CO dispersion models for signalized road intersections: Gaussian vs. empirical approach

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Abstract

A comparison has been made between a Gaussian and an empirical approach to model carbon monoxide (CO) atmospheric dispersion at a signalized road intersection. Starting from the Webster queue and the Kunselman modal emissions algorithms both implemented in the APRAC/3 model, the MODEM emission model has been applied for estimating dynamic emission rates along each link connecting to the intersection. As regards the Gaussian dispersion approach, both the algorithm implemented in the CALINE/4 model as well as the one in the APRAC/3 model have been applied. Their performances have been compared with an empirical approach developed by the authors which was based on a simplified box model applied to the intersection area. Experimental data measured in Firenze (Italy) have been used for calibrating each dispersion model to the study case. The calibrated models have then been applied over a different time period in order to test their performances. As a final result, the empirical box model proved to be more accurate than the Gaussian models.

1 Introduction

Signalized road intersections use to be crucial points for traffic-related pollutant concentrations, whose levels often prove to be very high [1]. Hence, an intersection model appears to be of fundamental importance as a forecasting tool, although in principle its structure is generally complex. In order to reproduce traffic behaviour along each link connected to the intersection, the application of the so-called “queue theory” is needed. Once data such as road topographic and geometrical features, vehicular flows, and lights intersection settings have been provided, parameters such as the queue maximum length, the number of vehicles...
stopped, and the mean delay can be evaluated. Thus, different driving kinematics (acceleration, cruise, deceleration, idle) affecting vehicles approaching to or departing from the intersection are computed. These in turn are the basic inputs for the emission model to estimate pollutant modal emissions along each link. On these bases, eventually pollutant concentrations can be evaluated by means of a dispersion model. As regards the latter, a comparison has been made between a Gaussian and an empirical approach, the former based on current literature algorithms and the latter suitably developed by the authors on the bases of a simplified box model applied to the intersection area.

2 Model development and application

The intersection modelling has been developed according to the scheme described in Fig. 1.

CO concentration estimation finally results from a model chain built in a cascade fashion by a dynamic emission model, a queue algorithm, a modal emission model, and eventually a dispersion model. Besides as an input for the latter, estimations by all the other models can be used for drawing a vehicle queue and a modal emissions behaviour at the intersection as well.

Figure 1: Block scheme of the intersection modelling for the estimation of CO concentrations.
2.1 Queue and emission models

According to the Fig. 1 block diagram, the first step has been aimed at the estimation of the dynamic emission factors affecting vehicles approaching to or departing from the intersection. Their behaviour is generally modelled as a sequence of the acceleration, cruise, deceleration and idle modes, which accounts for the emission model to be of a "dynamic" kind.

The dynamic emission model used was the MODEM [2] model, specific of the European car fleet and able to estimate inert pollutant emission rates as a (not continuous) function not only of driving speed ($v$), but also of the product between speed and acceleration ($v \cdot a$). Thus, every single kinematic mode can be managed. For the "acceleration/deceleration" mode, a constant value is set for speed and a positive or negative one (according to cases) for $v \cdot a$. For the "cruise" mode, $v$ is obviously constant, whereas is $v \cdot a = 0$ since $a = 0$. In the "idle" mode, both $v$ and $v \cdot a$ are set equal to zero, as $v = 0$ and $a = 0$. Numerical values (in not null cases) for kinematic parameters $v$ and $a$ have been set according to what suggested within the APRAC/3 [3] code, that is 30 Km/h for cruise speed and $\pm 1$ m/s$^2$ for acceleration/deceleration.

Queue parameters have been computed by means of the INSEC module, which is based on the Webster [4] algorithm and implemented in the APRAC/3 model. Once data such as vehicular flows, traffic lights phasing and intersection geometry and morphology have been input, parameters such as the queue maximum length, the number of vehicles stopped, and the mean delay per vehicle during an entire signal cycle can be calculated.

Emissions during the acceleration, cruise, deceleration and idle modes are estimated by means of the EMITX module, which is based on the Kunselman [5] modal emissions algorithm and implemented in the APRAC/3 model as well. Once INSEC-provided inputs are known, EMITX operates as to split each link into five segments, affected by a different driving mode: acceleration, cruise, deceleration, deceleration plus idle (second half of the queue), acceleration plus idle (first half of the queue). Starting from the estimations by the MODEM dynamic model - suited at the study case once car fleet composition has been provided -, the Kunselman modal emissions model determines an instantaneous emission rate as a function of vehicle speed and acceleration. Finally, this enables the EMITX module to calculate lineal emission rates (mg/s) for each of five sections, and thus over each link connected to the intersection.

