

Given a dynamic OD matrix (the demand) and a transportation network (the supply), LADTA calculates a dynamic user equilibrium between demand and supply, so that for every departure instant from the origin, each user is assigned a route in the network that minimizes its travel cost to destination. Also, LADTA allows for multi-class assignments, where a class is a set of users that are identical with respect to (i) their travel mode characteristics (e.g passenger cars, trucks) and (ii) their economic preferences (e.g. value of time). As an output of equilibrium, flows and speeds are available for every class, every instant, and every link in the network. Changes in traffic management (e.g. time varying tolls, speeds or capacities) are modelled by modifying accordingly the network data. Changes in demand management are modelled through the OD matrix and users preferences.

[1] The air quality model POLYPHEMUS is developed by CEREA (Centre for atmospheric research of ENPC_ParisTech and EDF).

Once link flows and speeds per vehicle class are available, REALITY computes road traffic emissions. For the rest of the paper, the word *emissions* (or *road traffic emissions*) will denote the primary pollutants directly emitted by vehicles on the road (this excludes for instance the evaporative pollutants emitted by parked vehicles). Road traffic emissions not only depend on traffic flow characteristics, but also on the composition of the fleet of vehicles, on the fuels used in the area of interest, and on numerous other factors, including weather conditions.

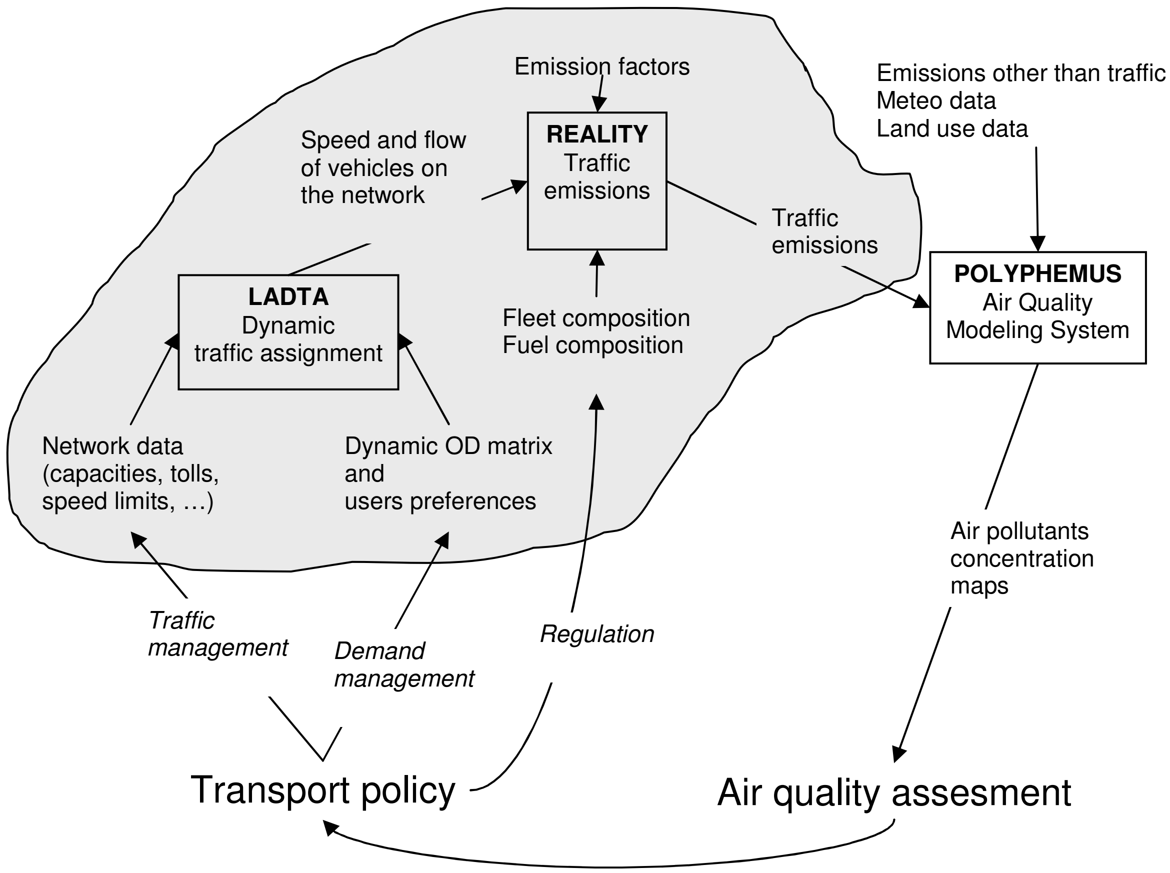

Figure 1: Ex-ante evaluation of transport policy using LADTA, REALITY and POLYPHEMUS.

For the time being, REALITY computes emissions for the following primary pollutants:

- **Particulate Matter (PM).** Particulate matter emissions comprise *exhaust particles* emitted for instance by diesel-fuelled engines, and *non-exhaust particles*. The presence of non exhaust-particles in the atmosphere due to road traffic is the result of brake wear, tyre wear, road surface abrasion and resuspension of dust on road surfaces.
- **Carbon oxides (COx).** They result from combustion of hydrocarbon fuels. When used in good conditions, a internal combustion engine would essentially emit carbon dioxide (CO_2) and water. But at low engine loads, products of incomplete combustion dominate. Carbon monoxide (CO) is one of them.

- **Nitrogen oxides (NOx).** Most of the NOx in road traffic emissions is composed of nitric oxide (NO), resulting from the oxidation of nitrogen by oxygen during combustion in the engines. Nitrogen oxide (NO_2) mainly results from a chemical reaction between NO and O. The fraction of NO_2 directly emitted by vehicles is usually taken as 5% (in volume) of the total NOx.
- **Nitrous oxide (N_2O).** Emissions are particularly important for catalyst vehicles.
- **Sulfur oxides (SOx).** SO_2 is emitted largely from diesel fuel. It is usually found within fine sulfate particles.
- **Volatile Organic Coumpounds (VOCs).** A large variety of organic chemical compounds are generated by road traffic. Some, like benzene or formaldehyde, have a direct impact on human health. Others present a high ozone forming potential.

2. THE TINY CITY EXAMPLE

This section illustrates, through an example, the use of LADTA and REALITY. The scenario presented here is entitled *the Tiny City example*. Albeit simplistic, this scenario deals with all aspects of a *ex-ante* air-quality assessment of a change in traffic management.

Because of recurring congestion on their daily way to work, the inhabitants of Tiny City are urging their mayor, Mr. Huge, to deploy traffic control strategies to improve their situation. At the same time, they are likely not to approve strategies that would increase pollution due to traffic: it is a well known fact that a vast majority of Tiny City towners claim to be environmentally conscious. Mr. Huge asked his traffic experts to elaborate a scenario to ameliorate traffic conditions in Tiny City. The current and projected traffic scenarios are presented through Sections 2.1 to 2.4. Whether the projected situation would be better or not (with atmospheric pollution concerns in mind) than the current situation is discussed Section 2.5 where the reader also discovers if Mr. Huge has succeeded in his re-election.

2.1. The Tiny City road network

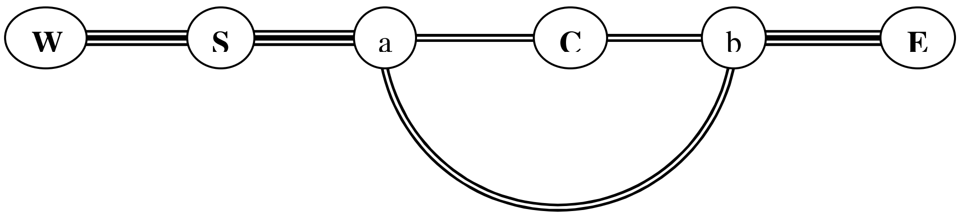

Figure 2: the Tiny City network.

