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A new methodological framework for within-day dynamic estimation of pollutant emissions in a large congested urban network

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This paper presents a new methodological framework to address the problem of estimating pollutant emissions for large congested urban networks in a within-day dynamic context. It consists of three main modules: 1) a module to compute pollutant emissions for general links; 2) a module to compute pollutant emissions for all links approaching a signalized intersection; 3) a module to compute pollutant emissions for all links approaching an unsignalized intersection. A dynamic mesoscopic assignment model is performed to derive the main dynamic input of each one of the modules. All the modules have been tested in a real case study (the district of Eur in the city of Rome, Italy), so confirming the reliability of the developed models and their applicability for the estimation of pollutant emissions.

Keywords: *Pollutant emission estimation, emission model, dynamic traffic assignment, mesoscopic simulation.*

1. Introduction

An accurate dynamic estimation of road emission becomes essential for urban areas characterized by congestion variable in time, especially for developing the most appropriate mitigation strategies in terms of traffic management operations.

Two main approaches are commonly adopted in literature to estimate road vehicles emissions: macroscopic and microscopic.

The macroscopic approach is based on aggregate variables, such as average speed, flows and vehicle kilometres travelled (Bai et al., 2007, Bai et al., 2008, EMEP/EEA emission inventory guide book 2010). In such a way, it is possible to estimate the emissions of all the network links, however the estimation accuracy is low, because speed variations are not taken into account, as well as the acceleration/deceleration time and vehicle specific power.

A lot of literature focuses on microscopic approaches that allow improvements to the emissions estimation, due to the knowledge of parameters about the drive cycles of vehicles and related to the different traffic flow conditions.

For example, Kraschl-Hirschmann et al. (2010, 2011) proposed a method to link the microscopic simulator VISSIM with the instantaneous emission model PHEM; Zhang et al., (2009) developed an urban microscopic traffic simulation model in order to predict and evaluate accurately the

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vehicle emission at the complicated traffic condition. Hussein Dia et al. (2006) compared two power-based models interfaced to a microscopic traffic simulator.

However, the microscopic approaches have a common limitation: they can be usually applied only for small networks, due to the huge input data need (Zhai et al., 2008).

For this reason, mesoscopic approaches, as an interesting alternative to the microscopic ones for cases in which detailed speed and acceleration data are not available (Yue and Rakha, 2009), started to develop: they are usually adopted to estimate light-duty vehicle (LDV) fuel consumption and emission rates on a link-by-link basis based on average speed, number of vehicle stops per unit distance, and average stop duration. Then these variables are used to construct synthetic drive cycles with four operation modes: deceleration, idling, acceleration, and cruising. Due to the simplistic drive cycles, the mesoscopic emission estimation cannot be expected to always match the microscopic one.

Regarding the possibility to follow the change in pollutant emissions, due to the dynamic of traffic conditions over time, some dynamic approaches have been recently developed: Liao et al. (2012) defined link-based and trip-based fuel consumption and emission model and integrated them with a simulation-assignment model DynaTAIWAN. Lin et al. (2011) presented an integrated modelling framework of a DTA model, DynusT, and Motor Vehicle Emission Simulator. Gori et al. (2012b) proposed a dynamic mesoscopic model to obtain values of pollutant emissions for large congested network, taking into account the within-day variations of traffic conditions and parameters related to the different state of vehicles (the queue length, the average speed of vehicles in the queue, the length of the link travelled at free-flow speed and so on).

This paper presents a new mesoscopic methodological framework to address the problem of estimating pollutant emissions for large congested urban networks in a within-day dynamic context.

The main aspects of the proposed method are: 1) the development of a module to compute pollutant emissions for general links, based on parameters related to the different state of vehicles (the queue length, the average speed of vehicles in the queue, the length of the link travelled at free-flow speed and so on), 2) the development of a module to compute pollutant emissions for all links approaching a signalized intersection, 3) the development of a module to compute pollutant emissions for all links approaching an unsignalized intersection, 4) all the modules are based on a mesoscopic approach in order to deal with large networks, and interface with a dynamic assignment model to take into account the within-day variations of traffic conditions.

In previous studies (Gori et al., 2012a, 2012b, 2013), the first two modules (general links and signalized intersections) have been outlined: in this paper the last module has been added (unsignalized intersections) and all modules have been systematized, combining them in a global methodological framework for the estimation of pollutant emissions.

The rest of the paper is organized as follows: section 2 describes the methodological framework and each one of the related module; in section 3 the main results obtained in previous works by the application of single modules to a real network case (the city of Brindisi in the Southern Italy) are summarized; a new case study is after presented (the district of Eur, Rome, Italy) and the methodological framework applied on it in order to generalize the results; finally section 4 summarizes the main conclusions.

2. Methodological framework

The methodological framework addresses the problem of estimating pollutant emissions for large congested urban networks in a within-day dynamic context.

It consists of three main modules:

1. a module to compute pollutant emissions for general links, based on parameters related to the different state of vehicles (the queue length, the average speed of vehicles in the queue, the length of the link travelled at free-flow speed and so on);
2. a module to compute pollutant emissions for all links approaching a signalized intersection;
3. a module to compute pollutant emissions for all links approaching an unsignalized intersection.

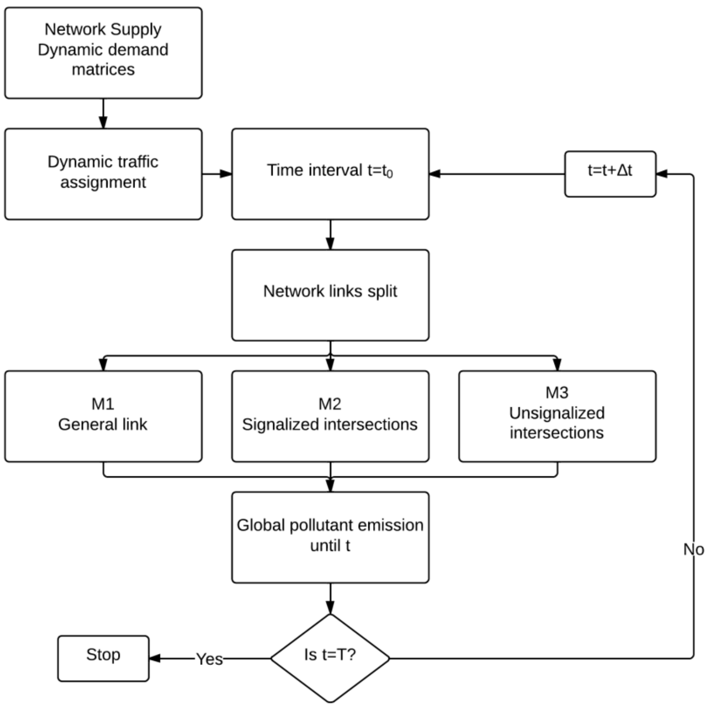

Figure 1. The architecture of the method

For a correct pollutant emission estimation it is necessary to make a distinction between the different links of a road network (general links, links approaching a signalized intersection, links approaching an unsignalized intersection), since the flow conditions may be significantly different between the different links: in the case of crossing links, the movements at the head of the links are regulated or by signals (for signalized intersections) or by give-priority rules (for unsignalized intersections); moreover some turning movements can be delayed by conflict volumes for both signalized and unsignalized intersections. The traffic dynamics generated in case of crossing links (and moreover between signalized and unsignalized ones) in terms of acceleration, deceleration, queue generation and spill-back are completely different from what can happen in a general link, where the main rule at the head of the link is to verify if there is sufficient downstream capacity.

