Incompleteness of the urban traffic plan in preliminary studies of environmental impact: the real case of “urban canyons”

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Abstract

The General Urban Plan (PRG) and the correlated Urban Traffic Plan (PUT) which have dictated the guidelines both of building and social-economic development of the city for at least twenty years, must hold in esteem the environmental effects coming from the choices of planning, such as the detrimental consequences that could be correlated with air pollution coming from urban traffic. In fact, the gaseous polluting concentrations in the roads of the city are closely connected to three main key-factors: volume and typology of car traffic, the shape ratio W/H between the height of buildings and width of roads and, at least, the meteoclimatic conditions of the area. In particular, the W/H ratio has a predominant influence on the dispersion of air pollution since it can cause a so-called “canyon effect”, a factor which has an extremely negative effect on the dispersion of gaseous pollution. Owing to previous reasons the PRG and PUT must be closely supported by a preliminary Study of Environmental Impact (SIA) which is able to determine the limits of the volume of car traffic in the zones of the city where there are many urban canyons or other sensible structures to avoid stagnation of gaseous concentrations. This paper wants to demonstrate the need to have the SIA as a support for the PUT, pointing out, by ADREA-HF 3D fluid dynamic environmental code and by experimental measurements in situ, the real possibility of having, under specific generic features of the boundary roads, concentrations of polluting gases higher than those fixed by Italian Environmental Law.

Keywords: carbon monoxide, urban canyon, air pollution control.
1 Generality

There are two possible situations of planning, that is:

- In the case of a forecast of territorial expansion of a town in non built-up areas, the SIA can show the settlement of W/H ratio to be adopted so as to not cause a “canyon effect” for air pollution coming from the urban traffic flows forecasted by PUT in function of density of population of areas, in its turn coming from the forecasting of PRG.

- In the case of already built areas, the SIA must show how the PUT has to settle the volume of traffic in function of existing W/H ratios to avoid stagnation of pollution caused by the “canyon effect”

To demonstrate that the planning of traffic flows must be done not only in function of demand of traffic mobility but mainly to define the sustainable volumes of traffic in environmental terms, the research has been organised in many steps:

- Choice of urban area having W/H ratio consistent with geometries of “urban canyon”.
- Choice of model of gaseous emissions from exhaust pipes representative both of volume and typology of car traffic in the chosen urban area.
- Investigation of meteoclimatic conditions of area.
- Modelling of fields of motion of pollutant gasses in function both of meteoclimatic conditions (wind, temperature, humidity) and W/H ratios.
- Forecast of fluidynamic of gasses inside canyons by ADREA-HF 3D code
- Validation of the model, both of gaseous emissions and theoretical dispersions by comparison between forecasted data coming from the model and those measured in situ by portable analysers.

By utilising this procedure, researchers have been able to point out some basic information about the trend of polluting concentration in real “urban canyon” of Catania city.

2 The real case

The investigated Urban Canyon is located in the commercial centre of Catania city (V. E. Orlando Street), as shown in figure 1. Along the whole course of this road there are several traffic flows both during the day and at night time. Geometrically, the street, with the roadway eight meters wide, is bordered continuously in both sides by buildings that are, on average, twelve meters high. On the ground of these geometric features the shape ratio W/H is 0.67, that is air motion inside the canyon, typical of “skimming flow” [1] as shown in figure 2.

With reference to figure 3, in the case of wind blowing in an orthogonal direction to the urban canyon, it is possible to notice, owing to the “skimming flow”, that the stagnation of pollution depends on the forming of a stable whirlwind which reduces the air mass exchange between the “canopy layer” and the “boundary layer”. There is also the forming of an additional contrary-rotating smaller whirlwind under the previous main whirlwind and as it is not possible to
exchange mass between the two whirlwinds. In this way, at the ground level of the canyon, the stagnation of air increases more and more, and consequently the polluting concentration too.

Figure 1: Plant of investigated area.

Figure 2: Flow regime as function of W/H shape- ratio [1].
Figure 3: Mean velocity vectors and stream traces on urban canyon.

Table 1: Classification of auto-vehicles.

