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Within-Day Dynamic Estimation of Pollutant Emissions: a Procedure for Wide Urban Network

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Abstract

Road vehicle emissions are an important aspect of the life quality and sustainability. Recent studies show that traffic flow-speed profiles and vehicular emissions are related. The increase of congestion leads to in an increase of pollutant emissions and, moreover, emissions are sensitive to different drivers behavior. In this context, it is possible to reduce vehicle pollutants emissions, decreasing congestion with traffic planning policies and on-line operations. The aim of the paper is to obtain reliable values of pollutant emissions in a wide urban network, taking into account the within-day variations of traffic conditions and parameters related to the different state of vehicles (congested and uncongested conditions such as the queue length, the average speed of vehicles in the queue, the length of the link travelled at free-flow speed and so on). The developed within-day dynamic emission model has been applied to the city of Brindisi (Italy) and the estimated emissions have been compared with the results of standard macroscopic approach in order to quantify the differences. Finally an analytical model to compute emissions at signalized intersections is presented.

Keywords: Pollutant emissions estimation, dynamic traffic assignment, traffic management.

1. Introduction

Road vehicle emissions are an important aspect of the life quality and sustainability. Since 1990s local authorities have spent time and resources trying to reduce pollutant emissions. At European level different legal instruments have been introduced to regulate road vehicle emissions [1] by setting emission standards on some

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pollutants for most vehicle types. However "..*many European countries do not expect to comply with one or more pollutant-specific emission ceilings set under EU and UN agreements for 2010..*" [1] and although technology has made major strides in reducing par-vehicle pollutants, the global emission value has been increased [2]. Recent studies [3], [4], [5], [6] show that traffic flow-speed profiles and vehicular emissions are related. In order to estimate emissions, three different approaches have been defined in the last years: macroscopic, microscopic and mesoscopic.

The macroscopic approach is based on the knowledge of aggregate variables, such as speed, flows and vehicle kilometers traveled [7], [8], [9]. In this way, it is possible to estimate the emissions of all the links of the network; however the estimation accuracy is low, because none of the information considers acceleration time, deceleration time and vehicle specific power.

The microscopic approach [10] can substantially improve the emission estimation, because it is based on the knowledge of parameters about the drive cycles of vehicles and related to the different traffic flow conditions. However, this approach can be applied only for small networks [11], because of the huge input data need.

The mesoscopic approach was developed to estimate light-duty vehicle (LDV) fuel consumption and emission rates on a link-by-link pattern based on average speed, number of vehicle stops per unit distance, and average stop duration. The model uses these variables to construct synthetic drive cycles with four operation modes: deceleration, idling, acceleration, and cruising. Due to the simplistic drive cycles, the mesoscopic estimations cannot be expected to always match microscopic ones. However, it constitutes an interesting alternative to microscopic models for cases in which detailed speed and acceleration data are not available [12].

To estimate emissions on a wide network, usually macroscopic or mesoscopic approaches are used. However both the approaches, using aggregated traffic estimates mask temporal variations of traffic conditions, thus biasing vehicle estimated emissions; using finely resolved traffic data, as the output of a dynamic assignment model, may significantly alter emissions estimation [8].

The aim of the paper is to obtain reliable values of pollutant emissions in a wide 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). The developed dynamic mesoscopic emission model has been applied to the city of Brindisi (Italy) and the estimated emissions are compared with the results of standard macroscopic approach in order to quantify the differences. Finally an analytical model to compute emissions at signalized intersections is presented as future development of the proposed model.

2. The methodology

The developed methodology is based on two main modules (Fig.1): a module related to the dynamic traffic assignment model (DTA); a module related to a post-processor in order to compute the emissions.

The first module is essential to capture the within-day variations of traffic conditions and parameters related to congestion; it is composed by the following phases: 1) calibration of the study network; 2) estimation of the dynamic origin-destination matrices (dynamic demand); 3) run of the dynamic traffic assignment; 4) collection of dynamic output needed for the post-processor.