So, in the hypothesis of breaking up the road network in their different links (links approaching a signalized intersection, links approaching an unsignalized intersection, none of the previous, *i.e.* "general" links), a dynamic assignment model is performed to derive the main dynamic input of each one of the module; each module is then applied on each subset of links and after the different pollutant emission contributes can be added in order to obtain the global dynamic pollutant emissions of the network.

The presented framework (Figure 1) can be considered a mesoscopic dynamic emission model: it adopts as input the output of a mesoscopic dynamic assignment model, it can work in a within day dynamic context following the congestion phenomena on the network and finally it can deal with large congested urban network.

In the following, each one of the module has been explained.

2.1 Module 1 – M1: general links

The basic idea behind module 1 (M1) is to split a link into two segments: one segment travelled by vehicles at free-flow speed and the other one travelled at the speed of vehicles in the queue.

The derived model, presented by Gori et al. in 2012a and 2012b, overcomes the common adopted macroscopic emission approach based on the average speed of the link (CORINAIR, EEA Technical report, 2010).

Once a dynamic traffic assignment (DTA) has been performed on the network, the dynamic output needed by the module are: 1) average link speed (S_l^t); 2) free-flow link speed ($S_{l(ff)}^t$); 3) speed of vehicles in queue ($S_{l(q)}^t$); 4) link length (L_{tot}); 5) queue length (L_q); 6) length of the link travelled at free-flow speed (L_{ff}); 7) link flow (Q_l^t).

Outputs S_l^t, $S_{l(ff)}^t$, L_{tot}, L_q and Q_l^t are raw dynamic output, while output $S_{l(q)}^t$ and L_{ff} have to be computed by a post-processor in the following way:

$$L_{ff} = L_{tot} - L_q \tag{1}$$

$$S_{l(q)}^t = \frac{L_q}{L_{tot}/S_l^t - L_{ff}/S_{l(ff)}^t} \quad \text{for each link } l \text{ and time interval } t \tag{2}$$

So, each link is split into two segments: one segment travelled by vehicles at $S_{l(ff)}^t$ and the other one travelled by vehicles at $S_{l(q)}^t$. The acceleration is not directly considered in M1. In fact in order to compute $S_{l(q)}^t$, the average speed of the link S_l^t is needed, but this average speed is a result of a mesoscopic dynamic assignment model that takes into account microscopic elements (lane changing models, gap acceptance models, car following models) together with macroscopic ones (triangular flow-density diagram): as a result, the main input for M1 (the average link speed S_l^t) is something between macro and micro, hence the term meso.

Emissions are then estimated as follows (CORINAIR, EEA Technical report, 2010):

$$E_{izr} = N_z \cdot M_{zr} \cdot e_{izr} \tag{3}$$

where:

E_{izr} = exhaust emissions of the pollutant i [g], produced in the period concerned by

vehicles of technology z driven on roads of type r (rural, highway, urban),

N_z= number of vehicles [veh] of technology z in operation in the period concerned,

M_{zr}= mileage per vehicle [km/veh] driven on roads of type r (rural, highway, urban) by vehicles of technology z,

e_{izr} = emission factor in [g/km] for pollutant i, relevant for the vehicle technology z, operated on roads of type r (rural, highway, urban).

If each link is split into two segments, as in M1, the computation of the emissions has to be done separately for the congested and the uncongested segment: N_z, i.e. the number of vehicles in the period concerned, is assumed as the link flow Q_l^t resulting from the dynamic simulation, while M_{zr} is split between L_{ff} and L_q. As a consequence, e_{izr} is split between the emission factor in correspondence of $S_{l(ff)}^t$ and the emission factor in correspondence of $S_{l(q)}^t$.

2.2 Module 2 – M2: links approaching a signalized intersection

The definition of the model to estimate pollutant emissions for links approaching a signalized intersection starts from an analytical model (microscopic level) based on Akcelic theory (Akcelic et al., 1999) and it is then adapted to deal with large congested networks (passing to a mesoscopic level). The model has been presented by Gori et al. in 2012b and 2013, considering the following hypotheses:

- the acceleration of vehicles exiting from the queue is considered constant (average acceleration rate);
- the deceleration is not considered: vehicle emission during deceleration phase exists, but it is low (about 5% with respect to the emission contribution during the acceleration phase, Shukla and Alam 2010), so a conservative approach can be applied;
- the length of the queue is considered as an average value for each time slice considered (T).

With respect to M1, each link is divided into three different parts: L_A, the length of link where the vehicles are at free speed; L_B, the length of the link where the vehicles are stopped in the queue; L_C, the length of the link where the vehicles are in acceleration phase. It is assumed that the lengths L_A, L_B, L_C are the distance travelled by each vehicle in the different traffic conditions on the same link, so they are analogous to the M_{zr} term in (3).

Two possible conditions are considered on each link approaching the signalized intersection:

1. the length of the queue (L_B) is low and incoming vehicles can accelerate up to the free speed;
2. the length of the queue (L_B) is high and incoming vehicles can't reach the free speed.

The emission estimation for a link k approaching a signalized intersection in the time slice T can be evaluated as follows:

$$E_{Tk} = (q_{Tk} L_A + Q_{nv} L_B + Q_{nv} L_C) e_a + (Q_{ns} L_B) e_b + (Q_{ns} L_C) e_c \quad (4)$$

with:

q_{Tk} = average hourly volume [veh/h] on link k at time T;

Q_{nv} = total hourly volume [veh/h] on link k that cross the intersection without any deceleration (i.e. vehicles not penalized by the traffic control): it is computed as the vehicles per cycle not subject to stop and go phases (q_{nv}) multiplied for the number of cycles C during the considered time slice T (T/C);

e_a = calibrated specific emission function to be adopted in L_A

Q_{ns} = total hourly volume [veic/h] subject to stop and go phases on link k : it is computed as the vehicles per cycle subject to stop and go phases (q_{ns}) multiplied by the number of cycles during the considered time slice (T/C);

e_b = calibrated specific emission function to be adopted in L_B;

e_c = calibrated specific emission function to be adopted in L_C.

The first term reports the emissions of vehicles running at free speed on the link: when the intersection is not in saturated conditions some vehicles can travel L_B and also L_C at free speed. For this reason in the first parenthesis there is the quantity Q_{nv} multiplied for e_a.

The second term reports the emissions on the link due to the vehicles stopped in the queue: only Q_{ns} are involved in this case. Finally the third term reports the emissions due to the acceleration phase.

The hourly volumes Q_{nv}, Q_{ns}, q_{Tk} in (4) replace the N_z term of (3), considering as the "period concerned" a time slice of one hour.

The computation of Q_{nv}, Q_{ns} (Akcelic 1987 and 1999) and L_B (Cantarella and Vitetta, 2010) depend on the conditions, saturated or not saturated, of the link approaching the signalized intersection.

In case of saturated conditions:

$$Q_{nv} = q_{nv} = 0 \tag{5}$$

$$Q_{ns} = q_{ns}\left(\frac{T}{C}\right) \text{ and } q_{ns} = q_n \text{ (the maximum flow rate discharge)} \tag{6}$$

$$L_B = \frac{D_{Tk}}{C}L = \frac{\dfrac{q_{Tk}(1-g)^2}{C}}{2\left(1-\dfrac{q_{Tk}}{s}\right)}L \tag{7}$$

with:

D_{Tk}=the total delay to cross the intersection related to the link k, approaching the signalized intersection

L=vehicles length factor (about 6.5-7m)

g=green time of link k, approaching the signalized intersection

s=saturation flow of link k, approaching the signalized intersection

In case of unsaturated conditions:

$$Q_{nv} = q_{nv}\frac{T}{C} = q_{Tk}\frac{g}{3600} \tag{8}$$

$$Q_{ns} = q_{ns}\frac{T}{C} \text{ and } q_{ns} = q_n\left(G_s - t_r - \frac{1-\exp\left(-m_q\left(G_s - t_r\right)\right)}{m_q}\right) \tag{9}$$

$$L_B = \frac{D_{Tk}}{C}L = q_{Tk}\frac{C\left(1-\dfrac{g}{C}\right)+\left(x_{Tk}-1\right)T}{2}L \tag{10}$$

with

x_{Tk} = saturation overflow of link k at time T, approaching the signalized intersection;

G_s= the share of green time where the flow is in saturated conditions;

m_q = coefficient of the exponential queue discharge flow model.