The Tiny City road network is depicted in Figure 2. It comprises motorways and arterials. The central business district of Tiny City is point **C**. a and b are interchanges where arterials to/from **C** connect to motorways. **S** is the Tiny City's suburban area. All the inhabitants of Tiny City live in **S**, and they all work in **C**. The beltway between a and b allows the transit of traffic coming from **W** and going to **E** to bypass the city center during peak hours. Free flow travel times and capacities of the Tiny City road network links are given in Table 1.

Link	**Free flow travel time** (h) Passenger cars	Trucks	**Capacity** (pcu/h)	**Length** (km)
W-**S**	0.1	0.15	4,000	12
S-a	0.1	0.15	4,000	12
a-**C**	0.1	0.15	2,500	8
C-b	0.1	0.15	2,500	8
b-**E**	0.1	0.15	4,000	12
a-b	0.3	0.45	4,000	16

Table 1: Links properties of the Tiny City road network.

For passenger cars, going from a to b by the beltway takes 6 minutes more than by passing through the city center. The time increase for trucks is about 9 minutes.

2.2. Demand on the Tiny City network

During the morning of an average working day, the travel demand on the Tiny City road network is as follows. Between 7 a.m and 8 a.m, Tiny City inhabitants go to work. A flow of 2,000 passenger cars per hour travels from **S** to **C**. The transit traffic, going from W to E, has started at 5 a.m, with a flow of 250 trucks per hour between 5 a.m and 6 a.m. This flow doubles between 6 a.m. and 9 a.m. It then decreases to 250 trucks per hour between 9 a.m and 10 a.m. The flow of transiting passenger cars follows the same pattern, starting at 500 pcu/h between 5 a.m and 6 a.m. In the sequel, it is assumed that one truck is equivalent, with regard to traffic flow, to two passenger cars.

2.3. Current traffic conditions

Using those inputs, one can measure traffic conditions on the Tiny City network using a dynamic traffic assignment (DTA) model. In what follows, the LADTA ToolKit (LTK), a computer implementation of LADTA, has been used. More details concerning both LADTA and the LTK are provided in Section 3.1.

Travel times at user equilibrium on the Tiny City network are plotted in Figure 3. Before 6:30 a.m, the travel time from **W** to **E** remains constant and equal to 30 minutes (0.5 hour) for passenger cars (pc), and to 45 minutes (0.75 hour) for trucks (tr). The best route for transit traffic is to go through the city center. The travel time for inhabitants of Tiny City, going from **S** to **C**, increases between 7 a.m and 7:30 a.m, from 12 minutes (0.2 hour) to 21 minutes (0.35 hour). After 7:30 a.m, it remains stable, and then decreases between 8 a.m. and 8:30 a.m. The increase in travel time is due to congestion on link a-**C**, which is used by both the inhabitants of Tiny City and the transit traffic.

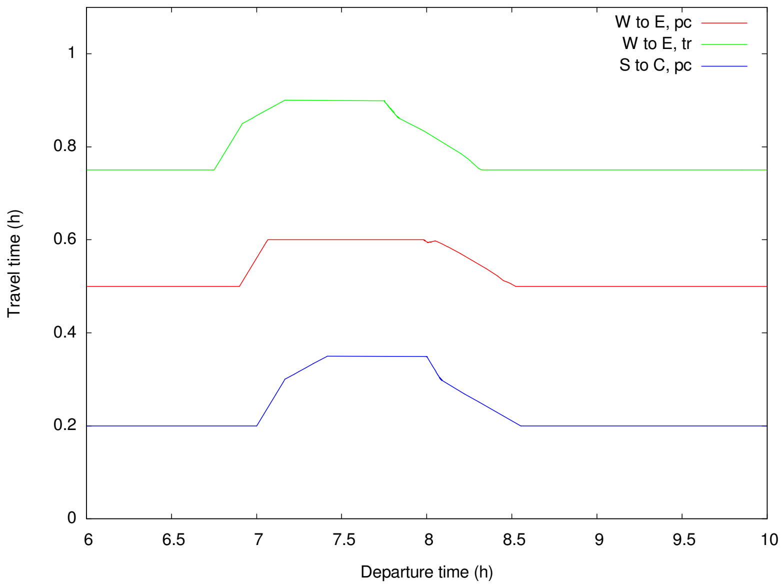

Figure 3: Travel times for some OD pairs on the Tiny City road network.

During the congested period, the transit traffic also uses the beltway. The increase in travel time of the route passing through the city center makes the beltway an interesting alternative. This can be observed on traffic flow patterns at equilibrium. Such patterns, for links a-**C** and a-b, are plotted in Figure 4. One can see that the transit traffic starts using the beltway (i.e. the link a-b) a short instant after 7 a.m. Between 7:30 a.m. and 8 a.m. the transiting trucks are equally distributed on the two possible routes. Transiting passenger cars can use again the route through the city center soon after 8 a.m., when all Tiny City inhabitants have reached their place of work.

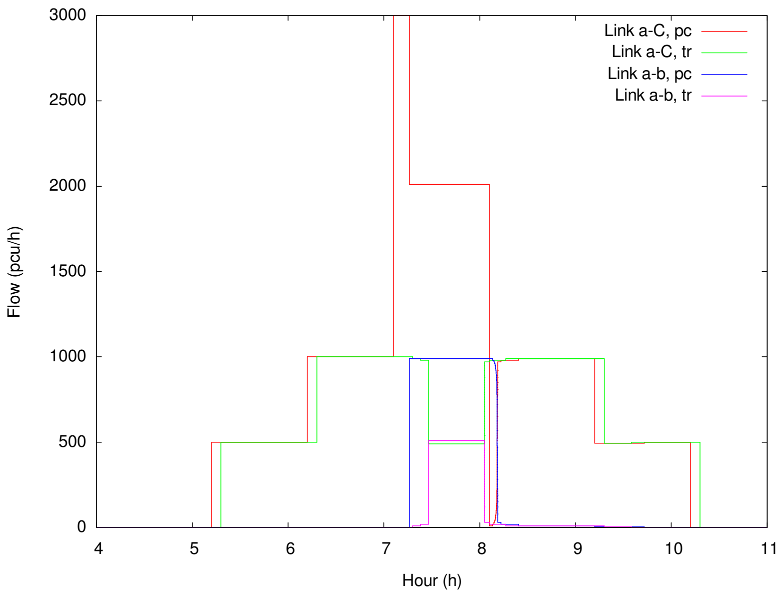

Figure 4: Flow profiles at equilibrium on the Tiny City road network.

2.4. Projected traffic conditions

The projected scenario defines two traffic management measures. First: enforce transiting trucks to use the beltway all the time. Second: add a travel time penalty of 3 minutes on link **C**-b. This still allows for transiting passenger cars to pass through the city center when it is not too heavily congested (allowing for transit passenger cars in the city center is a necessary condition to maintain business activity in Tiny City).

If this scenario was implemented, the traffic flow patterns (as computed by the LTK) would look like those plotted in Figure 5. The entire truck transit traffic would be diverted to the beltway. During the morning peak, half of the passenger cars transit traffic would also be diverted to the beltway, except during a short lapse of time after 7 a.m, during which all the passenger cars transit traffic would still use the route through the city center.