The dynamic traffic assignment can be easily run for a wide network and in a within-day dynamic scenario using a mesoscopic dynamic simulation model.

Usually the output of the mesoscopic dynamic simulation model are outflow, inflow, speed, density/occupancy, queue length for each link and for each time interval of the planning horizon. Link speeds are usually average link speeds taking into account congestion phenomena happened during the analyzed time interval; however in this way it is not possible to distinguish the different contributes of the congested and the uncongested phases, that is essential for the computation of reliable emission values. For this reason the post-processor module has two roles (Fig.1): to compute the emissions given the raw dynamic output and to compute the emissions after the dynamic output have been elaborated in order to take explicitly into account the congestion phenomena.

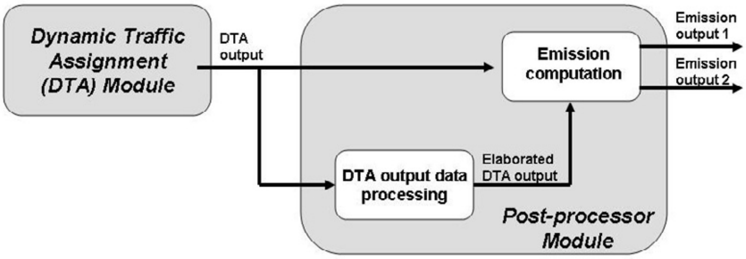

Fig. 1. Pollutant emission estimation methodology

The dynamic output needed by the post-processor 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}).

Output 1.,2.,4. and 5. are raw dynamic output, while output 3. and 6. are computed by the post-processor in the following way:

$$L_{ff} = L_{tot} - L_q \quad (1)$$

$$S_{l(q)}^t = L_q / [(L_{tot} / S_l^t) - (L_{ff} / S_{l(ff)}^t)] \qquad \textit{for each link } l \textit{ and time interval } t \quad (2)$$

Specifically, each link is split into two segments: one segment travelled by vehicles at free-flow speed and the other one travelled by vehicles at $S_{l(q)}^t$. Emissions are estimated as follows [9]:

$$E_{i,k,r} = N_k \cdot M_{k,r} \cdot e_{i,k,r} \quad (3)$$

where:

$E_{i,k,r}$ = exhaust emissions of the pollutant i [g], produced in the period concerned by vehicles of technology k driven on roads of type r,

N_k= number of vehicles [veh] of technology k in operation in the period concerned,

$M_{k,r}$= mileage per vehicle [km/veh] driven on roads of type r by vehicles of technology k,

$e_{i,k,r}$ = emission factor in [g/km] for pollutant i, relevant for the vehicle technology k, operated on roads of type r.

Emission factors e_{ijk} can be obtained given a specific emission function.

If each link is split into two segments, the computation of the emissions have to be done separately for the congested and the uncongested segment.

3. Application

3.1. Experimental design

In order to apply the explained methodology, the following settings have been assumed:

- 18 hours of dynamic traffic simulation (from 5:00 am to 11:00 pm);
- 2 sets of output of the dynamic traffic assignment (average link values for each time interval or dividing each link between congested and uncongested conditions)
- 3 pollutants (CO, NOx, PM10);
- 2 types of emission function.