2.2 Dispersion models

As already pointed out, the pollutant dispersion section has been managed by using a set of models resulting from different bases. The aim was to compare not only a Gaussian vs. an empirical approach, but also two of most currently used models for signalized intersections vs. a simplified empirical approach.

Gaussian approach has been carried out by applying the intersection algorithms implemented both in the APRAC/3 and in the CALINE/4 [6] models.

The APRAC/3 dispersion module aimed at estimating pollutant concentrations at a traffic lights intersection is named LINE. Its application
within the Fig. 1 model flowchart proved to be rather easy as it is naturally interfaced with the other APRAC/3 modules applied. LINE is able to calculate pollutant concentrations at the receptor point starting from a finite line source which is approximated by an array of point sources, whose mutual spacing is managed as to be suitably minimized. Concentrations are then calculated by means of a Gaussian equation applied to each point source. A coordinate transformation of the link endpoints is needed to apply such point source equation to all receptor-link configurations with respect to wind direction. Eventually, the individual contributions to concentration are summed to determine the overall effect from the traffic links connected to the intersection.

The application of the intersection algorithm implemented in the CALINE/4 code required, on the contrary, an adequate reformulation of the input interface. The main purpose was to make all the estimations provided by the queue and modal emissions models to be treated as an input by such dispersion model. In particular, the operational mode timing, the modal emission factors and the queue features have been provided. Once input both the intersection geometrical features and all the atmospheric variables too, concentrations at the receptor can be finally estimated through a Gaussian equation as well.

Furthermore, a third dispersion algorithm has been applied to estimate pollutant concentrations at the intersection receptor point. Such an algorithm, suitably developed by the authors, results from an empirical approach where a sort of simplified box model applied to each link connected to the intersection has been used [7], [8]. In particular, this implied the use of an equation such as:

$$C = \frac{Q_s}{(U + 0.5) x_0}$$  \hspace{1cm} (1)

where:
- $C$ (mg/m³) : modelled concentration;
- $Q_s$ (mg/mh): mean global emission rate per time and driving unit referring to the overall intersection area;
- $U$ (m/s) : predominant wind speed (at roof level);
- $x_0$ (m) : cross-section distance from receptor to road centerline (mixing length).

As regards $Q_s$, its estimation has been achieved once modal emission rates and metric extension referring to each of five link segments have been provided by the EMITX module. Starting from these values, global emission for each link is then calculated as an average weighted by the entire link length. Such value can be seen as an emission rate per time and driving unit (mg/mh), that is it represents the mean kinematic emission over the entire driving cycle. Finally, the $Q_s$ amount is obtained by summing each of such contributions over all intersection links.

As mentioned, concentration calculation at the receptor point is obtained by applying a sort of simplified local box model, where the cross-section width of the space domain where pollutant dispersion takes place is equal to that of each...
According to such box approach, concentration estimation at a receptor beside the road can be finally achieved as a ratio between global emission $Q_s$ and the product between predominant wind speed $(U+0.5)$ and mixing length $x_0$, that is the mean path travelled by every gas parcel from source to receptor.

### 3 Site description and experimental data

Models have been applied at the signalized road intersection connecting Via Leopardi, Via Colletta and Viale Gramsci in Firenze, Italy (Fig. 2). Viale Gramsci is a three-lane per direction road, whereas the other two links are one-lane per direction roads. Such site proved to be the only urban intersection one endowed with both a receptor point nearby and vehicle flow counters along each link.

As it can be seen from Fig. 2, pollutant dispersion has been treated in modal terms with respect to wind direction. Hence, the intersection area has been subdivided into four 90° wide sectors with the same orientation of each link, and thus according to cardinal directions.

The analyzed pollutant species was carbon monoxide (CO).

While both traffic and concentration data have been locally collected by the intersection area, atmospheric data have been provided by the Ximeniano observatory meteoclimatic station, located in the town centre and representative of conditions valid for the whole urban area.

![Figure 2: Overview of signalized road intersection in Firenze, where models have been applied.](image)
4 Model calibration and results

Models have been calibrated over the January to March 1994 time period, a wintertime one as its most significance with respect to pollutant gas chosen. The calibration process was based on the application of a linear regression analysis. For all applied dispersion models, calibration provided the linear correlation coefficients $r^2$ sorted by wind sector summarized in table 1.