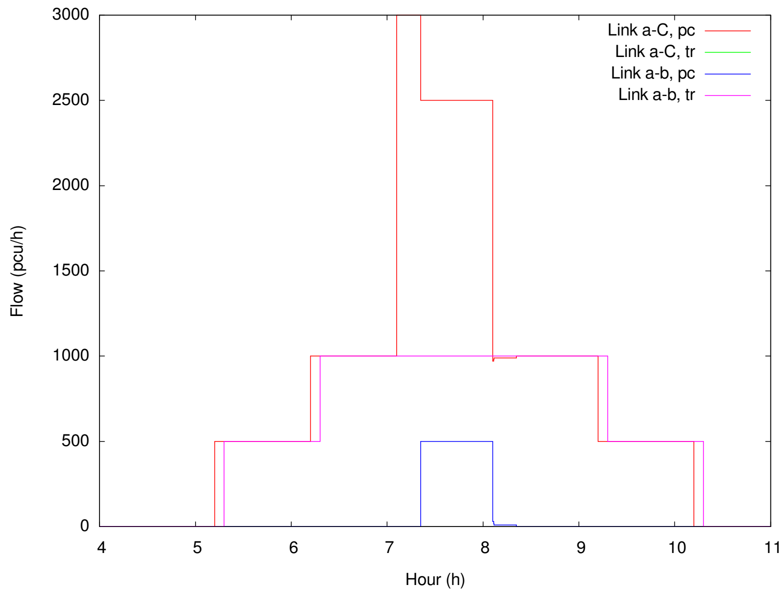

Figure 5: Flow profiles at equilibrium on the Tiny City road network (projected).

The projected travel time profiles are plotted in Figure 6, together with the travel time profiles in the current situation, to allow for comparison between the current and the projected situation. Transiting trucks are now using the beltway all the time, and experience a travel time of 54 minutes in the **W** to **E** direction. Transiting passenger cars see an increase of 3 min of their travel time, except during the morning peak during which the beltway and the route through the city center present the same travel time. Finally, Tiny City inhabitants clearly benefit from the projected measures. Their time loss in congestion has been reduced by more than 50%.

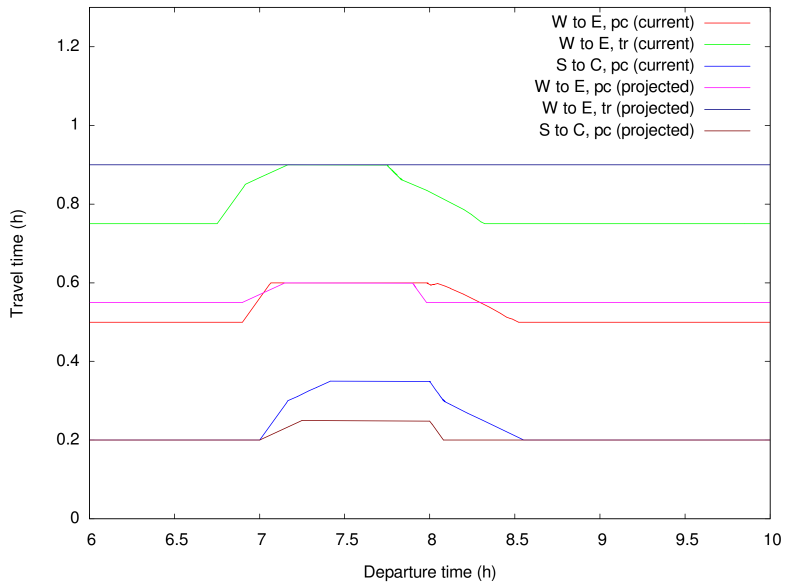

Figure 6: Travel times for some OD pairs on the Tiny City road network (projected and current).

2.5. From traffic data to emissions

Relating traffic data to traffic emissions has been the subject of a large body of literature for the past decade (see for instance the references cited in (Boulter P. and McCrae I., 2007; MOBILE, 2000). Following (Boulter P. and McCrae I., 2007), vehicle emissions models can be classified in four categories: instantaneous emission models, kinematic regression models, traffic situations models and average speed models. All those models do essentially express *hot emissions* as a function of the vehicle speed. Correction factors are applied to take into account road gradient, vehicle load, the use of auxiliaries such as air conditioning, cold start emissions and evaporative emissions.

Instantaneous emission models, such as EMPA (Ajtay et al., 2005), PHEM (Zallinger et al., 2005) or VERSIT+ (Smit, 2007) use few vehicle-operating variables and multidimensional look-up tables. PHEM for instance uses as vehicle-operating variables, the engine rotation speed and the effective engine power. During an emissions test, emissions measurements are used to fill in the cells of the look-up table. One can compute the emissions of a particular vehicle during a trip, by summing the instantaneous emissions over the duration of the trip. This kind of model can be applied when microscopic traffic simulators are used, since the vehicles operating variable are available at every model time step.

At the opposite side of the spectrum, *average speed models* (Eggleston et al., 1993; Joumard, 1999;) consider that the average travelling speed of a vehicle on a link allows for a good estimation of the vehicle's emission along the link. Those models are of high practical interest as they require less inputs than instantaneous models. As done by REALITY, average speed models found in the Emission Inventory Guidebook 2009 published by the European Environment Agency are applied here to estimate hot emissions on the Tiny City road network (see (EEA, 2009), Part 1.A.3.b, Tier 3 Methodology). In what follows, only hot emissions for CO are considered. For didactic purposes, all correcting factors are deliberately ignored.

All passenger cars in Tiny City are Euro 4 compliant with gasoline powered engines. Hot emissions for CO are based upon the Emission Factors (EF) defined by:

$$EF_{pc,l}(h) = \frac{a + c \cdot V_{pc,l}(h) + e \cdot .V_{pc,l}(h)^2}{1 + b \cdot V_{pc,l}(h) + d \cdot V_{pc,l}(h)^2}$$

where:

- $EF_{pc,l}(h)$ is the quantity of CO exhausted by one passenger car entering link l at instant h, per distance unit. It is expressed in $g.km^{-1}$.
- $V_{pc,l}(h)$ is the average speed of passenger cars on link l at instant h, expressed in $km.h^{-1}$.
- a,b,c,d,e are parameters set to the following values:

a	1.36E-01
b	-1.41E-02
c	-8.91E-04
d	4.99E-05
e	0.0

All the trucks in Tiny City are Euro 4, 3 axles trailer, with diesel powered engines. Roads in Tiny City have a 0% gradient, and all trucks have a load factor of 100%. Hot emissions for CO are based upon the Emission Factors (EF) defined by:

$$EF_{tr,l}(h) = e + \frac{a}{\exp(b \cdot V_{tr,l}(h))} + \frac{c}{\exp(d \cdot V_{tr,l}(h))}$$

where:

- $EF_{tr,l}(h)$ is the quantity of CO exhausted by one truck entering link l at instant h, per distance unit. It is expressed in $g.km^{-1}$.
- $V_{tr,l}(h)$ is the average speed of trucks on link l at instant h, expressed in $km.h^{-1}$.
- a,b,c,d,e are parameters set to the following values:

a	0.506901027
b	0.042877259
c	1.652054538
d	0.19652392
e	0.089541078

CO emissions on a link l during time interval $(h_1;h_2)$ are obtained by summing over the classes of vehicles and the time period the emission factors multiplied by the flow of vehicles of this class, i.e.:

$$E_l(h_1,h_2) = \sum_{c\in\{pc,tr\}} \int_{h=h_1}^{h=h_2} q_{c,l}(h) \cdot L_l \cdot EF_{c,l}(h)\ dh$$

where L_l is the length, expressed in km, of link l. Numerical results for the links in the Tiny City network are given in Table 2. Two time periods are considered: *all day* and the *morning peak* (from 7 a.m. to 8:30 a.m.), for both the current and projected situations.