Finally L_C is the part of the link where vehicles reach the free speed starting from zero. If the link is long enough to allow the vehicles to get the free speed: $L_C=v_{free}^2/2a$, otherwise $L_C=L_{tot}-L_B$.

Also in this module, all the input data needed to compute (4) can be derived, except for the specific emission factors, performing a DTA in a within day dynamic framework.

Specific emission factors evaluation

The specific emission factors e_a, e_b, e_c have to be defined in order to apply M2. In order to define e_a, as a first approximation, we take the specific emission value derived by speed-time diagram built in laboratory (drive cycle diagram) and relate it to the constant speed phase.

For the specific emission factor e_c for acceleration phase, Zhai et al. (2008), Li et al. (2012) proposed to estimate emissions from the Vehicle Specific Power (VSP in kW/ton), so deriving different average emission rate values [g/s] as a function of the VSP ranges. In such a way, specific emission factor e_c can be computed starting from the VSP approach and adopting the following guidelines:

1. Define different vehicles classes;
2. Define different link types as a function of the free speed of the links;
3. Depict an acceleration and a speed diagram for each vehicle class and each link type;
4. Depict a VSP diagram for each vehicle class and each link type, being the VSP a function of the acceleration and the speed;
5. Compute the emission diagram of a specific pollutant related to the obtained VSP diagram;
6. Integrate the emission value during the time needed by the vehicle to cover 1 km, so obtaining the specific emission factor.

In Table 1 examples of derived values for e_c, considering two vehicles classes (light and heavy vehicles) and three link types (depending on the free speed: 50km/h, 60km/h or 110km/h), are reported.

Fig. 2 and Fig.3 report respectively the steps 3,4 and 5 of the mentioned procedure for the computation of e_c, respectively for light and heavy vehicles along links with free speed of 50 km/h in order to obtain CO and NOx emission diagrams.

Table 1. Specific Emission Function For *Lc*

	Light vehicles [g/(km*vehicle)]		Heavy vehicles [g/(km*vehicle)]	
Link type	CO	NOx	CO	NOx
50km/h	8.03	0.79	19.1	42.1
60km/h	6.38	0.64	16.2	35.5
110km/h	10.3	0.56	14.6	30.2

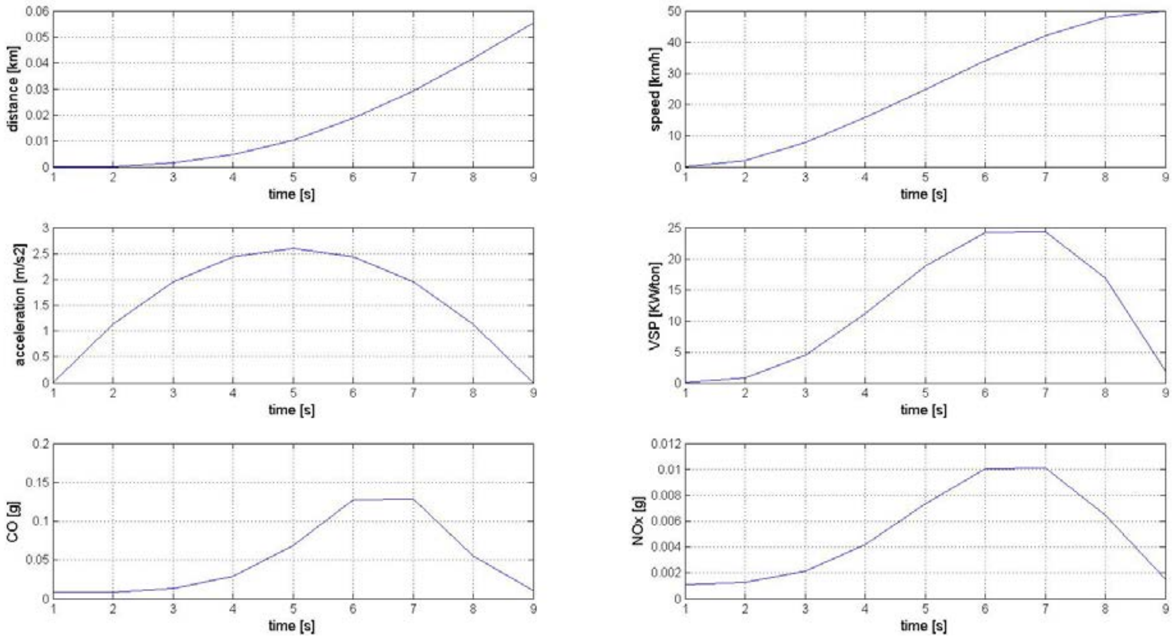

Figure 2. Kinematic parameters light vehicles (Link type 50km/h).

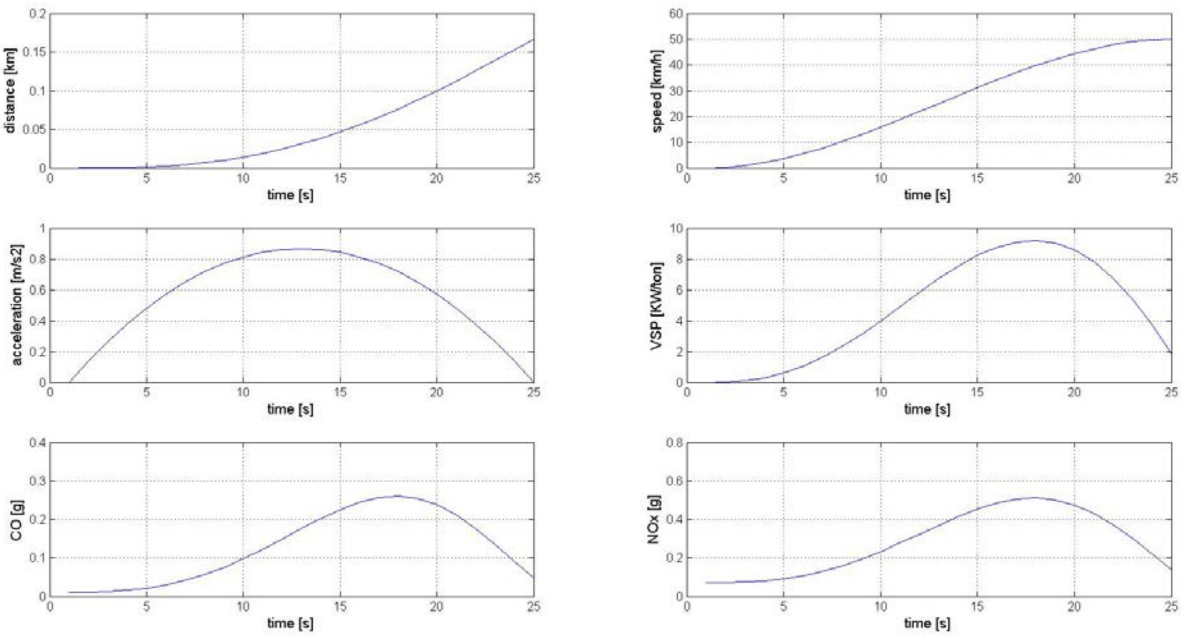

Figure 3. Kinematic parameters heavy vehicles (Link type 50km/h).

