Integrating environmental and traffic performance variables in urban road-network project assessment. An explorative study.

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Synopsis

More often and more often, besides improvements in traffic efficiency conditions (increase in average running speed), urban road-network projects are directed towards accident reduction and, more in general, towards the protection of the public safety through measures suitable to bring down environmental pollution levels (particularly air pollution) within tolerableness limits in relation to the context vulnerability.
In spite of this, whereas it’s possible to carry out easily the comparison between different project options as regards those matters concerning urban traffic efficiency (for example, through analitical/deterministic methodologies already for a long time tested such as HCM procedures), the road designer work becomes uncertain when improvements obtainable in terms of reduction in pollutant emissions have to be evaluated. That’s why pollutant emissions depend on characteristics of vehicles in traffic flow and on road operating conditions that are predictable after the implementation of the road project and the usual emission factor/rate models do not reflect reasonably on the on-road vehicles emissions of modal traffic events, such as those ones occurring at intersections.
It has seemed suitable to start a research program for defining a decision making tool to evaluate the effectiveness of urban road-network projects accounting for effects on efficiency of road traffic and on risk joined to pollutant emissions. In this way, considering the close relation between emission phenomena and the instantaneous characteristics of road traffic, a specific research has been devoted to model and to measure vehicle pollutant emissions in different situations (for geometry and traffic), typical in urban areas.
This paper reports the results of a first exploratory analysis, based on realistic driving patterns, directed towards the definition of driving cycles typical of intersection situations. The correlation between usual efficiency parameters (control delay, queue lenght, etc) and the emission level have been also explored.

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In spite of the standards imposed as from the nineties for controlling vehicular polluting emissions, transportation system continues to represent one of the main sources for air pollution; extremely critical conditions taking place in urban areas more and more frequently drive local administrations to adopt temporary measures, as for example traffic restraint actions.
Unlike what is recorded for other sources of air pollution (production activity of electrical energy, combustion installations, etc.), this is due to concomitance of two factors: the slowness characterizing the process of renewal of the existing fleet with vehicles meeting new regulations and the growth of vehicular fleet and distance recovered and then of the related fuel consumptions.
This state of things justifies the growing interest in not restrictive actions as regards road traffic that can contribute to pull down the vehicular polluting emissions and, within these, in actions directly influencing operational conditions of road traffic (speed, acceleration, deceleration), that are closely linked to engine running and emission factors.
Evaluation of benefits obtainable through this kind of actions is not yet integrated in practice of traffic improvement assessment and presents many aspects of uncertainty.
This is mainly due to objective difficulty in capturing differences in emissions depending on traffic operational conditions at micro scale level, for which instantaneous characteristics of motion (generally described by speed and acceleration) become so much relevant that emission estimates cannot be more carried out with general emission models, like the ones used for national and regional emission inventories.
As it will be said in the following, in order to obtain realistic estimates for polluting emissions, it is necessary use models sensible to operational conditions, able to reflect variations in traffic conditions and geometric characteristics. It also means that, to obtain a realistic estimate of vehicle emissions at micro scale level, accurate vehicle activity profiles (representative of on-road conditions) and corresponding activity-specific emission rates are required.
Data availability for emission estimates can become critical when, as it is for project assessment problems, is not possible to make direct measures of vehicular modal activity and it is necessary, then, to resort to predictive models able to represent individual vehicle profiles along a specific street segment or in intersection situations. Moreover, when models have to be applied in evaluating air quality effects of traffic improvement actions, it can be also desirable to correlate vehicle emissions to performance indicators traditionally applied to traffic analysis (for example, those ones assumed in HCM methodologies).
Starting from these considerations, in order to develop a methodology suitable for the evaluation of urban road projects, in this paper a preliminary survey has been carried out with the objective: i) to examine the modal activity influence on emission levels; ii) to identify the most appropriate scale (microscopic and/or mesoscopic) in evaluating effects of traffic improvements on the emissive phenomenon; iii) to value delay events in traffic flows in terms of vehicle emissions.

CURRENT RESEARCH IN VEHICLE EMISSIONS EVALUATION

As already mentioned in the introduction, emission models usually applied to device national or regional emissions inventories, like ones integrated in CORINAIR procedure, are not useful for the evaluation of vehicle emissions at micro scale level. As they are thought for wide-area analysis, they are generally based on an aggregate representation of on-road vehicle activities and a series of assumptions regarding average driver behaviour; typically they only provide a single emission rate for each average speed level starting from emission rates obtained in standard laboratory test conditions and adjusting them on the basis of observed differences between the laboratory and field conditions (temperature, speed, vehicle load, vehicle fleet, mileage, type of fuel, etc.). That is the fundamental reason why this kind of models cannot reflect variations in driving behaviour and become less and less interesting as long as the driving cycles encountered in the field differ from those considered for their implementation.
In opposite to in wide-area air quality analysis approaches, for which emission rates linked to average speed can be appropriate, current researches underline that vehicle emission rates correlate to specific engine operating modes; it means that increasing engine loads (due to activity such as hard accelerations, high speeds and operations on steep grades), as well as rapid load reduction events (hard/long deceleration), result in significantly elevated motor vehicle emission rates compared to stable engine operations (Cicero-