Link	All day		Morning peak (7-8:30 a.m.)	
	Current	Projected	Current	Projected
W-**S**	57.6	57.6	21.6	21.6
S-a	83.9	83.9	47.9	47.9
a-**C**	15.8	13.1	6.4	6.3
C-b	12.4	6.5	2.7	1.9
a-b	8.5	16.6	8.4	8.2
b-**E**	58.0	59.1	20.0	23.1
TOTAL	**236.3**	**236.8**	**106.9**	**109.0**

Table 2: CO emissions, per link, in kg.

Figures in the total row of Table 2 show that for the whole network and all day period, CO emissions do not change when comparing the current situation to the projected situation. There is even a very small increase (around 2%) in CO emissions for the whole network during the morning peak. When looking at arterials connecting the city center to the beltway (i.e. links a-**C** and **C**-b), the gains are significant, with a drop of 30% for the all day period.

Once implemented, the projected traffic management measures gave the expected results. Tiny City inhabitants are happy to get to their workplace faster and having in a cleaner air. Mr. Huge is re-elected with a comfortable majority. It is now time to leave Tiny City and to come back to LADTA and REALITY.

3. LADTA AND REALITY

This section provides a more technical overview of the two models (Sections 3.1 and 3.2), along with some application results on the Paris area road network (Section 3.3).

3.1. LADTA

As stated before, LADTA is a analytical model that expresses a dynamic user equilibrium between the demand and the supply on a transportation network, so that for every departure instant from the origin, each user in the demand is assigned a route in the network that minimizes its travel cost to destination. LADTA not only allows for multi-class assignments with fixed departure time, as illustrated in the Tiny City example (see Section 2), but also for multi-class assignments with departure time choice. The computer implementation of LADTA is called the Ladta ToolKit (LTK). While still being experimental software, the LTK and the algorithm implemented therein have been designed to handle arbitrarily large networks in a efficient manner. The design principles of the LTK, together with an application to the Paris area road network are fully detailed in (Aguiléra and Leurent, 2009).

This section focuses on a formal presentation of the model. The *user optimum assignment with fixed departure time* is stated as a fixed point problem in Section 3.1.1, along with some helpful notations. Then the u*ser optimum assignment with departure time choice* problem is stated in a similar way, in Section 3.1.2. The existence of such fixed points has been established recently by (Meunier and Wagner, 2010) in a continuous game theory framework. The reader interested by numerical algorithms and implementation of the assignment with departure time choice can refer to (Aguiléra and Wagner, 2009).

3.1.1. User optimum assignment with fixed departure time

A road network is modelled as a directed graph $G=(N,A)$, where N is a finite set of nodes and $A \subseteq (N \times N)$ is the set of arcs in G. A route r in G is a finite, non empty, sequence of connected arcs. R denotes the set of routes in G. Users of the transportation network are modelled as a continuum of microeconomic agents, where each user belongs to a user class u. U denotes the set of user classes. To each route r in R is associated a route traversal time function $t_{r,u}(h)$, where h is a departure instant from the head node of the route, taken in a continuous set of instants H. Also, a route traversal cost function $c_{r,u}(h)$ is associated to each route r in R. If $i=(o,d), o \neq d$ is a distinguished pair of nodes in $N \times N$, then $R_i \subseteq R$ denotes the set of routes starting at o and ending at d. $x_{i,u}(h)$ is the density of users wishing to depart from o at instant h, and $X_{i,u}(h) = \int_{h'<h} x_{i,u}(h')dh'$ is the cumulated distribution of such users.

Route choice

Given a fixed set I of o-d pairs, a demand $X_{I,U} = \{X_{i,u}\}$, and a set of route traversal cost functions $c_{R,U} = \{c_{r,u}\}$, a *route choice* RC is the definition of a set $X_{I,R,U} = \{X_{i,r,u}\}$ of distributions of users on routes per o-d pair such that, for all (i,h,u) triples, the two following equations hold:

$$\sum_{r \in R_i} X_{i,r,u}(h) = X_{i,u}(h) \tag{1}$$

$$x_{i,r,u}(h) \neq 0 \Rightarrow c_{r,u}(h) = \min_{r \in R_i}\{c_{r,u}(h)\} \tag{2}$$

Eq. (1) expresses that, at every departure instant, the demand of users of class u on the o-d pair i is distributed among the routes of this o-d pair. Eq. (2) expresses that only routes of minimal cost are chosen. Using a compact notation:

$$X_{I,R,U} = \mathrm{RC}\left(X_{I,U}, c_{R,U}\right)$$

Traffic flowing

Knowing a distribution $X_{I,R,U}$ of users on routes, a *traffic flowing* TF is a function that returns a set of routes traversal cost and time functions. Using a compact notation:

$$\left(c_{R,U}, t_{R,U}\right) = \mathrm{TF}\left(X_{I,R,U}\right)$$

LADTA uses a vertical queue model to simulate traffic flow along a link l, with a bounded capacity at its exit. The model has three inputs: a vector $X^{+}_{l,u}(h)$ of cumulated flows entering the link; the capacity flow rate of the link $\kappa_l(h)$; a vector $t_{0,l,u}(h)$ of minimum travel time functions. Outputs are: the vector of exit cumulated flows $X^{-}_{l,u}(h)$; a vector of traversal time functions $t^{+}_{l,u}(h)$; and if needed the queued volume $Q_l(h)$. There are two constraints on the exit flows. The *capacity constraint* imposes :

$$\frac{\partial X^{-}_{l}}{\partial h}(h) \le \kappa_l(h)$$

with $X^{-}_{l} = \sum_u \varepsilon_u X^{-}_{l,u}$ and ε_u the passenger car equivalent of a class u user. The *minimum traversal time constraint* imposes that, for any couple of instants (h_1, h_2) :

$$X^{-}_{l,u}(h_2) = X^{+}_{l,u}(h_1) \;\Rightarrow\; h_2 - h_1 \ge t_{0,l,u}(h_1)$$

A vector of traversal time functions $t_{l,u}$ is *acceptable* if the associated vector of cumulated output flow $\chi^{-}_{l,u}$, defined by $\chi^{-}_{l,u}(h + t_{l,u}(h)) = X^{+}_{l,u}(h)$, verifies both constraints. $t^{+}_{l,u}$ is defined as the component wise lower bound in the set of acceptable vectors of traversal time functions. The associated vector of cumulated output flows $X^{-}_{l,u}$ is defined by $X^{-}_{l,u}(h + t^{+}_{l,u}(h)) = X^{+}_{l,u}(h)$. For every exit instant $\hbar$, the queue volume verifies

$$Q_l(\hbar) = \sum_u \varepsilon_u X^{+}_{l,u}(h_u) - X^{-}_{l}(\hbar)$$

with h_u such that $h_u + t_{0,l,u}(h_u) = \hbar$

User optimum assignment with fixed departure time

Given a demand $X_{I,U}$, a *user optimum assignment with fixed departure time* $\mathrm{UOA}\left(X_{I,U}\right)$ is a route choice $\tilde{X}_{I,R,U}$ such that:

$$\mathrm{UOA}\left(X_{I,U}\right) = \tilde{X}_{I,R,U} \in \left\{\mathrm{RC}\left(X_{I,U}, \mathrm{TF}\left(\tilde{X}_{I,R,U}\right)\right)\right\}$$

The LTK currently uses a Method of Successive Averages based algorithm to compute this fixed-point.

3.1.2. User optimum assignment with departure time choice

The dynamic assignment with departure time choice is modelled in a supply demand framework where the supply is a network of bottlenecks and the demand a set of microeconomic agents. Those agents are characterized by economic preferences (value of time and delay cost function), temporal preferences (preferred arrival time) and physical characteristics (vehicle type). The network is subject to congestion and hence to a given demand the supply model associates a set of arc traversal time functions. Similarly the demand reacts to the supply by adjusting the time varying flows at the entrance of each route of the network according to the level of congestion.