To estimate e_b, the average emission factor during queue, it is necessary to separate the unsaturated condition from the saturated one. In the unsaturated condition the queue is removed at each cycle length, as a consequence $e_b \equiv e_c$ (and L_B=0).

In the case of saturated conditions, some vehicles can cross intersection only after a certain number of cycles (k), so vehicles emit pollutants according to the number of stop and go phases in the queue (L_B). The number of cycle lengths that occur before crossing the intersection can be estimate using formula (11) where the first ratio is the average number of vehicle in queue while the second one is the capacity of the intersection for each cycle length:

$$k = \frac{L_B}{L} \cdot \frac{1}{n_{vs}} \tag{11}$$

with:

$$n_{vs} = s \cdot \frac{g}{3600} \text{ (Akcelik,1999)} \tag{12}$$

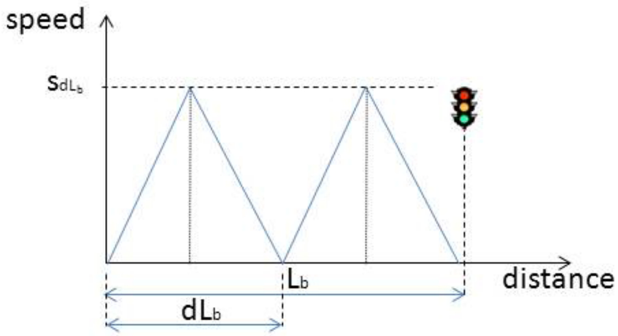

Figure 4. Example of stop and go diagram.

At each effective green g the vehicles in queue move forward for a distance dL_B (Fig.4):

$$dL_B = n_{vs} \cdot L \tag{13}$$

As a first application we have considered the value of vehicle acceleration equal to the value of deceleration (triangular speed-time diagram, Fig.4).

Thus in saturated conditions, starting from the e_c value, *i.e.* using the VSP approach, the specific emission factor e_b can be estimated as a weighted sum of the distance spent in the queue to accelerate at each cycle:

$$e_b = \frac{e_c \cdot L_B}{dL_B \cdot k \cdot 0.5} \tag{14}$$

Considering the triangular speed-time diagram the e_b can be estimated adopting the following simplified formulation:

$$e_b = e_c \cdot L_B / 2 \tag{15}$$

2.3 Module 3 – M3: links approaching unsignalized intersection

Module 3 is reported in this paper for the first time: it estimates pollutant emissions at unsignalized intersections; as already done for M2, starting from the microscopic theory, we arrive to a mesoscopic model with the adoptions of appropriate simplifications.

Specifically, module 3 is divided into the three following cases:

1. unsignalized intersections with three approaches;
2. merge areas (ramps);
3. unsignalized intersections with four approaches.

Case 1: unsignalized intersections with three approaches

Before defining the mesoscopic approach developed, a synthetic scheme of the case and a summary of the discussion at the microscopic level are reported below.

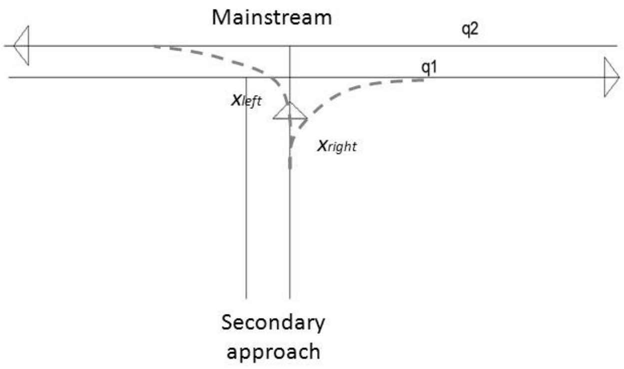

Figure 5. Example of an unsignalized intersection with three approaches.

In an unsignalized intersection with three approaches, a mainstream and a secondary approach are considered; the latter presents both right and left turn movements. In order to estimate the queue (and consequently the emissions) generated along the secondary approach, the following formula can be adopted starting from a microscopic approach (HCM2010, Di Gangi and Mussone, 2010):

$$Q95 = 900T\left[\frac{v_x}{cm_x} - 1 + \sqrt{\left(\frac{v_x}{cm_x} - 1\right)^2 + \frac{\frac{3600}{cm_x}\frac{v_x}{cm_x}}{150T}}\right]\frac{cm_x}{3600} \tag{16}$$

where:

Q95 represents the 95th percentile of the number of vehicles in the queue;

cm_x the effective capacity of the movement x (left, right) from the secondary approach [veh/h];

v_x flow value of movement x (left, right) [veh/h];

T the time duration of the period of analysis [h].

The effective capacity cm_x is defined starting from the theoretical capacity cp_x to be corrected through appropriate coefficients that take into account interferences with pedestrians and other vehicles.

In particular, the theoretical capacity cp_x is influenced by the conflict flow qc_x for the movement x, by the follow-up time tf_x and by the critical gap tc_x, as in (17):

$$cp_x = qc_x \frac{\exp\left(-qc_x \frac{tc_x}{3600}\right)}{1 - \exp\left(-qc_x \frac{tf_x}{3600}\right)} \tag{17}$$

with the critical gap value computed as follows:

$$tc_x = tc_{base} + tc_{HV} \cdot PHV + tc_G - tc_T - t3_{LT} \tag{18}$$

where:

tc_{base}: the basic value of the critical gap provided by the Highway Capacity Manual 2010 (HCM2010);

tc_{HV}: a corrective factor that takes into account the heavy vehicles;

PHV: the percentage of heavy vehicles;

tc_G: a corrective factor that takes into account the slope of the street;

tc_T: a corrective factor that takes into account the two-stage gap-acceptance process;

$t3_{LT}$: a corrective factor that takes into account the intersection geometry.

Once *Q95* is computed, the length of the queue is calculated by:

$$L_B = Q95 \cdot L_j \tag{19}$$

where L_j represents the average length of the vehicle.

In order to pass from a microscopic approach for unsignalized intersections to a mesoscopic dynamic approach, the following simplifications were performed:

- the effective capacity cm_x is set equal to the theoretical one cp_x
- the critical gap value is computed as follows:

$$tc_x = tc_{base} + tc_{HV} \cdot PHV \tag{20}$$

the queue length along the secondary axis is computed as the mean of both the queues derived by the two turning movements (right and left turning movements from the secondary approach to the mainstream):

$$Q95 = mean\left(Q95_{right}; Q95_{left}\right) \tag{21}$$

Q95,x computed using equation (16), where:

$$cm_x = cp_x = \frac{q_1}{nl} \frac{\exp\left(-qc_x \frac{tc_x}{3600}\right)}{1-\exp\left(-qc_x \frac{tf_x}{3600}\right)} \tag{22}$$

$$cm_x = cp_x = \left(q_1 + \frac{q_2}{nl}\right) \frac{\exp\left(-qc_x \frac{tc_x}{3600}\right)}{1-\exp\left(-qc_x \frac{tf_x}{3600}\right)} \text{ in case of left movement} \tag{23}$$

with:

nl number of roadway lanes

q_2, q_1 the flows on the mainstream axis, as reported in Fig.5.

In the case of mainstream roads (or main axis) with more than 2 lanes for the roadway, the intersection cannot be considered as an unsignalized intersection, as it is usually a signalized one.

Finally, in order to compute the emissions, the same equation adopted for signalized intersections (4) has been adopted, but:

Q_{nv}=0 because there are no vehicles crossing the intersection without any deceleration (there is not a "green time" as in the signalized intersection);

Q_{ns}= q_{Tk} = average hourly volume [veh/h] on link k at time T;

L_B= $Q95 * Lj$ adopting (19)

L_C= as in the signalized intersections, *i.e.* if the link is long enough to allow the vehicles to get the free speed: $L_C=v_{free}^2/2a$, otherwise $L_C=L_{tot}-L_B$;

$L_A=L_{tot}-L_B-L_C$.