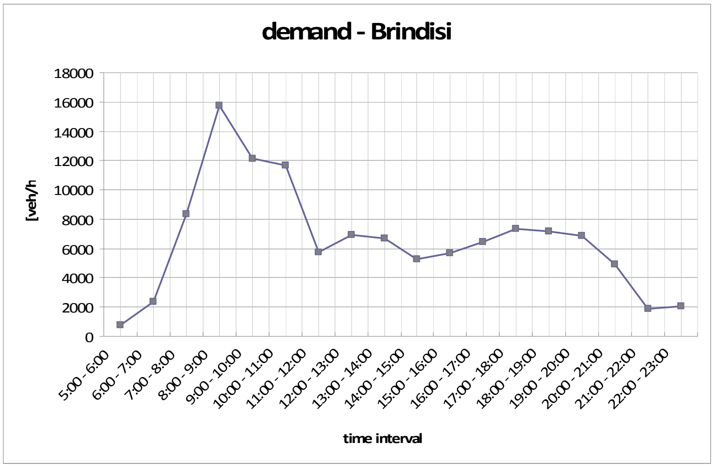

Fig. 2. Distribution of traffic demand for the city of Brindisi

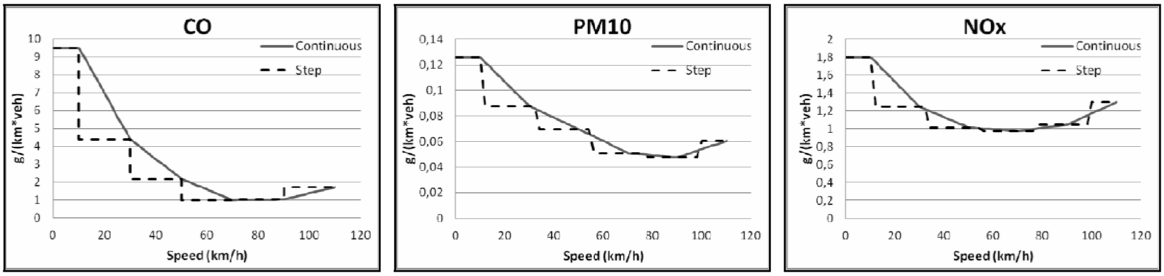

Fig. 3. Step and continuous emission functions for CO, NOx and PM10

The adopted network is the network of Brindisi (the city is located in Puglia Region, Italy), characterized by about 90,000 inhabitants, 43 centroids, 884 links, 306 regular nodes (with 14 signalized intersections).

The total peak hour traffic demand has been estimated in about 16,000 vehicles using the standard four-steps models and the 18-hours distribution (Fig. 2) has been derived considering available traffic flow data of a similar city context.

The dynamic traffic assignment (DTA) of the 18-hours demand on the Brindisi network has been performed using the mesoscopic model DYNAMEQ [13], [14]. The main output of DTA as average density, average speed and queue length for each link and for each time interval, along with link attributes like length and free speed have been exported to the post-processor model in order to obtain for each time interval and for each link:

- the average flow;
- the length travelled at free-flow conditions (at free speed);
- the average speed of vehicles in the queue.

Emissions of CO, NOx and PM10 have been then computed considering the following two sets of output:

- Set 1: average link values for each time interval (flow, speed) and the total length of the link;
- Set 2: the average link flow value for each time interval and the link divided between congested and uncongested condition (free-speed/length of the link travelled at free-flow conditions, the average speed of

vehicles in the queue/ queue length).

Using the two different sets of output as reported in points 1. and 2., it is possible to compute respectively:

- the 18-hours average emissions profile;
- the 18-hours emissions profile taking into account congested and uncongested conditions of each link.

The adopted emission functions required to compute the total emission value for each pollutant (Fig.3) is:

- a step function with constant values of specific emission factor for different speed ranges;
- a continuous function obtained interpolating single values of specific emission factors corresponding to single speed values.