Delay cost function

A delay cost function D is a positive and continuous mapping between delays and cost units, such that $D(d) \to +\infty$ when $|d| \to +\infty$. In practice, D is often such that $D(0) = 0$, but this is not a requirement.

Optimal routes and departure instants

When travelling from o to d, if a user $x_{i,u}$ wants to reach the destination d at a given arrival instant h^*, following a given route r in R_i, he has to choose a departure instant h such that $h + t_{r,u}(h) - h^* = 0$. More generally, if D_u is a delay cost function associated to the user class u, and if $x_{i,u}$ wishes to minimize its total traversal cost, he has to choose a departure instant h that minimizes :

$$G_{u,h^*}(r,h) = c_{r,u}(h) + D_u\left(h + t_{r,u}(h) - h^*\right)$$

Departure choice

For a given arrival instant h^*, let $x^*_{i,u}(h^*)$ be the density of users of class u on the o-d pair $i = (o,d)$ wishing to minimize their total traversal cost from o to d. Let $\Gamma_{i,u}(h^*)$ the subset of $R_i \times H$ where the total traversal cost G_{u,h^*} reaches its minimum. Then any set of density functions χ_{i,u,h^*} such that :

$$\int_{(R,H)} \chi_{i,u,h^*} = \int_{(r,h)\in\Gamma_{i,u}(h^*)} \chi_{i,u,h^*} = x^*_{i,u}(h^*)$$

defines a departure choice $X_{I,R,U}$, using the demand density functions defined by $x_{i,r,u} = \int_{h^*} \chi_{i,u,h^*}(r,\bullet)$. Using a compact notation:

$$X_{I,R,U} = \mathrm{DC}\left(X^*_{I,U}, \left(c_{R,U}, t_{R,U}\right)\right)$$

User optimum assignment with departure time choice

Given a demand $X^*_{I,U}$, a user optimum assignment with departure time choice $\mathrm{UOA}^*\left(X^*_{I,U}\right)$ is a route choice $\tilde{X}_{I,R,U}$ such that:

$$\mathrm{UOA}^*\left(X^*_{I,U}\right) = \tilde{X}_{I,R,U} \in \left\{\mathrm{DC}\left(X^*_{I,U}, \mathrm{TF}(\tilde{X}_{I,R,U})\right)\right\}$$

3.2. REALITY

REALITY (Lebacque, 2010) is a model that calculates emissions of pollutants produced by traffic on a road network. A road network consists of many links. On each link there is a volume of traffic that varies by time of day and moves at various speeds depending on its density. Each car is a moving source of pollution. Given the volume of traffic at different times of day and the corresponding time dependent variations in speed, pollutant emissions vary on each link at different times of day.

The objective in the design of REALITY is to capture variations in pollutant emissions on any given network. Two different levels of pollutant emissions are calculated, link level, and grid cell level pollutant emissions. Traffic produced pollutants are dispersed in the air. To measure advection and dispersion, the network is partitioned among grid cells of fixed sizes. A grid cell is a rectangle. The user decides on the size of a grid cell. Once the size of a grid cell is determined, then it stays fixed for the duration of analysis. The typical order of magnitude of the size of a grid cell is a square kilometer. A typical grid cell in the context of the REALITY model represents an area that contains several network links. The number of links in each grid cell depends on the size of the grid cell, and its position on the network. For example, in the case of Ile de France (Paris and the suburbs), a grid cell of area approximately equal to 20 square kilometers that is situated within the center of Paris can have as many as 1116 links in it. There are also no-link grids. These grids cover the gaps, or are at the periphery of the network. Grid cell emission is the sum of the emissions of all the links in a grid cell.

REALITY is a new model in the sense that it calculates pollutant emission as a function of volume and speed of traffic at various times of day. It provides more realistic emission levels that vary in time and represent the level of activity on a network. The time intervals vary depending on the needs of users. Emissions can be calculated for one large interval of 24 hours (a whole day), or they can be calculated per hour, per fraction of an hour, or simply for any instant of time. Emissions are calculated for each link in the network. They are also calculated for grid cells in the form of tables of emissions. In such a table each entry represents a grid cell. Many grid cells contain at least one link. Links can stretch among several grids. Each grid in this case contains a fraction of a link. For each fraction of a link, a fraction of a total emission on the link is calculated. Thus each entry in the table is the total grid cell emission resulting from the sum of link emissions that are contained in the grid cell.

REALITY consists of three main blocks: pre-processing, processing, and post-processing. At the pre-processing stage, input data is read and several necessary quantities needed as input for other programs are calculated. In the processing stage, the following variables are calculated: a) emission factors per link, by pollutant type, by vehicle class, and by time of day, b) link emissions by pollutant, vehicle class, and time of day, c) grid cell emissions by pollutant, vehicle class, and time of day, and finally d) emission tables of pollutants for a lattice consisting of many grid cells. There are in total 7 major programs. The programs are sequential. The seven programs are 1) data-treatment and 2) find-min-max-long-lat-link, in the pre-processing block. The following four programs are in the processing block: 1) emission-factor-calculator, 2) link-emission, 3) link-to-grid, and 4) grid-emission. The post-processing block is the last program: 1) graphics. The description of each program is given in the following sections. All the programs are written in C++. The graphics program is written using the free software program Scilab. The operating system of REALITY is the UNIX system. REALITY requires three free software packages to be installed prior to the installation of REALITY itself. The three required free software packages are: Kdevelop (C++), Scilab, and Python. Python will eventually be used to connect all 7 programs.

3.2.1. Pre-processing

<u>data-treatment algorithm</u>

The primary input into the data treatment program is: network data and fleet composition. The network data includes geometry and traffic data. Geometry data is the latitude and the longitude of the end points. Traffic data includes average link flows and speeds. Link flows are given by vehicle category and by time of day (h). Vehicle category refers to a broad classes of vehicles with similar technologies. An example of two different vehicle categories is passenger cars, and heavy duty vehicles. Similarly, link speeds are given by vehicle category and by time of day. The primary input data is the output of a dynamic traffic assignment model, or in some cases is obtained from field measurements (e.g. traffic loop data). Fleet composition is the percentage of each vehicle class in each vehicle category. Vehicle class refers to fuel type consumption, weight, or engine capacity, and age of each vehicle. The algorithm data-treatment reads in the input data, and calculates the following items:

- *flows on links by vehicle class* – represented here by variable $q_{k,l}(h)$, where l indicates a link number and k represents a vehicle class. Vehicle classes range from passenger cars differentiated by their weight, engine capacity, to heavy-duty vehicles also differentiated by weight and engine capacity. To calculate traffic volume split between vehicle classes, the model uses vehicle fleet by vehicle age composition data (Lacour, Joumard, 2002). In the present version of REALITY two vehicle classes are considered: cars to represent all passenger (light) vehicles, and trucks to represent all classes of heavy duty vehicles. Age usually, refers to the time lapse between the date of purchase and the present.
- *fuel consumption* – the program calculates fuel consumption for each vehicle class, as a function of fuel type. It is assumed that fuel consumption is a function of vehicle speed and class. If no information on engine capacity is available, then this variable can be substituted by vehicle weight. Fuel consumption for pollutants is calculated

using speed dependency-fuel consumption tables found in (EEA, 2009), as implemented in COPERT[2].