Case 2: merge areas (ramps)
The merge areas (ramps) in an urban context can be considered as a simplification of case 1. In fact in a ramp, only the right turning movement from the secondary approach (the ramp) to the mainstream axis exists; the main difference respect to the hypotheses done for case 1 is that in a ramp there is a certain probability of crossing the intersection without any deceleration (p_{free}).

So, in order to apply equation (4), we have to distinguish between the two following cases:

1. if v_x (the turning movement, in this case the right turning movement) < cm_x
   $Q_{nv}= v_x \cdot p_{free}= v_x \cdot (1- v_x/ cm_x)$;
   $Q_{ns}= v_x- Q_{nv}$;
   $L_B=0$.
2. if v_x (the turning movement, in this case the right turning movement) >= cm, x
   $Q_{nv}=0$;
   $Q_{ns}= q_{Tk}$;

L_B can be computed using (19), where the Q95 value can be obtained from expression (16).

Case 3: unsignalized intersections with four approaches
Only the first two cases will be reported in this paper, this case is currently under study.The complexity of the problem for case 3 is in the number of turning movements and conflicts that have to be taken into account in the development of a mesoscopic dynamic emission model. The studies related to the application of the proposed models for cases 1 & 2 will allow the development of a reliable research line for the future development of case 3.

3. Application of the methodological framework

Both M1 and M2 have been individually tested in previous works of Gori *et al.* (2012a, 2012b, 2013).

In the following the main results derived from these applications are briefly reported; in particular we refer to what has been obtained using the Brindisi network (90,000 inhabitants, 43 centroids, 884 links, 306 regular nodes with 14 signalized intersections, a total peak hour traffic demand of 16,000 vehicles) and in the comparison of each module with the common macroscopic approach of CORINAIR (EEA Technical report, 2010):

- Regarding M1 (general links):
    a. if the difference between free-flow and congested conditions are not explicitly taken into account, i.e. using the average traffic conditions as in the common macroscopic approach instead of M1, the emission evaluation can be usually rough especially for some kind of pollutants (for the computation of CO, there are also differences of 20%);
    b. this difference could be an underestimation or an overestimation and it depends on the traffic conditions of the network and on the trend of the specific emission functions adopted, in particular:
        i. if the link is completely congested, the emissions computed using M1 are equal to emissions computed using a macroscopic approach;

   ii. if the congestion is very low, the emissions computed using a macroscopic approach are greater than emissions computed using M1;
   iii. for intermediate levels of congestion, the overestimation or underestimation of emissions cannot be known a-priori, but it is strictly correlated to the shape of the specific emission function adopted (Gori et al., 2012b).

- Regarding M2 (links approaching a signalized intersection):
  a. the macroscopic approach could be not a sufficiently suitable method to compute emissions in case of urban links with traffic variability and congestion phenomena; in fact, precisely where the presence of signalized intersections generate queues, there is a strong discrepancy between the macroscopic approach and the adoption of M2 (14% for CO, 117% for NOx and 62% for PM10);
  b. the differences between using M2 instead of the common macroscopic approach is strictly correlated with the length of the links approaching the signalized intersection, the traffic signals parameters and the length of the queue:
     i. with the specific emission factors (e_a, e_b, e_c) adopted for CO in the experiments of Brindisi, it happens that usually long links with short queue bring to an underestimation of CO emissions by M2 respect to the macroscopic approach, while for short and congested links it is exactly the other way round.
  c. The computation of e_c from the Vehicle Specific Power can strongly influence the results (Gori et al., 2013):
     i. for example, the resulting value of e_c for NOx, combining light and heavy vehicles, is one order higher than the average emission factor adopted by the macroscopic approach. Moreover the relation between NOx and VSP is always growing, while the variation of the average emission factor respect to speed (macroscopic approach) is very low: in such a condition the macroscopic emission model could hardly estimate a right increment of emission during the acceleration phase.
     ii. *Vice versa*, the relationship CO-VSP can be approximated by a second order polynomial, which means that for high VSP the CO specific emission is lower than the peak value and, moreover, the CO emission functions adopted in the macroscopic approach are able to adequately represent the increment of emission due to acceleration.
- about the adoption of the results of a DTA as an input of M1 and M2, instead of the adoption of the results of a static assignment model:
  a. in case of high congestion on the network, static and dynamic assignment can result in similar values of link speeds, while static link flows are expected to be higher than the dynamic ones: in this case the emissions derived from the use of a static model are higher than the emissions computed with a dynamic approach.
  b. in case of no congestion, with similar values of static and dynamic link flows, the link speed computed by a dynamic simulator are usually greater or equal to the link speed computed by a static simulator, if a triangular fundamental diagram is adopted for the dynamic assignment model (as in the dynamic simulator adopted for the Brindisi experiments):

i. in such a case the dynamic emissions are greater than the static ones if high speed roads are considered (the computation of emissions are based on the right side of the emission functions);

ii. for local roads usually the static emissions are greater than the dynamic ones because the computation of emissions are based on the left side of the specific emission functions.

In this paper, the models developed have been applied on the test network of the district of Eur in Rome, Italy, in order both to validate the results from the study in Brindisi and to compare the emission values with the different levels of congestion that can occur on a road network. Moreover M3 is here adopted for the first time and its contribution has been evaluated.

3.1 Application to the Eur network

The Eur network (Fig.6) consists of 21 centroids, 218 links, 64 regular nodes with 17 signalized intersections, a total peak hour traffic demand of 30,000 vehicles: the Eur network is smaller than the Brindisi network reported in the previous section, but more congested (Tab.2) and with a higher number of traffic signals.

The dynamic input of the different modules have been obtained by performing a dynamic traffic assignment (DTA) of the morning demand (from 6:00am to 10:00am, according to the demand profile of Fig.7) using the DYNAMEQ model (Florian et al., 2006) and recording the traffic simulation until the complete discharge of flows on the network (2:00 pm).

The outputs of the dynamic assignment model have been collected every 10 minutes; the same "time resolution" has been used to compute emissions of CO, NOx and PM10 by adopting the following three emission estimation methods:

1. a macroscopic approach adopting average speeds and the corresponding average specific emission factor (CORINAIR approach, EEA Technical report, 2010);
2. module 1 (M1) for all the links (218 links);
3. module 2 (M2) for all the links approaching a signalized intersection (62 links), module 3 (M3) for all the ramps and the 3 approaches unsignalized intersections (69 links), CORINAIR for all the remaining links (87 links).

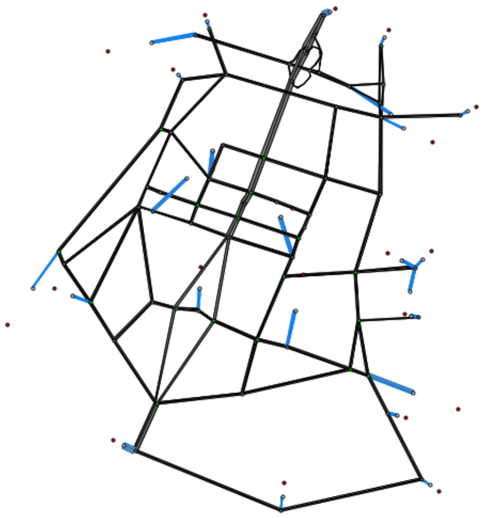

Figure 6. The "Eur" network.