Fernandez P. et al., 1994; Barth, M. et al., 1997; Le Blanc, D.C. et al., 1995; Yu, L., 1998; Enns, P. et al., 1994).
Several models have been developed by researchers to predict emissions as functions of specific operating modes or engine load surrogates that represent the on-road operating conditions leading to high instantaneous emission rates, such as accelerations and decelerations. They are the necessary premise for valuing the effects deriving from traffic-flow improvement projects and allow to go beyond limits of models applied to traditional on-road emission inventories.
Typically the input of these models is represented by vehicle fraction of time spent in each operating mode; as consequence different researches have been devoted to obtain good estimates of microscopic on-road modal vehicle activity both through numeric simulations (Aycin, M.F. et al., 1999; Hallmark, S. L. et al., 1999, Chundury, S., 2000) and field studies by means of instrumented vehicles or external observations of driving behaviour in real conditions (Grant, C., 1998; Roberts, C.A. et al., 1999; Matzoros, A., 1990; Frey H.C. et al., 2001).
Characteristics of modal models can differ even so much in regard to the level of analysis disaggregation; similarly to models applied to traffic analysis, they can be distinguished as follows:

- macroscopic models, by which vehicular activity is macroscopically segregated into modal zones including time spent, idling, accelerating, decelerating, cruising. They generally use deterministic algorithms to calculate queue lenghts and idle time per vehicle (e.g.: Wayson, R.L., 1997; Al-Deek, H.M., 1997);
- microscopic models, utilizing some manner of simulation to obtain microscopic vehicle profiles related to mode specific emission production or fuel consumption rates. They include a wide class of models studied for specific applications ranging from micro-area level to regional one. Examples of these models can be found in several works (e.g.: Al-Omishy, H.K., 1998; Rakha, H.A., 1997; Skabardonis, A., 1997; Williams, M.D. et al., 1999; Liao, T., 1998; Fellendorf, M. et al. 2000);
- mesoscopic models, which combine properties of both microscopic and macroscopic simulation models (e.g. assuming the individual vehicle as unit of traffic flow, but considering their movement being governed by the average speed on the travel link); generally in these models travel simulation takes place on an aggregate level and does not consider dynamic speed/volume relationships (e.g.: Ben-Akiva, M. et al., 1998; Dion F., et al., 2000).

It must be noted that for different reasons the estimate of modal activity by simulation models can result unsuited as input to emission models. Also for microscopic models, for all their attractiveness due to the level of detail, limitations exist in their ability to describe accurately specific velocity-acceleration combinations that are crucial to use with modal emission models (Hallmark, S.H. et al. 1999; Yu, L., 1998). In light of this, research efforts have been devoted to estimate on-road vehicle activity as representative as possible of real world conditions. Moreover, from the above analysis it is equally clear that reliability of the vehicle emission estimates is highly conditioned by local variables (especially by fleet compositions, traffic conditions typical of the examined road environment, users' behaviour, etc.), so that experience gained in a specific context is not directly transferable to other one.

BASIC ASSUMPTIONS

Based on the above considerations, consistently to objectives of the present research, the following evaluations will be developed considering a disaggregation level typical of microscopic models; nevertheless, to get out of disadvantages of these models, methods shown in the NCHRP Report 535 (Dowling, R. A. et al., 2005) have been considered, because they express an updated synthesis between numeric microsimulation approaches and experimental ones through direct observations of modal activity.
According to this methodology, modal activity is expressed as proportion of total vehicle-hours (VHT) that fall in a speed/acceleration category.
Vehicle modal activity tables issued by mentioned report are related to link type (i.e. the link classification based on the design, traffic, and control characteristics) and to the volume-to-capacity ratio (v/c); speed/acceleration frequency distributions *v(i,j)* derived from tables are then in the general form:

$$v\,(i,j) = \mathrm{F}(\text{link type, v/c}) \tag{1}$$

A particularity of speed/acceleration frequency distributions (SAFDs) considered in NCHRP Report 535 is that one can use a single distribution of time spent using the ratio of speed over free-flow speed. By this way they represent normalized time-spent speed/acceleration relationships, which make it possible to account for differences in road design characteristics.
An other important characteristic for the purpose of the present research is that vehicle modal activity is also related to the volume-to-capacity ratio, so that different level of traffic demand can be taken in consideration.
SAFDs considered in the calculations related to facilities of interest (arterials) are grafically represented in figure 1 and 2, respectively for uncongested and congested situations.