- *arc lengths* – the length of link l, represented as L_l. It is calculated given the latitude and the longitude of the end points of the links in a network, and a reference variable which is the earth's radius.

find-min-max-long-lat-link algorithm

The input data into this program is the latitude and the longitude of the end points of links, the size of grid cells, and the longitude and the latitude of the starting point of a lattice of grid cells that covers the network under the study. The program find-min-max-long-lat-link reads in the input data, and calculates the following items:

- N_x the number of horizontal grids.
- N_y the number of vertical grids.
- the minimum required grid that covers the network.

3.2.2. Processing

emission-factor-calculator algorithm

This section summarizes the method of calculation of basic emission factors. Emissions of pollutants such as CO, VOC, NOx, PM, SOx, CO2 are calculated from emission factors. The unit of measurement is grams per kilometer, (gr/km). The input into this program is the average speed on a link (per vehicle category) and vehicle fleet composition. Vehicle fleet includes categorization of vehicles based on compliance with different emission regulations. Compliance with emission regulations depends on the age profile of the vehicle fleet. The emission factors are calculated for hot emissions.

When calculating emission factors for traffic-based emissions, attention has to be paid in choosing the right coefficients and the right equations. This is a particularly difficult task. Tables of coefficients are provided in COPERT for each pollutant type. There is also a list of potential generic functions to choose from for each pollutant. These equations range from second degree polynomial functions of average speed to exponential functions to log normal functions of speed. In REALITY the coefficients are taken from COPERT. These coefficients are then updated based on the findings in the literature. The same applies to the functions for the estimation of emission factors. The functions are chosen based on the recommendations in the COPERT manual. These functions are modified if necessary based on the findings of field studies.

The procedure for modifying coefficients is as follows: first a set of coefficients that correspond to a particular pollutant, vehicle class, and engine capacity, are chosen. Emission

[2] COPERT is a European emission inventory calculation model used for the calculation of yearly emission factors for various types of road vehicles. In COPERT, many tables of speed dependency of emission factors and fuel consumption by pollutant type and vehicle class are provided. Required information can be extracted from these tables.

factors are calculated per pollutant type, by vehicle class, and engine capacity as is suggested in COPERT. The estimated emission factors are then compared with emissions factors calculated from other sources. If the values are comparable, no modification to the calculated emission factors is applied. Otherwise, if there is a large discrepancy, then different set of coefficients is used to calculate a new set of emission factors. This process is repeated until the calculated emission factors are satisfactory. The function used to calculate emission factors depends on average speeds. The form of the function used is taken from COPERT. A typical formula used to calculate a link emission factor before adjustment is shown below:

$$\tau_{p,l,k}(h) = a_{p,k} + b_{p,k} \cdot V_{l,k}(h) + c_{p,k} \cdot V_{l,k}^2(h)$$

Here $\tau_{p,l,k}(h)$ is the emission factor for pollutant p, for vehicle class k on link l, at instant h. The coefficients $a_{p,k}$, $b_{p,k}$ and $c_{p,k}$, are taken from tables in COPERT, and adjusted as is described above. $V_{l,k}(h)$ is the average speed of vehicle class k on link l at instant h.

Factors such as temperature, humidity level, and wind affect emission factors. To account for variations in temperature, humidity and wind, correction factors are applied to emission factors. Emission factors are corrected given four correction factors. 1- speed correction factor (SCF), 2- temperature correction factors (TCF), 3- humidity correction factor (HCF), 4)- wind correction factor (WCF).

<u>link-emission algorithm</u>

The input into this program is the emission factors per link, and link length. The program takes this information and calculates link emissions per hour. Link emissions are calculated using the following formula:

$$e_{p,l,k}(h) = \tau_{p,l,k}(h) \cdot q_{l,k}(h) \cdot L_l$$

here, $e_{p,l,k}(h)$ is the emission of pollutant p, on link l, for car class k, at instant h. $\tau_{p,l,k}(h)$ is the emission factor computed by program emission-factor-calculator. $q_{l,k}(h)$ is the flow of vehicles of class k on link l. Finally, L_l , is the length of link l.

<u>link-to-grid algorithm</u>

The input into this model is the grid and the coordinates of entry and exit points of each link. These coordinates are given in the form of latitudes, and longitudes of the end points. The objective of this program is to assign links to grid cells. There are two possibilities: either a link is totally contained in a grid cell, or it traverses several grid cells, meaning that only a segment of the link is in each grid cell. If a link intersects several grid cells, the program divides the link among these grid cells by attributing to each grid cell a fraction of the link.

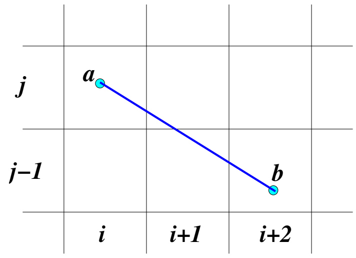

Figure 7: link to grid assignment.

A graphical representation is shown in Figure 7. (i), (i+1), (i+2), represent columns and (j-1), (j) rows of the grid in this example. The link (a,b) traverses the four grid cells (i,j), (i+1,j), (i+1,j-1), (i+2,j-1). The intersection of link (a,b) with each traversed grid cell is assigned to that cell. It is possible to have grid cells that contain no links.

grid-emission algorithm

Input into this model is the list of grid cells and the outputs of previous programs. The majority of grid cells contain either the totality of a link, or fractions of links. A few grid cells may not have any links in them. For these grid cells, total emission is assumed to be null. Another input into the program is the link flow by vehicle class, and length. The program then calculates total emission for each grid cell. The formula used to calculate grid cell emission is shown below:

$$\phi_{p,c,k}(h) = \sum_{l} \alpha_{l,c} \cdot e_{p,l,k}(h)$$

Here, $\phi_{p,c,k}(h)$ is the total emission of pollutant p for vehicle class k in grid cell c. Total emission is calculated as the sum of link emissions. In each grid cell, the emission is calculated for the fraction of the link that is included in the grid cell. Fractional link emission is calculated multiplying the link emission $e_{p,l,k}(h)$ by the fraction $\alpha_{l,c}$ of link l in cell c (calculated by link-to-grid algorithm). These link emissions are then summed over the links.

3.2.3. Post-processing

graphics algorithm

At this stage of the model, graphical representation is used for the verification and visualisation of the results. This program is written in Scilab. The program gives two types of graphical representation: graphical representation of link emissions, and graphical representation of grid cell emissions for all pollutants resulting from road traffic activity.

The input into this program is the geometry of links. The program also takes link and grid cell emission tables produced by the grid emission algorithm. The program displays link emissions at a given instant by attaching a color to each link that depends on the pollutant emission level by vehicle class, on that link, per instant h. The graphical representation of grid cell emissions are done by displaying grid cells with colors depending on emission values. Colors range from deep blue (zero emission) to dark red (high emission).

3.3. Application to the Paris area road network.

The link emissions for CO for passenger vehicles for the Paris area at 7 a.m. on a typical work day is given in Figure (8). Grid cell pollutant emissions for CO, and NOx for trucks and passenger vehicles for the Paris area at 7 a.m. on a typical work day are presented below in figures (9) to (12):

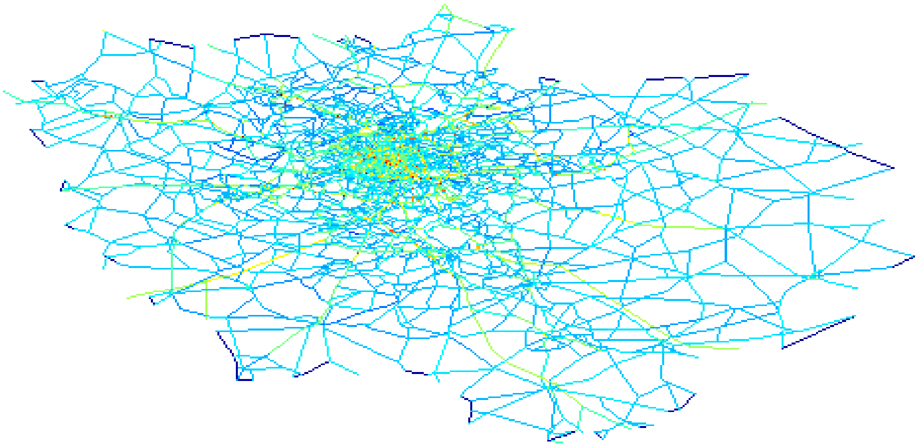

Figure 8: links emissions for CO for passenger cars for the Paris area at 7 a.m. on a typical work day.