Table 2. Comparison between Brindisi and Eur network (network performances)

	time analysis	VHT [h]	VKT [km]	avg speed [km/h]	speed stand deviation [km/h]	Network Total Length [km]
Brindisi	06:00-23:00	14,493.49	691,907.10	52.40	7.50	251.50
Eur	06:00-10:00	12,391.30	293,665.00	29.90	11.50	91.60

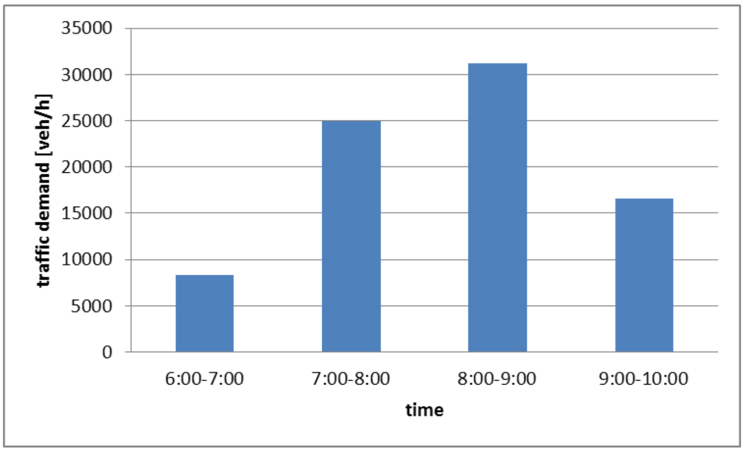

Figure 7. The demand profile for the "Eur" network.

In point 3, CORINAIR has been applied for all the remaining links and not M1 (as suggested by the methodological framework), in order to estimate the contribution of the mesoscopic models in M2 and M3 (signalized and unsignalized intersections) with respect to the macroscopic approach.

Results show that emissions computed with M1 are generally lower than emissions computed by CORINAIR, as already obtained by the authors for the Brindisi network (Gori et al., 2012b), reaching also differences of 15% in this case (CO emissions, Fig.8).

Continuing with the comparison between CORINAIR and M1, but passing at the level of single elements of the network:

- if a link is completely congested (length of the queue greater than the 80% of the link length, L_q/L_{tot}>80%), M1 and CORINAIR give approximately the same result; the differences between the two models reach, on average, values of about $|1{\cdot}10^{-3}|$ kg/h of CO emission;
- *Vice-versa*, if the congestion is very low (length of the queue lower than the 2% of the link length, L_q/L_{tot} <2%), CORINAIR usually overestimates emissions respect to M1; the maximum differences between the two models reach in this case values of CO emission two orders higher than the previous case ($|1{\cdot}10^{-1}|$ kg/h).

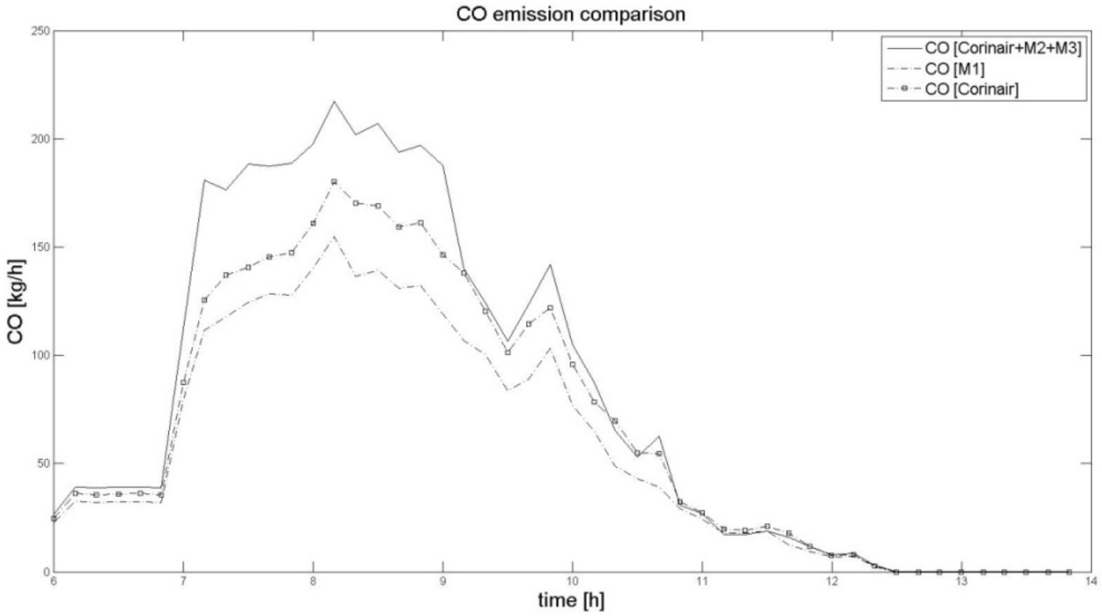

Figure 8. CO distribution with the three methods.

When M2 and M3 are introduced at intersections, the differences both respect to CORINAIR and respect to M1 increase and in particular they are translated in a strong overestimation for all the pollutants:

- for CO, on average during the peak period: +30% respect to CORINAIR approach, and + 45% respect to M1 approach, Fig.8;
- for NOx, on average during the peak period: +60% respect to CORINAIR approach, and + 65% respect to M1 approach, Fig.9;
- for PM10, on average during the peak period: +40% respect to CORINAIR approach, and +55% respect to M1 approach, Fig.10.

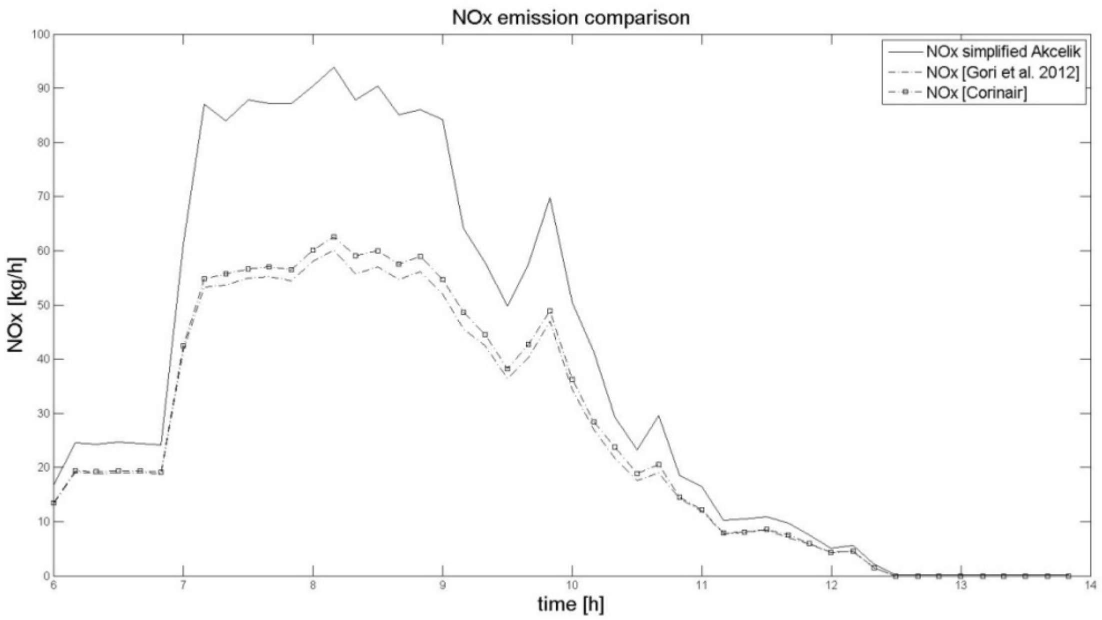

Figure 9. NOx distribution with the three methods.