Consistently to the adopted methodology, running exhaust emissions rates q_R *(i,j)* to be considered for specified SAFDs are those provided by Comprehensive Modal Emission Model (CMEM), as they are presented in the NCHRP Report 535; total emission E_R will be in the form:

$$E_R = \sum_{ij} q_R(i, j) \cdot v(i, j) \tag{2}$$

where *v(i,j)* identifies the joint speed-acceleration frequency distribution (cumulative vehicle-seconds) for the *i*th speed category and *j*th acceleration category.
As it is well known, CMEM considers carbon monoxide (CO), hydrocarbon (HC) and oxides of nitrogen (NOx); it does not provide emission rates for heavy-duty vehicles and it is calibrated on a composite light-duty vehicle representative of US fleet. As an example, figure 3 shows CMEM light-duty vehicle CO emission rates for each speed/acceleration category.

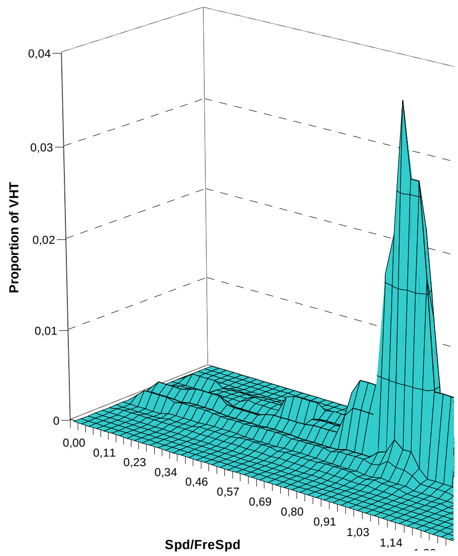

Figure 1: Vehicle modal activity for uncongested arterials(*) (NCHRP 535, 2005)

(*) Proportion of time spent in 0/0 speed/acceleration category (0,2006) is not represented

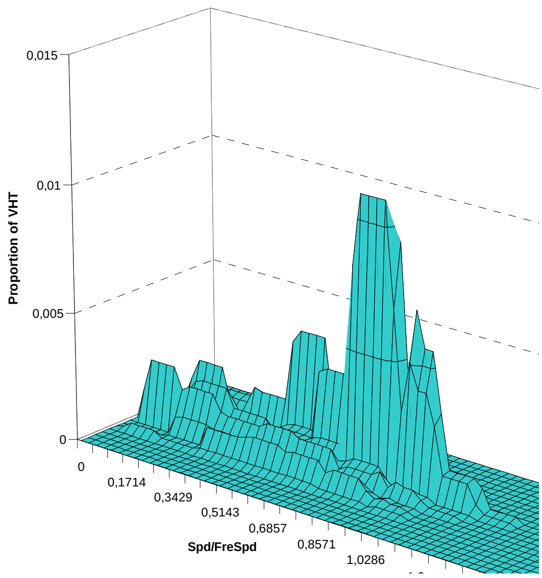

Figure 2: Vehicle modal activity for congested arterials(*) (NCHRP 535, 2005)

(*) Time spent in 0/0 speed/acceleration category (0,5317) is not represented

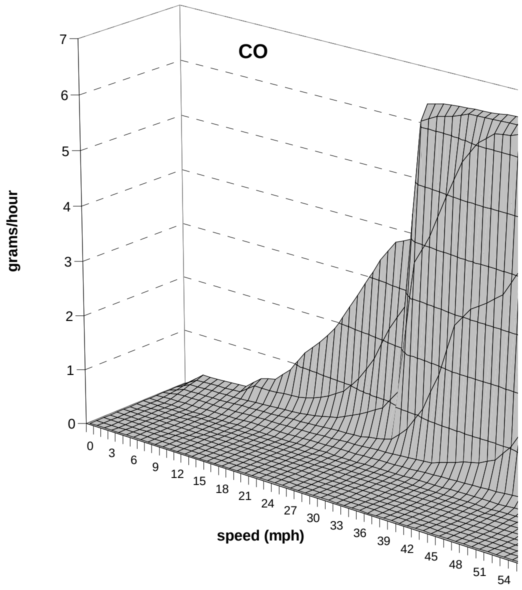

Figure 3: CMEM Light-duty vehicle CO emission rates.

DERIVING EMISSION FUNCTIONS FOR ARTERIALS

The above explained assumptions allow to represent easily the examined phenomenon through emission functions that, for each pollutant, relate the emission rate to specific operational conditions.
Consistently to indicators used to carry out traffic analysis, in order to characterize operational conditions on arterials, the average-speed/free-flow-speed ratio has been used; this variable can be determined considering that, for an assigned speed-acceleration frequency distributions *v(i,j)*, it must result:

$$\textit{average speed} = \sum_i [s_i \cdot \sum_j v(i,j)] \qquad (3)$$

where s_i represents the value of the *i*th speed category.
In order to obtain estimates of intermediate conditions within the congested situation (average speed equal to 0,28) and the uncongested one (average speed equal to 0,65), three other SAFDs have been built assuming a proportinal criterion for valuing each proportion of time spent in the different speed/acceleration category. Intermediate SAFDs are then compatible with assigned average speeds, but, differently from those ones characterizing extreme conditions, they don’t correspond to real driving patterns and will be used only for indicative purposes.
Results of the above described analysis are shown in figures 4a, 5a and 6a for each pollutant and for different design characteristics of arterials (fre-flow-speed ranging from 40 to 60 km/h).
Emissions factors in grams for unit of VHT are clearly unrelated to permanence time of vehicles on arterials; the last one for a single vehicle will be as long as traffic conditions come near congested conditions.
In order to highlight the influence of motion time on emissive phenomenon, emission functions have been counted again, as shown in figures 4b, 5b and 6b expressing emission rates in grams for unit of veic·km.
Both representations clearly show the influence both of arterial characteristics and of operational conditions linked to traffic flows. Note that emission rates as above counted can be interpreted as the weighted mean of CMEM matrix elements with regard to the frequency of the correspondent bin in the proper speed/acceleration frequency distributions.
Changing operational conditions (for example from uncongested to congested situations), variations in emission rates only depend on vehicle modal activity modifications; using traffic analysis language, last ones derive from a different distribution between delay events (i.e. conditions inducing vehicle to decelerate, to stay in idle, to accelerate) and cruise events, during that the vehicle moves just about uniformly at cruise speed.

EMISSION FACTORS RELATED TO TRAFFIC EVENTS

In order to highlight the specific contribution of delay and cruise events, above considerations suggested to aggregate SAFDs elements with regard to idle, acceleration, deceleration and cruise modes; emission factors related to each elementary event can then be obtained using partial aggregation of distributions as input to CMEM model.

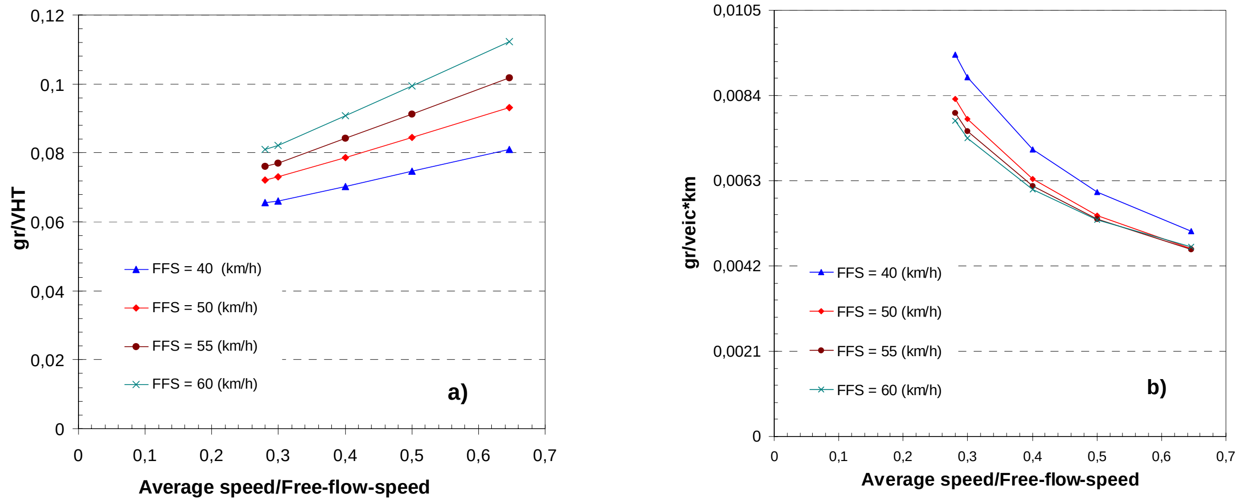

Figure 4: CO emission functions in (gr/VHT) and in (gr/veic*km)