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>Displacement</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Cars</td>
<td>&lt;1400 cc</td>
<td>Gasoline</td>
</tr>
<tr>
<td>Passenger Cars</td>
<td>&lt;2000 cc</td>
<td>Diesel</td>
</tr>
<tr>
<td>Light Heavy Duty</td>
<td>&lt;3.5 t</td>
<td>Diesel</td>
</tr>
<tr>
<td>Two Wheelers (2 stroke engine)</td>
<td>&lt;250 cc</td>
<td>Gasoline</td>
</tr>
<tr>
<td>Two Wheelers (4 stroke engine)</td>
<td>&gt;250 cc; &lt;750 cc</td>
<td>Gasoline</td>
</tr>
</tbody>
</table>

People adopted Carbon Monoxide (CO) tracer pollutant gas as having a good chemical stability in an urban atmosphere, since easiness in the use of measurement equipment, typical gas emitted by vehicular traffic, high sensitivity as both CO and traffic load tend to have a similar trend of variation during the day.

Input data required by the investigation are:
- Value of car traffic flow
- Features of circulating fleet of cars (class of power, kind of fuel, age of cars)
- Emission factors (EF) of Carbon Monoxide
- Mean velocity of car traffic flow
- Fuel consumption of car in function of class of power and relative discharge - rate of exhausts.

Moreover:
- The traffic flow has been obtained by surveying
- The features of circulating vehicles have been obtained by data of Public Register of Auto-vehicles (PRA) and by the data from the Automobile Club of Italia.
- The classification of vehicles has been done as shown in table 1.
- People unified all the cars with petrol engine in one power-category, (1400 cc) and also the cars with diesel engine in another power-category (2000 cc).
- Light heavy vehicles have been classified in function of their load capacity (less than 3.5 tons).
- The vehicles have been subdivided into two categories according to the function of the type of engine typology (2 or 4 stroke engine)
- For each class of vehicles, some functions to evaluate them have been associated, with data coming from Corinair European Project [2] emissions and fuel consumptions both depending on mean velocity of flow traffic
- The discharge rate of exhausts has been calculated by:
  \[ \dot{m}_{\text{AIR}} = (1 + \varepsilon) \cdot \dot{m}_{\text{AS}} \]  
  (1)
- where: \( m_{\text{AIR}} \) = mass flow-rate; \( \varepsilon \) = excess of air; \( m_{\text{AS}} \) = stoichiometric mass flow-rate
- The discharge rate of concentration of CO in exhausts has been calculated by:
  \[ q_{\text{CO}} = \frac{m_{\text{CO}}}{(m_{\text{CO}} + m_{\text{AIR}})} \]  
  (2)
- Where: \( m_{\text{CO}} \) = mass flow-rate of CO in exhausts calculated from data of fuel consumptions and utilising the following data coming from by surveying and by technical bibliography:
  - Mean velocity of car traffic flow: \( V = 10 \) km/h
  - Ratio of air/fuel: \( \alpha = 17 \) for gasoline engine and \( \alpha = 20 \) for diesel engine
  - Excess of air: \( \varepsilon = 1.20 \); Air density: \( \rho = 1.01 \) kg/m³ (T=350 K)

For each category of vehicles, the results of the calculation are shown in Table 2:

By the data shown in table 2, people have been able to define:
- flow-rate of emission and concentration of CO (mean values) for each category of motor vehicles (table 1) referred to weighted mean on distribution of motor vehicles classes
- the “characteristic emission” of “mean vehicle” referred to composition of vehicular traffic checked during the surveying time.

Results are summarized in table 3.