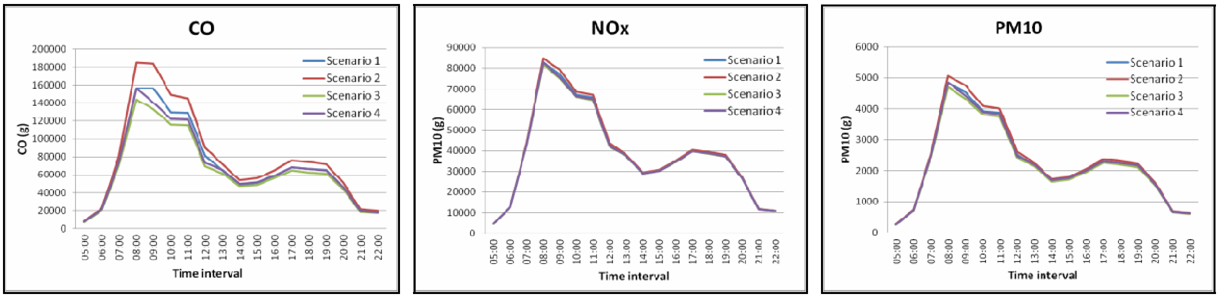

Fig. 6. 18-hours emission profile of CO, NOx and PM10 for the four scenarios (Brindisi network)

Values of specific emission factors are computed using COPERT [15]. Finally the peak interval (from 8:00 am to 11:00 am) has been simulated performing a static assignment [16] and the resulting emissions (derived by a macroscopic approach) have been compared with the dynamic mesoscopic results.

3.2. Results

3.2.1. Results of the dynamic mesoscopic approach

First results on Brindisi network show the 18-hours emission profile of CO, NOx and PM10 for the following four scenarios (Fig.6):

- scenario 1: the emissions are computed considering the step emission functions and Set 1 as DTA output;
- scenario 2: the emissions are computed considering the continuous emission functions and Set 1 as DTA output;
- scenario 3: the emissions are computed considering the step emission functions and Set 2 as DTA output;
- scenario 4: the emissions are computed considering the continuous emission functions and Set 2 as DTA output.

During the 18 hours of simulation, the network shows average values of emission of about 70,800g for CO, 38,600g for NOx, 2,200g for PM10 (Fig.6). Maximum values of pollutant emissions have been obtained for scenario 2, with values of 185,200g for CO, 84,800g for NOx, 5,070g for PM10.

Adopting set 1 as DTA output and using step function instead of continuous emission function (scenario 1 - scenario 2) can lead to an underestimation of emissions of -18% for CO, -3% for NOx, -5% for PM10: the results underline the need for an accurate calibration of reliable emission functions. However the underestimations can be halved adopting the most accurate set 2 as DTA output (scenario 3 – scenario 4).

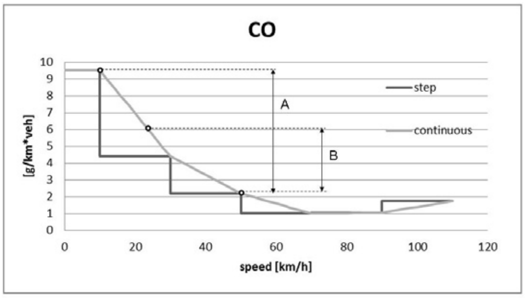

Fig. 7. Role of the emission function for the computation of emission values

Once the emission function is fixed, for example considering the step emission function, if the more accurate set 2 DTA output are adopted (scenario 3 – scenario 1), the obtained emission values are lower than -15% for CO, -3% for NOx and -4% for PM10 respect to use the less accurate set 1. Considering the continuous emission function (scenario 4 – scenario 2), the differences reach the -23% for CO, -5% for NOx and -7% for PM10. It means that if the difference between free-flow and congested conditions are not explicitly taken into account, i.e. using the average traffic conditions, the emission evaluation can be usually rough especially for some kind of pollutants.

The underestimation or the overestimation of the emissions depends on the traffic conditions of the network and on the trend of the emission functions.

In the Brindisi network using set 2, a lower value of emissions are obtained respect to use set 1, *i.e.* $El_{set1} > El_{set2}$.

Fixed a link l of length L_{tot}, travelled by a flow f, a lower value of emissions can be obtained using set 2 respect to use set 1 if:

$$L_{tot} e_i(S_l^t) > L_q\, e_i(S_{l(q)}^t) + L_{ff}\, e_i(S_{l(ff)}^t) \quad (4)$$

The expression (4) can be write as: $B > \alpha A$ for $0 < \alpha \leq 1$ (5)

with

$B = e_i(S_l^t) - e_i(S_{l(ff)}^t)$

$A = e_i(S_{l(q)}^t) - e_i(S_{l(ff)}^t)$

$\alpha = L_q / L_{tot}$

In case of urban links with $S_{l(ff)}^t$ not greater than 60 km/h, we are moving along the left side of the emission function; A and B measures are the differences between emission function values as reported for example for the continuous emission function of CO in Fig.7.