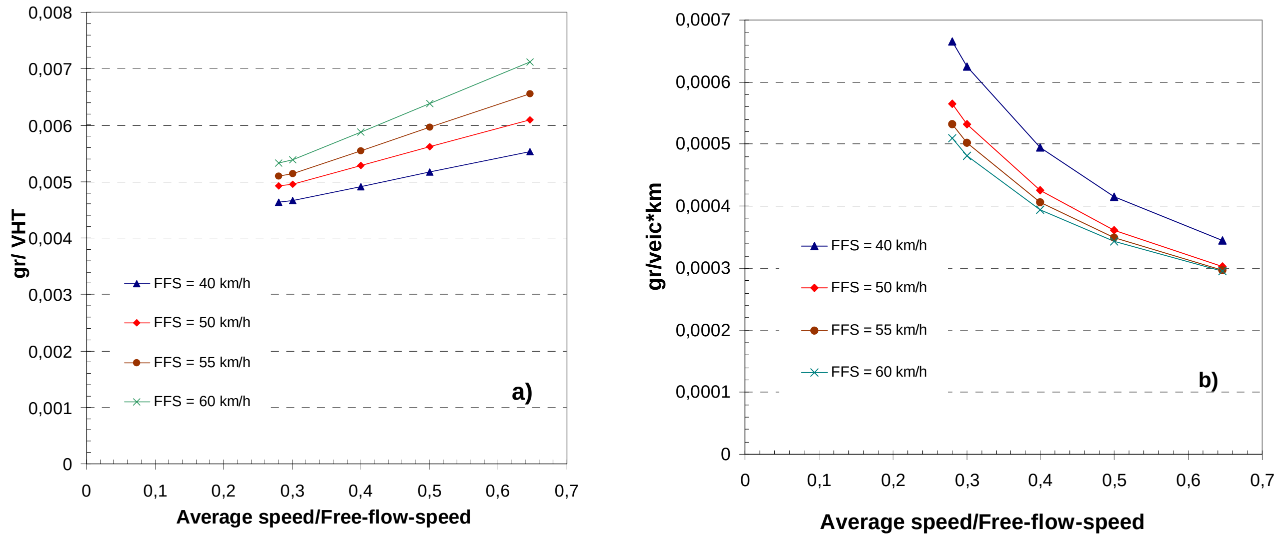

Figure 5: HC emission functions in (gr/VHT) and in (gr/veic*km)

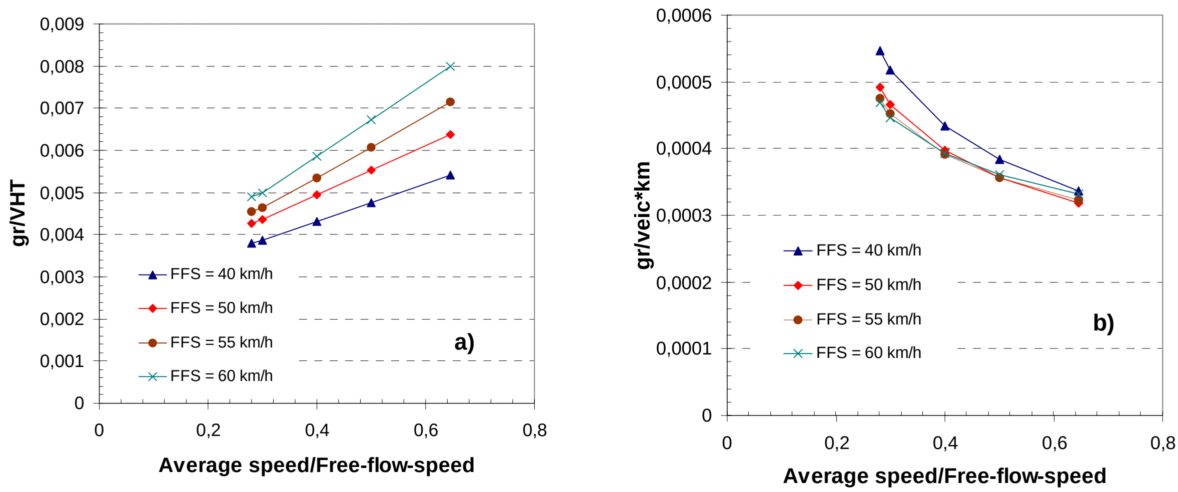

Figure 6: NO_X emission functions in (gr/VHT) and in (gr/veic*km)

For this purpose, a decision criterion has been stated for the analysis of SAFDs - both for uncongested and congested conditions, as well as for intermediate volume-to-capacity ratios; results from direct observations of driving patterns referred in literature (Frey, H.C. et al., 2001), as well as real speed-acceleration frequency distributions obtained in different operational conditions (from LOS A to F), reported by Carlson and Austin (1997), contributed to indicate the following criterion for recognizing each single traffic event:

	istantaneous speed/acceleration range		
Modal activity	speed	acceleration	deceleration
idle	≤ 3 mph	≤ 1 mph/sec	≥ - 1 mph/sec
acceleration	all	≥ 2 mph/sec	-
deceleration	all	-	≤ -2 mph/sec
cruise	> 3 mph	≤ 1 mph/sec	≥ - 1 mph/sec

Application of this criterion for the arterial SADFs analysis in the different traffic conditions (from uncongested to congested situations) lead to identify proportion of time spent by vehicles in each modal activity as shown in table 1.

Tab 1: Proportion of time spent by vehicles in each modal activity

Average Speed/Free-flow-speed	% time spent by traffic event			
	Idle	Acc	Dec	Cruise
0,65	20,99	10,77	8,01	60,23
0,50	34,41	11,16	8,31	46,10
0,40	43,59	11,43	8,51	36,45
0,30	52,76	11,70	8,72	26,80
0,28	53,88	11,74	8,75	25,63

Considering then speed/acceleration categories falling within limits of definition of each modal activity, it is possible to obtain through the CMEM model the contribution gived by each mode to emissive phenomenon. Calculations have been developed for the extreme traffic conditions, obtaining the results shown in figure 7 in the case of FFS = 55 km/h.