<table>
<thead>
<tr>
<th>Sector</th>
<th>APRAC/3</th>
<th>CALINE/4</th>
<th>Local Box</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>0.15</td>
<td>0.18</td>
<td>0.52</td>
</tr>
<tr>
<td>East</td>
<td>0</td>
<td>0.32</td>
<td>0.42</td>
</tr>
<tr>
<td>South</td>
<td>0</td>
<td>0.26</td>
<td>0.54</td>
</tr>
<tr>
<td>West</td>
<td>0.46</td>
<td>0.39</td>
<td>0.38</td>
</tr>
</tbody>
</table>

By looking at table 1, the APRAC/3 intersection dispersion model exhibits a rather poor correlation level, with estimations highly sensitive to wind direction. When wind bearing is from both the east and south sectors, a null correlation resulted, despite the occurrences referring to the other sectors and the west one in particular, which proved to be the one also encompassing the optimal wind direction wide range. Such results thus suggest that the LINE module, even once calibrated, is only able to manage wind directions basically bearing upwind with respect to the receptor point.

The calibration of CALINE/4 intersection model showed a better correlation level, though the $r^2$ values cannot be defined as definitely acceptable. However, calibration has been positively carried out for all sectors and the west one in particular, which again proved to be the most accurate one.

On the other hand, the calibration of empirical local box model provided some higher correlation coefficients with the exception of the west sector, where the other two models perform better. Such $r^2$ value actually differs from the model general ones, which for the other sectors range from 0.42 to 0.54. However, such values lead to the conclusion that the calibration process provided the best fitting for the empirical algorithm rather then both the Gaussian ones.

Once calibrated, dispersion models have been then applied over a different time period (the month of January 1995) in order to test their performances. Such results are plotted in Fig. 3, where a number of typical statistical indicators applied by sector have been used to compare CO measurements vs. estimations. Such figure refers to the CALINE/4 and local box models only since, according to table 1 values, the calibration of APRAC/3 model proved to be basically impossible for the most of sectors.
Figure 3: Comparison between CALINE/4 and local box models performances by means of some statistical indicators applied by sector (January 1995).

The comparison shown in Fig. 3 leads to a number of considerations. As a whole, the empirical box model performs better than the CALINE/4 one for all sectors with the exception of the west one, for whom a confirmation of the calibration results apply. This can be seen through all the statistical indicators.
being used. As far as the north, east and south sectors are concerned, box model related mean errors range from -0.34 to 0.51 mg/m³, whereas CALINE/4 values range from -0.45 to 0.96 mg/m³. The corresponding standard deviations are also higher for the CALINE/4 model (1.30÷2.21 mg/m³) than the other one (1.33÷1.80 mg/m³). Same results apply for mean absolute errors and their corresponding standard deviations.

Best CALINE/4 CO estimations result for the north sector, with values roughly comparable with those by the box model, whereas worst performances occur within the south sector, which on the contrary proves to be the more accurate sector for the empirical model. As far as the latter is concerned, its worst performances occur, as mentioned, in the west sector. Again, such result clearly differs from those regarding all the other sectors.

Summarizing, CO concentration estimations provided by the empirical box model can be defined as more accurate than those by the Gaussian CALINE/4 intersection model. By theirselves, such box model estimations can also be defined as acceptable, as shown in Fig. 4, where a sample measurement vs. estimation scatter plot is pictured.

![Local Box model](South sector - January 1995)

$$r^2 = 0.65$$

Figure 4: CO measurements vs. estimations scatter plot for local box model (South sector- January 1995).

5 Conclusions

An empirical dispersion model for estimating carbon monoxide concentrations at signalized road intersections has been set up. The model, based on a simplified
box model applied to the intersection area, results from a comparison with respect to two of most currently used intersection models, that is those implemented in the APRAC/3 and CALINE/4 models. Starting from the Webster queue and the Kunselman modal emissions algorithms both implemented in the APRAC/3 model, the MODEM emission model has been applied for estimating dynamic emission rates along each link connecting to the intersection. Experimental data measured in Firenze (Italy) have been used for calibrating each dispersion model to the study case. The calibrated models have been then applied over a different time period in order to test their performances. As a final result, the empirical model proved to be more accurate then the Gaussian ones, providing some acceptable performances as well.

The model presented in this paper has been implemented into a Geographic Information System focused on the city of Firenze, which was developed with the aim of managing atmospheric pollution due to urban traffic [7], [8].

References