Expression (5) states that if $\alpha = 1$ (the link is completely congested), A is equal to B and the emissions computed using set 2 are equal to emissions computed using set 1. If $\alpha \sim 0$ (the congestion is very low), although B can be reduced, αA is usually lower than B and the emissions computed using set 1 are greater than emissions computed using set 2. For intermediate values of α, the overestimation or underestimation of emissions using set 1 or set 2 cannot be known a-priori, but it is strictly correlated to the shape of the emission function.

If the local roads of Brindisi network are considered (only the links characterized by a value of $\alpha > 0$, *i.e.* with queue), B is equal or higher than αA, as expected.

3.2.2. Comparison between macroscopic approach and dynamic mesoscopic approach

The second step of the study would like to compare the emissions derived from the previous dynamic approach with the standard macroscopic approach, that derives emission values from the knowledge of macroscopic parameters. For this reason, a static assignment, for the peak interval from 8:00 am to 11:00 am, has been performed on the Brindisi network using EMME. Values of macroscopic parameters such as flow and speed are then collected and the emissions computed using both the step and the continuous emission functions.

Table 1. Comparison of CO, NOx and PM10 emissions during the 3 peak-hours between DYNAMEQ and EMME

	Step (s1)				Continuous (s2)			
Time interval	08:00	09:00	10:00	11:00	08:00	09:00	10:00	11:00
Emme CO [g]	124,218.30	124,218.30	85,765.73	80,481.46	164,316.12	164,316.12	113,954.50	107,176.8
Dynameq CO [g]	156,714.30	156,518.40	129,766.47	129,310.52	185,169.53	183,172.83	148,899.60	145,071.00
Δ [%]	26.2	26.0	51.3	60.7	12.7	11.8	30.7	35.4
	Step (s1)				Continuous (s2)			
Time interval	08:00	09:00	10:00	11:00	08:00	09:00	10:00	11:00
Emme NOx [g]	82,637.56	82,637.56	62,007.39	59,019.50	83,989.28	83,989.28	63,191.79	60,166.62
Dynameq NOx [g]	82,815.80	77,175.38	67,068.19	65,990.17	84,793.79	79,214.13	68,577.58	67,146.16
Δ [%]	0.2	-6.6	8.2	11.8	1.0	-5.7	8.5	11.6
	Step (s1)				Continuous (s2)			
Time interval	08:00	09:00	10:00	11:00	08:00	09:00	10:00	11:00
Emme PM10 [g]	4,499.45	4,499.45	3,296.47	3,129.20	4,963.31	4,963.31	3,675.63	3,496.79
Dynameq PM10 [g]	4,826.54	4,535.90	3,927.72	3,868.93	5,067.42	4,757.50	4,093.72	4,010.90
Δ [%]	7.3	0.8	19.1	23.6	2.1	-4.1	11.4	14.7

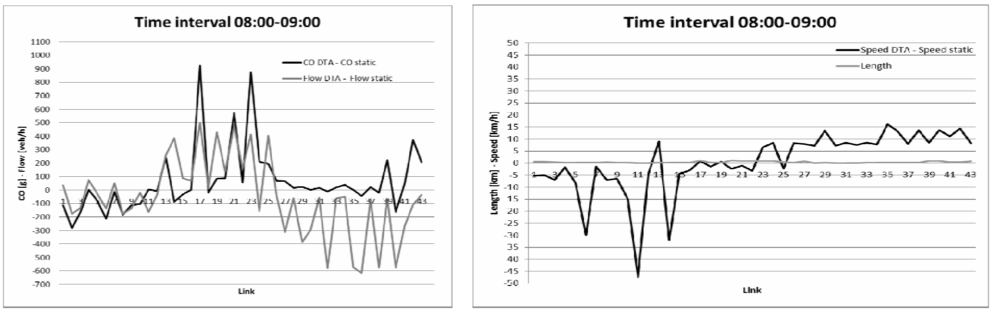

Fig. 8. CO emissions difference, flows difference, link length difference and speeds difference between dynamic and macroscopic approach for a subset of links of a high speed road of Brindisi network