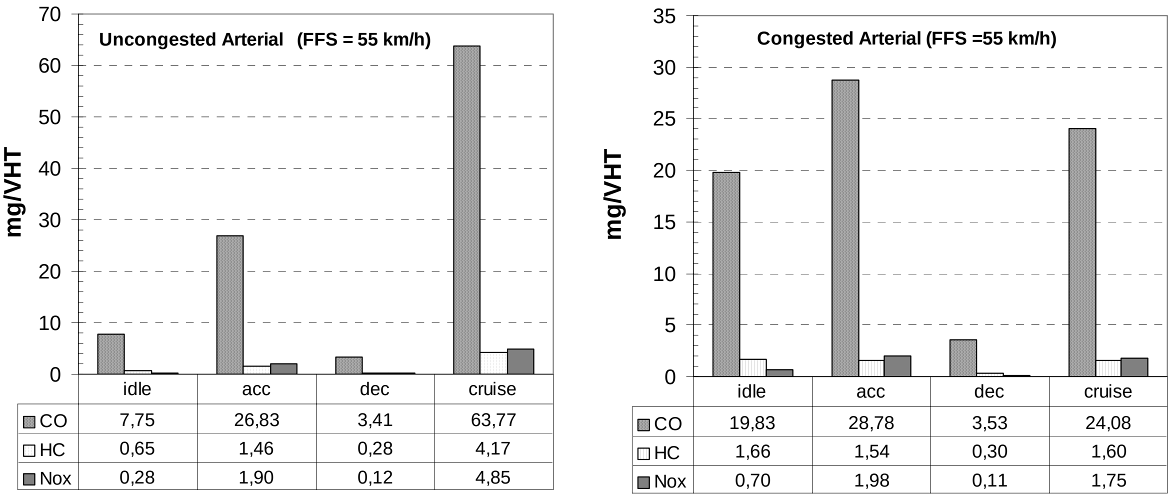

Figure 7: Emissions related to modal activity in uncongested and congested conditions.

It clearly notices that varying operational conditions the contribution of acceleration and deceleration modes, independently from the considered pollutant, maintains just about constant; on the contrary, considerable variations can be observed for idle and cruise, with ratios that as regards pollutants vary in the range 1:2,5÷1:2,8.

The explanation of this result it is not immediate. In this regards, it needs to consider that the contribution of each modal activity on the total emission derives from two concomitant factors:

- from particolar distribution of speed/acceleration categories characterizing each mode and from variations due to changed operational conditions;
- from the time globally spent in each modal activity, as well varying with operational conditions.

In order to highlight the weight of each factor, as above described, the following has been considered:

$$E_R = \sum_{ij} q_R(i,j)\cdot v(i,j) = \sum_{m}\sum_{i,j} q_R^m(i,j)\cdot v^m(i,j) = \sum_{m} \tau^m \cdot \sum_{i,j} \frac{q_R^m(i,j)\cdot v^m(i,j)}{\tau^m} \qquad (4)$$

where the symbols, with the same meaning as above stated, refer to single modal activity (m = idle, acceleration, deceleration, cruise) and

- τ^m is the proportion of time spent in a specific mode;
- $\sum_{i,j} \frac{q_R^m(i,j)\cdot v^m(i,j)}{\tau^m}$ represents the emission linked to m mode, i.e. the quantity of pollutant that would be emitted if vehicle spent all its time in a single mode.

Calculations of emissions by single mode, in accordance with equation 4, have been carried out for congested and uncongested arterials. Figure 8 shows an example of results obtained for the case before examined (FFS = 55 km/h).