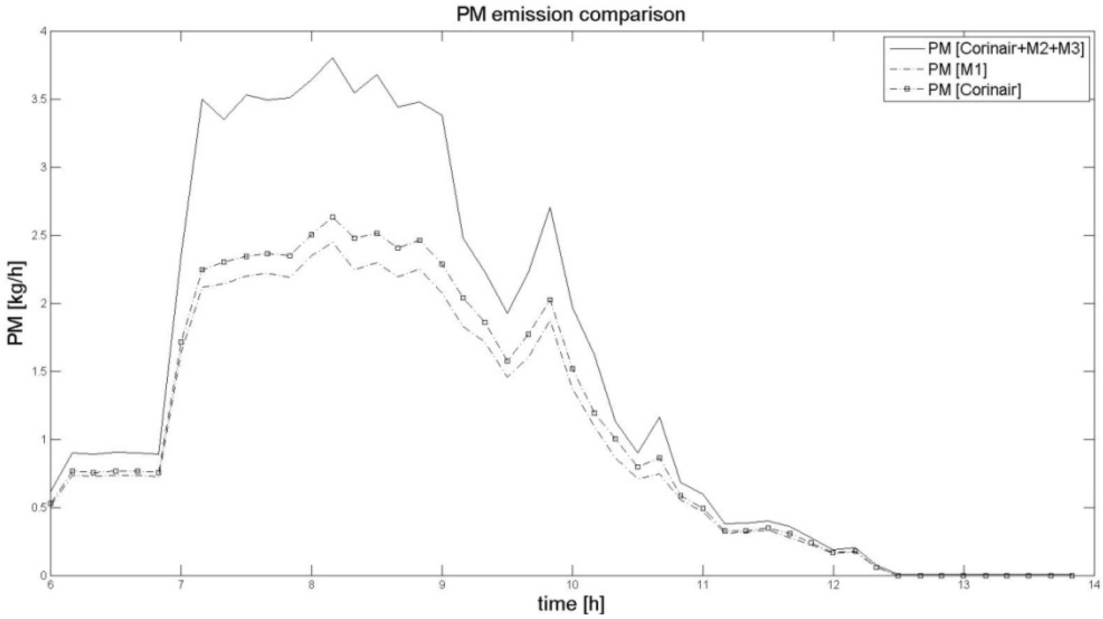

Figure 10. PM10 distribution with the three methods.

In the Brindisi network, the differences on the whole network between the CORINAIR model and the combined application of CORINAIR+M2 were very low (not higher than 4%), because the contribution in the emission estimation of the links approaching the signalized intersections were damped by the remaining links of the network for which the CORINAIR approach have been adopted. In fact signalized intersections represent 5% of the total number of the nodes in Brindisi and, moreover, it is a network characterized by an urban freeway with high value of crossing traffic demand (Fig.11, a). Otherwise, in the Eur network the differences between CORINAIR and the combined application of CORINAIR+M2+M3 became sensitive, due to the fact that now the signalized intersections represent 26% of the total number of the nodes (the total CO emissions mainly concentrated along the main signalized corridor of the network, Fig.11, b); moreover, we have the possibility to accurately estimate emissions also for unsignalized intersections (M3 has been applied for the first time in the case of the Eur network).

Focusing only on links approaching the signalized intersections and on the differences between using the CORINAIR approach also for these links respect to use the appropriately developed M2, for the Eur network we obtain that the differences between the two models can be very strong, as already obtained for Brindisi: in particular for this case, we reach a difference in absolute value of 36% for CO, of 122% for NOx and of 100% for PM10.

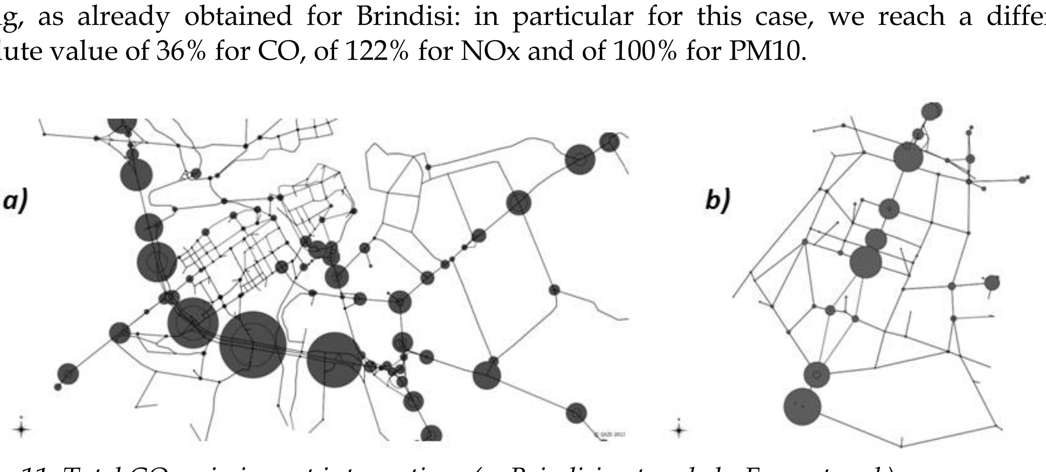

Figure 11. Total CO emissions at intersections (a- Brindisi network, b- Eur network)

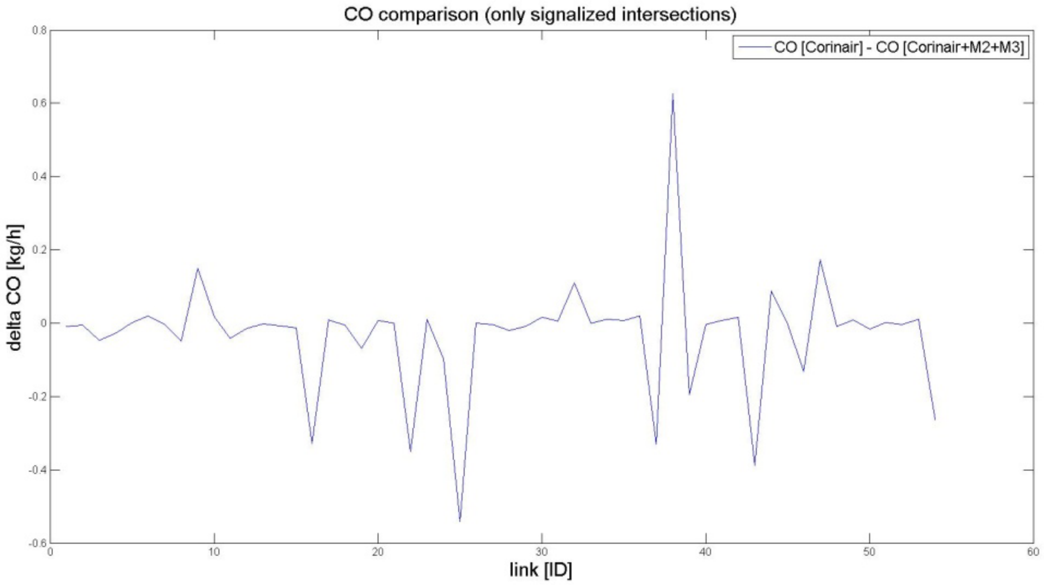

Figure 12. Differences of CO emissions at links approaching signalized intersections using CORINAIR or M2.

As reported in Section 3, the differences between using CORINAIR or M2 for links approaching a signalized intersection is strictly correlated with the length of these links, the traffic signals parameters and the length of the queue; generally it happens that long links with a short queue result in an underestimation of CO emissions of M2 with respect to CORINAIR, while for short and congested links it is exactly the other way round. Fig.12 reports the differences of CO emissions at links approaching signalized intersections using CORINAIR or M2: There are few links where CORINAIR CO emissions overcome M2 CO emissions, i.e. as expected, we are faced with a high congestion network.