Emission results for CO, NOx and PM10 are finally compared with the dynamic emission results obtained for scenario 1 and scenario 2. During the 3 peak-hours, the results, concerning all the pollutants, show a difference between the macroscopic and the dynamic approach with the dynamic approach that usually estimates higher emissions respect to the macroscopic one (for the Brindisi network).

As obtained with the dynamic case analysis before, also in the comparison with the macroscopic approach the higher differences are obtained for the CO pollutant: in this case using step emission function (Tab.1 - step) the dynamic case shows a difference that can reach the 61% of the emissions computed by the macroscopic approach. Only for NOx during time interval 8:00-9:00 am the emission computed with the macroscopic approach is higher (+6.6%) than the emission computed with the dynamic approach.

With the adoption of the continuous emission function (Tab.1 - continuous), the underestimation of the macroscopic approach persists, but the difference can be reduced from 61% to 35%, while for the PM10 pollutant we pass from an underestimation to an overestimation of the emissions computed with the macroscopic approach.

As reported in the previous section, the underestimation or the overestimation of the emissions depend on the traffic conditions of the network, as a result of the traffic model adopted, and on the trend of the emission functions. The same assumption is true when the macroscopic and the dynamic model are compared.

In case of high congestion on the network, static and dynamic assignment leads to 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 macroscopic approach are higher than the emissions computed with the dynamic approach.

Otherwise, in case of no congestion, with similar values of static and dynamic link flows, the link speed computed by DYNAMEQ are usually greater or equal to the link speed computed by EMME, due to the adoption of the triangular fundamental diagram of the dynamic assignment model: 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); 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 emission functions.

These last results can be easily explained with an example on the Brindisi network considering a subset of links related to a high speed road (free speed of 110 km/h, Fig.8). Along some links (see links 2 and 8) macroscopic emissions are higher than the dynamic ones: it corresponds to similar values of link speeds while static link flows are higher than the dynamic ones. On other links (see for example links 39 and 42) the dynamic emissions are higher than the macroscopic ones: it corresponds to similar values of link flows while dynamic link speeds are higher than the static ones.

4. An analytical model to compute emissions at signalized intersections

Future developments of the model will focus on signalized intersections in order to distinguish between vehicles in queue and vehicles entering/exiting the queue (deceleration and acceleration phases) using data of Dynamic Traffic Assignment (DTA). An analytical model is actually going to be tested based on Akcelic [17] theory.

4.1. Akcelic simplified theory for signalized intersections

In order to apply the analytical model to a large scale urban network, the following hypotheses have been considered:

- only cars and light duty vehicles are considered (the emissions of heavy duty vehicles depend on different parameters respect to the emissions of cars and light duty vehicles; cars and light duty vehicles specific emission factor is expressed as [g/(km*vehicle)], while the specific emission factor for heavy duty vehicles is expressed as [g/(kW*t))]);
- 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, so a conservative approach can be applied);
- the length of the queue is considered as an average value for each time slice considered (T).

For the application of the analytical model, each link of the network is divided in 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.