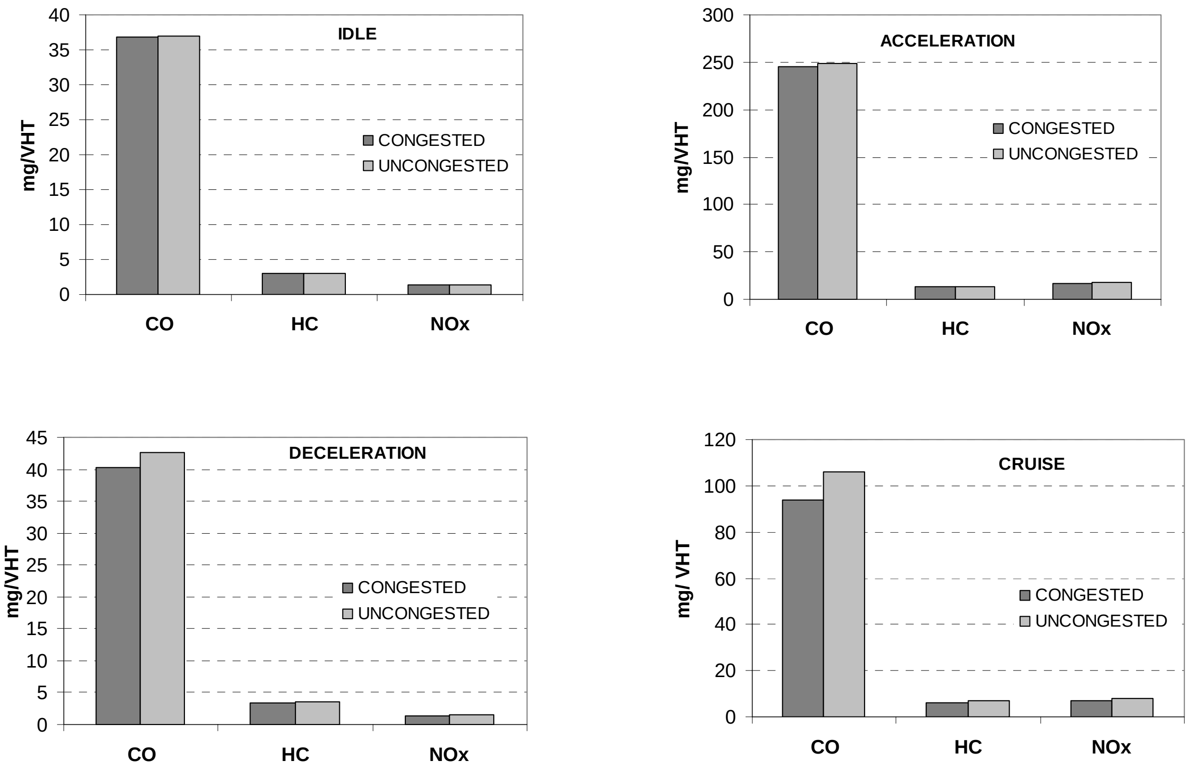

Figure 8: Single mode emissions (SME)

The substantial stability of single mode emissions varying operational conditions, independently from the type of considered pollutant, allows to recognize that the total emission level derive mainly from proportion of time spent in each modal activity and from the emission level correlated to it (single-mode-emission factor, SMEF); on the contrary, the variations that at microscopic level characterize the distribution of speed/acceleration categories are quite marginal if they are considered within the same modal activity both in absolute sense and with regard to the imprecision by which it is possible to obtain vehicle emission estimates.

FORECASTING MODAL ACTIVITY ON ARTERIALS

In the evaluation of traffic improvement projects, results of above described analysis underline the importance both of the total motion time estimate and, above all, of its distribution with regard to vehicle modal activity; on an other point of view, they show the need to recognize in the traffic analysis context the aliquot part of motion time related to delay events.

More in general, the previous discussion about emission factors related to traffic event shows that, without any loss of accuracy, it is possible to reach estimates of polluting emissions made by vehicles in a determined traffic condition, from emission factors proper of each mode (e.g., through modal emission models based on effective SAFDs) and from the distribution of the motion time in modal classes (idle, acceleration, deceleration, cruise) defined at mesoscopic level.

For pratical application purposes, then, modal activity derived from usual traffic study methodologies could be a valid alternative to employ traffic microsimulation models or to driving patterns obtained through experimantal devices (e.g. floating instrumented car, laser guns, GIS, etc.).
An example of this approach will be briefly shown in the following for urban arterials in accordance with methodology suggested by HCM procedures.
In this case, it is well known that total time spent by vehicles has two principal components:
- running time, i.e. time taken to traverse the entire arterial lenght (or segments of it), less any stop-time delay; as well as average running speed, it captures the effect of interactions among vehicles due to differences in speeds among drivers or to downstream vehicles accelerating from a stop and having not yet reached FFS. On the basis of its characteristis, running time can be used as an estimate of time spent in the cruise mode;
- control delay at intersections, i.e. the additional time spent decelerating-stopping-accelerating at intersection approaches; it includes, by the modal activity profile, deceleration, idle and acceleration modes.

On the basis of these assumptions, proportion of time spent in cruise mode can be directly derived from traffic analysis results.
On the contrary, distribution of control delay elementary components must be estimated. A method applicable to signalized intersections can be derived again from HCM procedures, considering that proportion of time spent in acceleration mode and in deceleration one are each other in a stable ratio (see table 1) and that the total control delay is the sum of two parts: time spent in queue (d_{vq}) and time spent in acceleration/deceleration (d_{ad}). Then, the latter component can be empirically estimated by the fraction of vehicle stopping applying empirical correction factors (CF) appropriate to lane group free-flow-speed and the average number of vehicles stopping per lane in each cycle:

$$d_{ad} = CF \cdot \frac{V_{stop}}{V_{tot}} \quad (5)$$

where:
V_{stop} = number of vehicles with stop
V_{tot} = number of vehicles arriving at intersection *i* during analysis period (T).
Evaluation of the correction factor CF can be done on the basis of the exhibit A16-2 in HCM 2000; determination of V_{stop} will be done on the basis of the arrival process applicable to the examined case, considering control cycle characteristics.
Looking at V_{stop}, evaluation can be simply reached in the case of uniform arrival process considering the continuum model showed in figure 9.