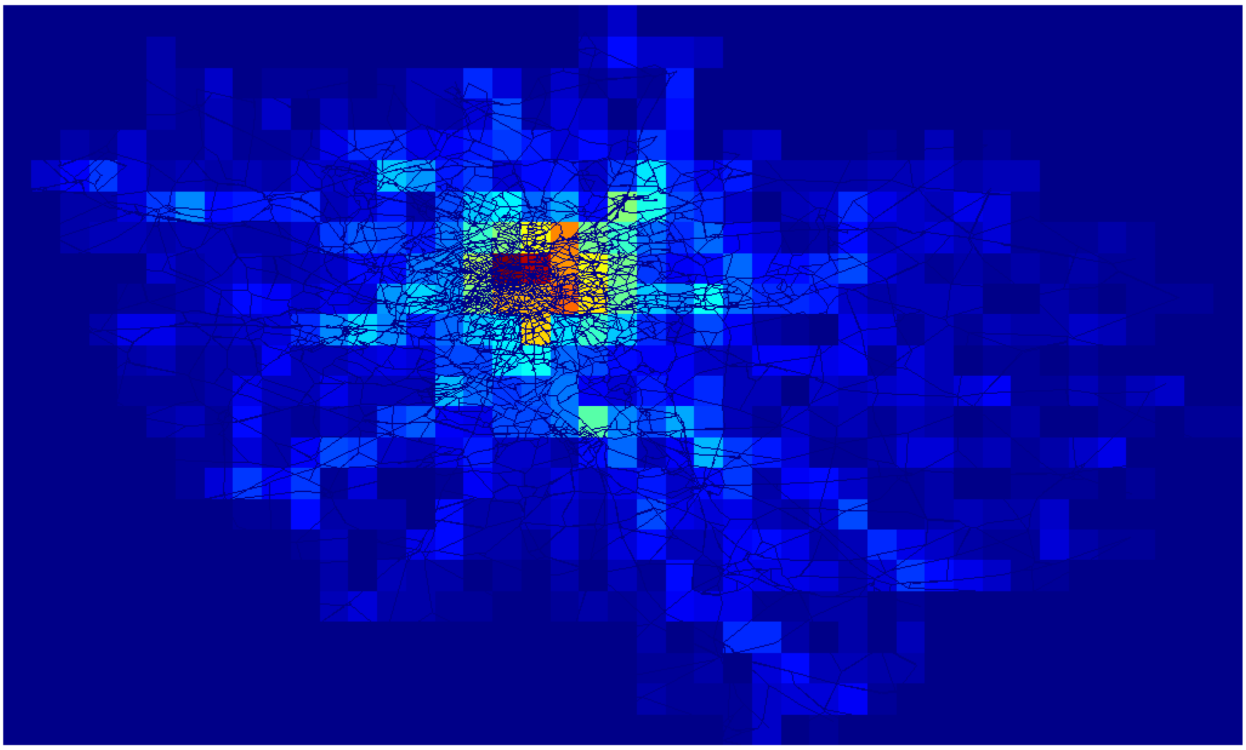

Figure 9: CO emission levels by grid cells for diesel trucks, for the Paris area at 7 a.m. on a typical work day.

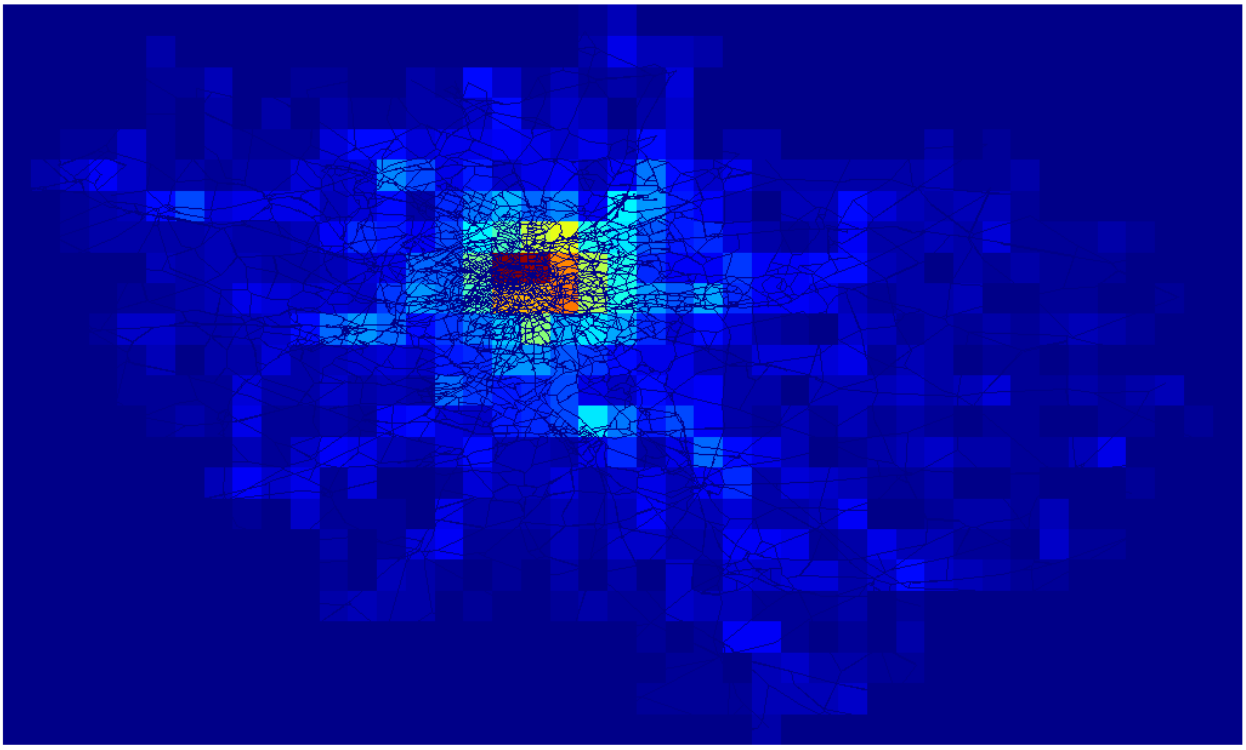

Figure 10: CO emission levels by grid cells for gasoline passenger cars, for the Paris area at 7 a.m. on a typical work day.