Focusing now on links approaching unsignalized intersections, in particular on the differences between using the CORINAIR approach for these links with respect to using the appropriately developed M3, for the Eur network we find that the differences between the two models reach percentage values of 193% for CO, of 219% for NOx and of 198% for PM10.

In the M3 case, despite the high percentage differences respect to CORINAIR, we are speaking of low values of emissions because only ramps and unsignalized intersections with three approaches are considered. For example, CO emissions on the unsignalized intersections reach maximum values of 20kg/h (Fig.13), respect to the 200kg/h of the whole CO emission of the network (Fig.8).

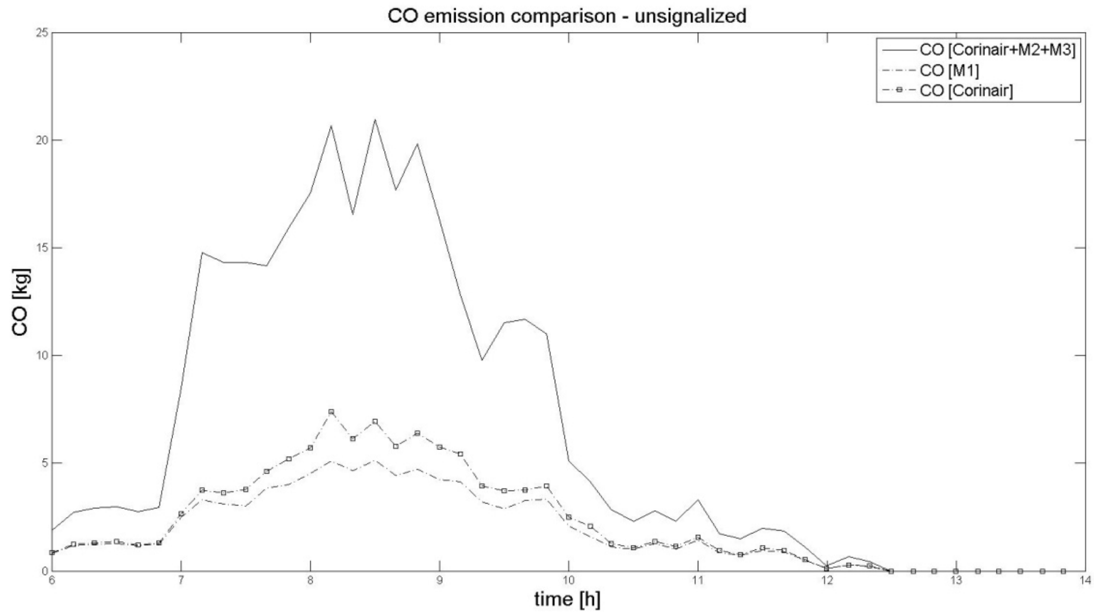

Figure 13. CO distribution with the three methods only for links approaching unsignalized intersections (M3).

Figure 14 reports the differences of CO emissions at links approaching unsignalized intersections using CORINAIR or M3: M3 always overestimates the emission computed by CORINAIR.

The same result is also obtained for NOx and PM10: it depends mainly by the hypothesis adopted for unsignalized intersections with three approaches, where Q_{nv}=0 because no vehicles cross the intersection without any deceleration. However this hypothesis can be considered sufficiently analogous to what happens in reality (there is no "green time" as in the signalized intersection), especially in our case where the main goal is to find reliable values of pollutant emission: when a vehicle slows down approaching an unsignalized intersection and then accelerates to take the mainstream, for the purposes of calculating emissions, it is taken as the engine being switched on at that time.

4. Conclusions

The paper focus on the development of a new methodological framework to deal with the problem of estimating pollutant emissions for large congested urban networks in a within-day dynamic context. It consists of three main modules: 1) a module to compute pollutant emissions for general links, based on parameters related to the different state of vehicles (the queue length, the average speed of vehicles in the queue, the length of the link travelled at free-flow speed and so on), 2) a module to compute pollutant emissions for all links approaching a signalized intersection, 3) a module to compute pollutant emissions for all links approaching an unsignalized intersection.

The input of all the modules are data derived from a Dynamic Traffic Assignment (DTA) at the equilibrium point, so considering the variability of traffic conditions during time. It has been applied in the real case of the Eur network, a district of the city of Rome in Italy, comparing the obtained results with those obtained in previous studies. The results demonstrate the reliability of the adopted models and their capability to:

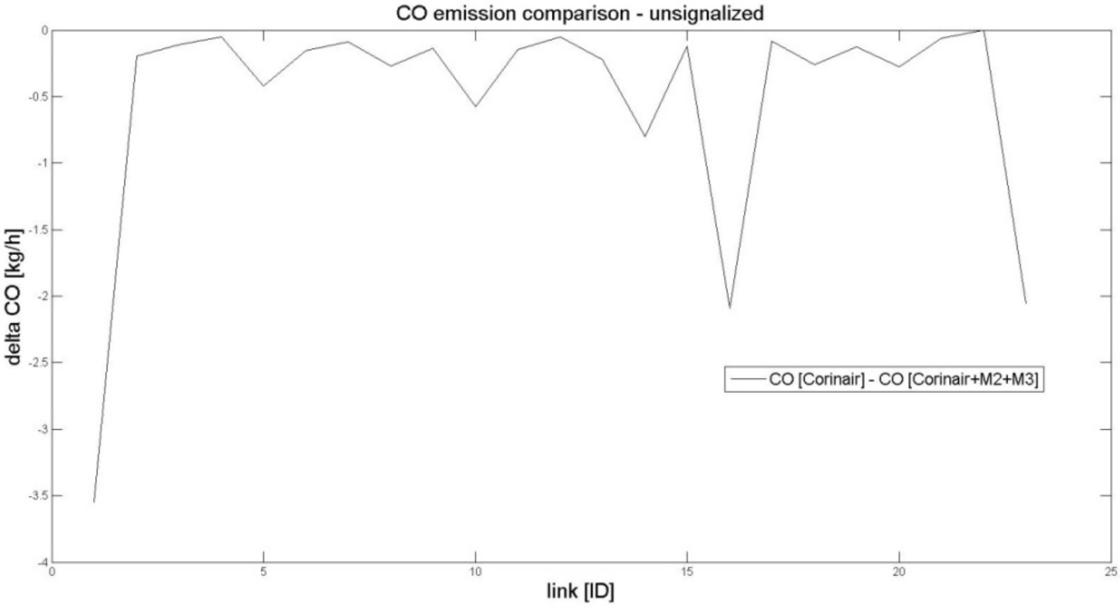

Figure 14. Differences of CO emissions at links approaching unsignalized intersections using CORINAIR or M3.

1) estimate pollutant emissions with a higher level of analysis respect to the basic macroscopic approach that adopt average link speed data;

2) distinguish between vehicles in queue and vehicles entering/exiting the queue (deceleration and acceleration phases);

3) overcome the limits of using only a mesoscopic model that basically divides each link into a segment travelled at free flow speed and a segment travelled at "queue speed" (the so called module 1, M1), for links approaching signalized and unsignalized junctions;

4) provide a map of the intersections showing the different degree of emission level as an operative instrument for the decision support process.

Future developments of the work will face with both practical and methodological developments: from the practical point of view, it is necessary to validate the emission estimate not only by simulation, but also using real data. In fact, actually the validation is done by simulation, comparing the model with other already developed models and trying to understand if the behaviours/the trends are similar (except for the natural differences due to the different models characteristics). One idea could be to validate the procedure with probe vehicles equipped with both GPS and emission detectors. The proposed methodology could be improved by adopting real drive cycle of vehicles approaching the intersections, so overcoming the limits of the actual adopted simplified diagrams. Moreover the model for unsignalized intersections has to be improved, taking into account unsignalized intersections with four approaches in order to complete the framework of the developed dynamic mesoscopic emission models.

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