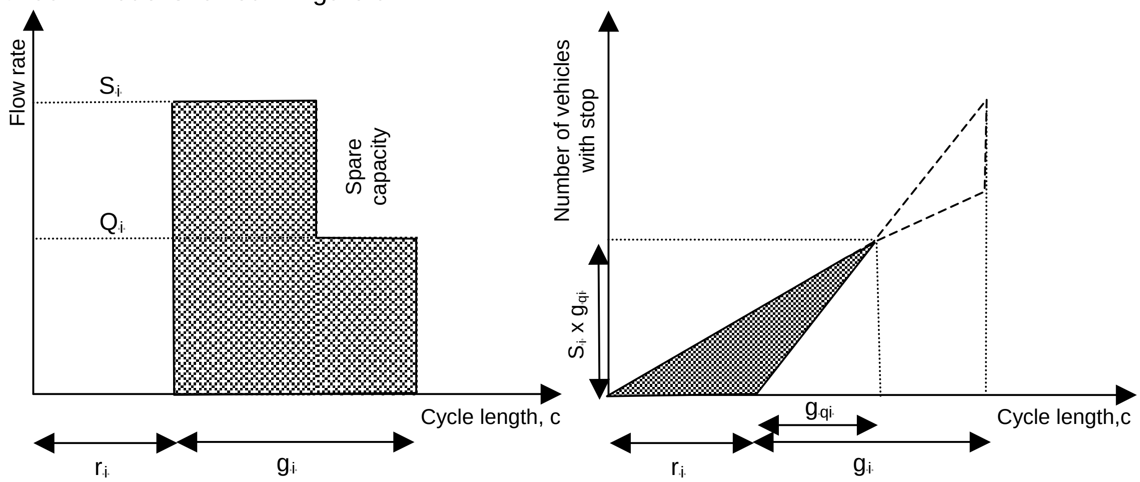

Figure 9: Relevant characteristics and parameters for the continuum model

Referring to the characteristics and parameters of this model, for the i^{th} intersection along the arterial, total number of vehicles with stop will be the sum of:
- vehicles arriving during the red period forced to a stop; total number of them in the analysis period will be:

$$V'_{stop} = Q_i \cdot r_i \cdot \left(\frac{T}{c_i}\right) \quad (5a)$$

where:
Q_i = flow rate at intersection *i* (vph)
r_i = effective red period (s)
c_i = cycle length (s)
T = analysis period in hours;

- vehicles arriving during the clearance time g_{qi}, i.e. during the time the queue is discharging at the saturation rate S_i until the queue is dissipated:

$$V''_{stop} = Q_i \cdot g_{qi} \cdot \left(\frac{T}{c_i}\right) \tag{5b}$$

where:

S_i = saturation flow (vph)

$g_{qi} = \frac{(Q_i \cdot r_i)}{(S_i - Q_i)}$ is the clearance time (s) and other symbols have the same meaning as above specified.

CONCLUSIONS

By means of models now available for valuing vehicle emissions, the analysis previously illustred has allowed to derive, at the scale required for urban road network project assessments, the relative weight of emission factors in relation to traffic events and the importance that in practical applications assumes the estimate of trip time and of its modal distribution.

Depending on the substantial stability of single mode emissions in different operational conditions, independently from the type of considered pollutant, it has shown that the total emission level derives mainly from proportion of time spent in each modal activity and from the emission level correlated to it; at the same time, results of the analysis highlight that the variations characterizing at microscopic level the distribution of speed/acceleration categories are quite marginal if they are considered within the same modal activity.

From a methodological point of view, the exploratory study referred in this paper suggests that, without any loss of accuracy, it is possible, for a specific traffic condition, to reach estimates of polluting emissions made by vehicles from emission factors proper of each mode, such as they can be preventively obtained through modal emission models based on effective SAFDs, and from the distribution of the time spent in modal classes (idle, acceleration, deceleration, cruise), defined at mesoscopic level. From that, modal activity analysis carried out at micro scale level, required by modal emission models, will be still necessary for valuing reliable emission factors by single mode (idle, acceleration, deceleration, cruise); nevertheless, this kind of evaluation (for each pollutant to be considered), can be mainly standardized depending on the type of road, volume-to-capacity ratio and fleet composition. As consequence, mesoscopic level for vehicle modal activities, as it is usual in traffic analysis, will result appropriate to reach accurate emission estimates.

These considerations, even if developed at a qualitative level, allow, as well, to highlight some fundamental lines along which move subsequent investigations in order to develop a methodology suitable to be adopted in current practices of traffic studies in urban areas:

- to deduce real driving patterns able to reflect both different road and traffic conditions, as well as drivers' characteristics related to the area of interest;
- to analyze vehicle modal activity on segments and at intersections, in order to derive elementary (by mode) speed/acceleration category distributions;
- to evaluate emission factors by speed/acceleration categories, reflecting fleet composition different from the one considered by CMEM model, so they will be applicable to regional fleet characteristics;
- to derive standard single model emission factors, as above specified, to be used in the practice of urban road network project assessment.

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