Moreover two conditions have been 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:

$$E_{T,k} = (q_{T,k} * L_A + Q_{nv} * L_B + Q_{nv} * L_C) * e_a + (Q_{ns} * L_B) * e_b + (q_{T,k} * L_C) * e_c \quad (6)$$

with:

$q_{T,k}$ = 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 occurred during the considered time slice (T/Cycle);
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 for the number of cycles occurred during the considered time slice (T/Cycle);
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 run at free speed L_B and also L_C. 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 computation of Q_{nv}, Q_{ns} [17] and L_B [18] depend on the conditions, saturated or not saturated, of the link approaching the signalized intersection. In case of saturated conditions:

$$Q_{nv} = q_{nv} = 0 \quad (7)$$

$$Q_{ns} = q_{ns} \cdot T/C \text{ and } q_{ns} = q_n \text{ (the maximum flow rate discharge)} \quad (8)$$

$$L_B = (D_{T,k}/C) \cdot L = [(q_{T,k} \cdot C \cdot (1-g/C)^2)/(2(1- q_{T,k}/s))]L \quad (9)$$

with:

$D_{T,k}$ = the total delay to cross the intersection related to the link k, approaching the signalized intersection
L = vehicles length factor (about 6.5÷7 m)
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:

$$Q_{nv} = q_{nv} \cdot T/C = q_{T,k} \cdot g/3600 \quad (10)$$

$$Q_{ns} = q_{ns} \cdot T/C \text{ and } q_{ns} = q_n \cdot (G_s - t_r - ((1-\exp(-m_q(G_s - t_r)))/m_q) \quad (11)$$

$$L_B = (D_{T,k}/C) \cdot L = q_{T,k} \cdot [((C \cdot (1-g/C))/2) + (x_{T,k} - 1) \cdot T/2] \cdot L \quad (12)$$

with

$x_{T,k}$ = 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 $L_C = L_{tot} - L_B$.

4.2. Specific emission factors evaluation

The specific emission factors e_a, e_b, e_c have to be defined. In CORINAIR specific emission functions are evaluated considering different typical drive cycles. In order to define e_a, the drive cycle can be analyzed in order to choice only one value related to the constant speed phase. For the estimation of e_b, that is the average emission factor during queue, it is necessary to consider separately the unsaturated condition from the saturated one. In the first case the queue is removed at each cycle length, while in the second case some vehicles can cross intersection only after a certain number of cycles.

In saturated conditions vehicles emit according with the number of stop and go phases in the queue. Starting from this approximation we can estimate e_b as follow: $e_b= e_b^*$ for unsaturated conditions, $e_b= e_b^*(1+\alpha)$ for saturated conditions, where the parameter α is strictly related to k, that is the number of stop and go in queue ($\alpha =f(k)$)

The number of cycle lengths to wait before crossing the intersection can be estimate using the following formula 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:

$$k = \frac{L_B}{L} * \frac{1}{n_{vs}} \tag{13}$$

$$n_{vs} = s * g / 3600 \tag{14}$$

Once the number of stop and go k has been estimated, the parameter α can be computed as follows:

$$\alpha = dLB * 0.5 * \frac{e_c}{e_b} * k \quad \text{with } dL_B = n_{vs} * L \tag{15}$$

The value $n_{vs}* L_{hj}*0.5$ represents the average distance spent in queue to accelerate. At each effective green g the vehicles in queue move forward for a distance that has been assumed to be the 50% of $n_{vs}* L$. Finally the fraction e_c/e_b represents the increase of emission factor due to the acceleration. Specific emission factor e_c for acceleration phase can be taken from existing references.

5. Conclusions

The paper presents a dynamic mesoscopic approach to obtain reliable values of pollutant emissions in a wide urban network. It takes into account the within-day variations of traffic conditions and parameters related to the different states of vehicles. This model has been applied to the city of Brindisi (Italy): the results show its capacity to pass the limits of the current approaches, to obtain an accurate estimation of the emissions especially for some kind of pollutants (CO) and its capacity to test different off-line and on-line traffic strategies in order to work both on emission and congestion [19] [20].

Emissions estimated by the model have been compared with the results of standard macroscopic approach showing that the differences can reach very high values (the 61% of the emissions computed by the macroscopic approach). Finally, an analytical model to compute emissions at signalized intersections has been introduced as a promising development of the proposed model.

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