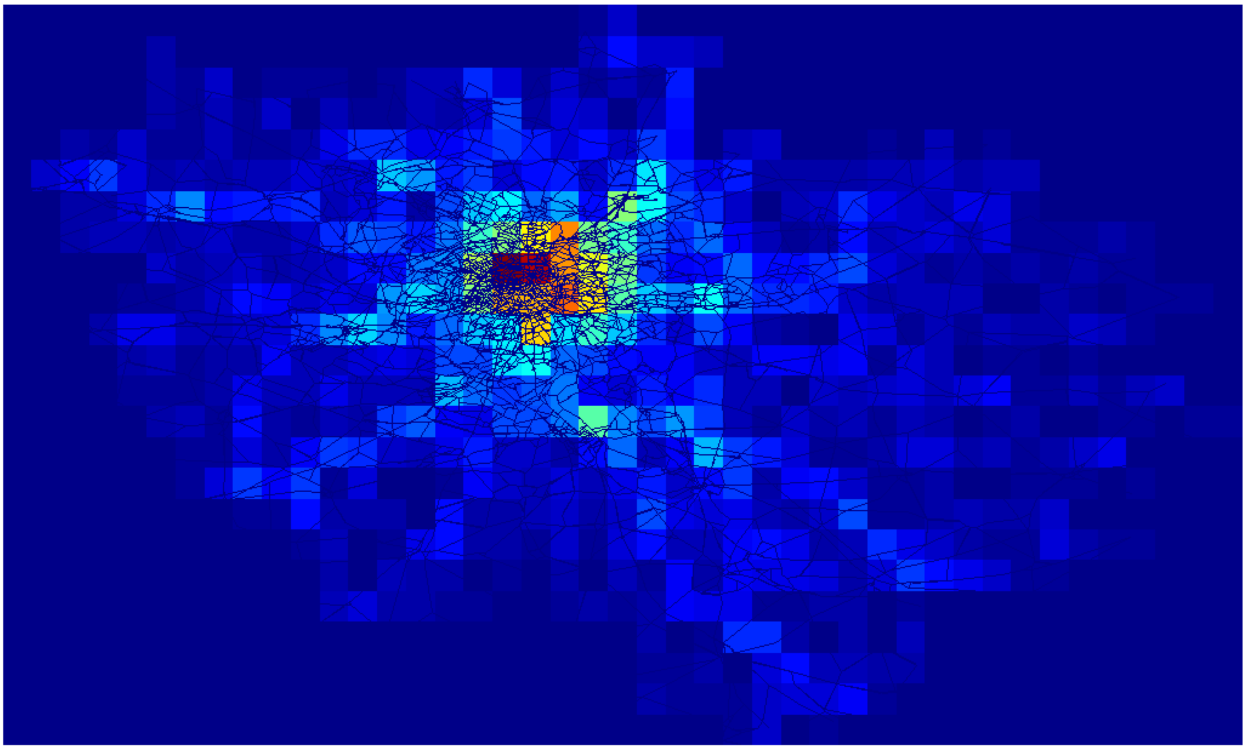

Figure 11: NOx emission levels by grid cells for diesel trucks, for the Paris area at 7 a.m. on a typical work day.

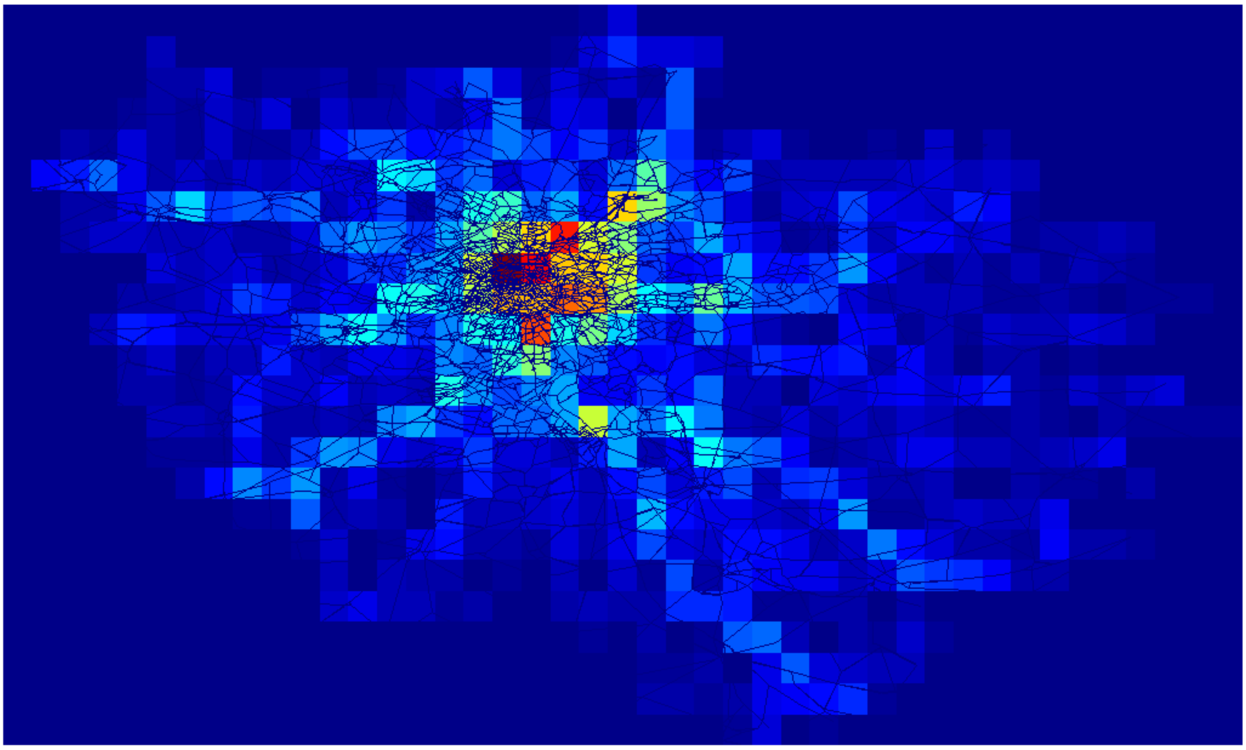

Figure 12: NOx emission levels by grid cells for gasoline passenger cars, for the Paris area at 7 a.m. on a typical work day.

CONCLUSION AND FUTURE WORKS

The authors believe that accurate forecasts of vehicles' emissions at a regional scale will be needed in a near future to help in the design and operation of traffic policies.

Prerequisite to such forecasts is the ability to model traffic activity on every link of a large road network, in a time continuous way. To our knowledge, analytical dynamic traffic assignment models are the appropriate, if not only, models that meet this prerequisite. In this paper, an analytical dynamic traffic assignment model called LADTA was presented. It's computer implementation, the Ladta ToolKit (LTK), can handle large networks in a efficient manner. Computing an assignment over the Paris area road network, that comprises around 40,000 links and 3 millions OD pairs, can be done in a few hours, using today's available standard computers. For the time being, LADTA models traffic flowing in an over-simplified manner. We are currently improving the model to deal with: queue spillbacks across link boundaries and flow interactions at intersections.

REALITY is introduced as the first version of the modelling package. The model will be improved to include the following items:

1. Estimation and application of the four correction factors. 1- speed correction factor (SCF), 2- temperature correction factors (TCF), 3- humidity correction factor (HCF), 4)-wind correction factor (WCF).

2. Up to now pollutant emissions resulting from hot emissions are calculated. The model will include pollutant emissions of cold start emissions. This routine will involve adding several new variables to the model. These variables include a) trip chaining activities, b) adding surface parking garages and side street parking to the physical network, and accounting for indoor parking garages, c) adding data on the number of occupied parking places in parking garages and estimations of the number of side street occupied parking spaces per interval of time, d) localized meteorological variables (temperature, wind, humidity), e) local pollutant concentration levels close to the ground by coupling REALITY with the air quality platform Polyphemus, of CEREA (Centre for atmospheric research of ENPC_ParisTech and EDF). Cold start emissions will be then integrated with hot emissions.
3. Addition of a search routine for finding optimal criteria in choosing functions for calculating emission factors.
4. Addition of fleet composition data and inclusion of new members:
   - mopeds (scooters)
   - motorcycles
   - buses including GNCs (buses that run on natural gas)

Other improvements to the model will depend on the findings after application of REALITY in a variety of real situations.

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