### Table 2: Flow-rate of CO emissions.

<table>
<thead>
<tr>
<th></th>
<th>[g_{\text{CO}}/\text{km}]</th>
<th>[kg_{\text{std}}/\text{km}]</th>
<th>[%]</th>
<th>[kg_{\text{std}}/\text{h}]</th>
<th>[m³/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline Passenger Cars (ECE 15/04)</td>
<td>32,084</td>
<td>2,295</td>
<td>1,400</td>
<td>22,95</td>
<td>22,73</td>
</tr>
<tr>
<td>Gasoline Passenger Cars (91/441/EEC)</td>
<td>7,199</td>
<td>1,872</td>
<td>0,380</td>
<td>18,72</td>
<td>18,53</td>
</tr>
<tr>
<td>Gasoline Passenger Cars (94/12/EEC)</td>
<td>4,894</td>
<td>1,872</td>
<td>0,261</td>
<td>18,72</td>
<td>18,53</td>
</tr>
<tr>
<td>Diesel Passenger Cars (No catalytic)</td>
<td>1,444</td>
<td>2,376</td>
<td>0,061</td>
<td>23,76</td>
<td>23,53</td>
</tr>
<tr>
<td>Diesel Passenger Cars (94/12/EEC)</td>
<td>1,132</td>
<td>1,890</td>
<td>0,060</td>
<td>18,90</td>
<td>18,71</td>
</tr>
<tr>
<td>Gasoline Light Duty Vehicle (No catalytic)</td>
<td>1,592</td>
<td>3,000</td>
<td>0,053</td>
<td>30,00</td>
<td>29,70</td>
</tr>
<tr>
<td>Gasoline Light Duty Vehicle (93/59/EEC)</td>
<td>0,838</td>
<td>2,759</td>
<td>0,030</td>
<td>27,59</td>
<td>27,31</td>
</tr>
<tr>
<td>Motorcycle (2-T cc&lt;250 cm³)</td>
<td>19,720</td>
<td>0,960</td>
<td>2,055</td>
<td>9,60</td>
<td>9,50</td>
</tr>
<tr>
<td>Motorcycle (4-T 250-750 cm³)</td>
<td>42,190</td>
<td>1,489</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3: Values of mean emissions.

<table>
<thead>
<tr>
<th></th>
<th>Mean flow emission</th>
<th>Mean Concentration of CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline Passenger Cars</td>
<td>21,11 m³/h</td>
<td>0,93%</td>
</tr>
<tr>
<td>Diesel Passenger Cars</td>
<td>21,73 m³/h</td>
<td>0,06%</td>
</tr>
<tr>
<td>Light Duty Vehicles</td>
<td>29,47 m³/h</td>
<td>0,05%</td>
</tr>
<tr>
<td>Motorcycle</td>
<td>11,37 m³/h</td>
<td>2,32%</td>
</tr>
<tr>
<td>Representative Vehicle</td>
<td>17,60 m³/h</td>
<td>1,40%</td>
</tr>
</tbody>
</table>
3 Model of dispersion

ADREA-HF code is based on the finite volume concept in Cartesian Coordinate system. Conservation laws and related equations are applied to a defined three-dimensional atmospheric domain. The set of governing equations for the mean flow field parameters are expressed in tensor notations and reported as follow:

- **Mixture mass:**
  \[
  \frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{3}
  \]

- **Mixture momentum:**
  \[
  \frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\rho K_{mj} \frac{\partial u_j}{\partial x_j}\right) + \rho g_i \tag{4}
  \]

- **Mixture energy:**
  Equation is expressed in terms of internal energy and temperature:
  \[
  \frac{\partial \rho e}{\partial t} + \frac{\partial \rho u_i e}{\partial x_i} + P \frac{\partial u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\rho c_p \frac{K_{mj}}{\sigma_h} \frac{\partial T}{\partial x_j}\right) \tag{5}
  \]

- **Heavy fluid mass transport:**
  Equation is expressed in terms of mass fraction transport:
  \[
  \frac{\partial \rho q_w}{\partial t} + \frac{\partial \rho u_i q_w}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\rho \frac{K_{mj}}{\sigma_h} \frac{\partial q_w}{\partial x_j}\right) \tag{6}
  \]

where: \(\rho=\)fluid density, \(e=\)fluid mixture internal energy, \(C_p=\)fluid mixture specific heats, \(P=\)fluid mixture total pressure, \(g_i=\)gravity acceleration component, \(u_i=\)velocity components \((u,v,w)\), \(x_i=\)distance \((x,y,z)\), \(K_{mi}=\)momentum eddy viscosity, \(q_w=\)heavy fluid mass fraction, \(\sigma_h=\)effective Prandtl number. Turbulence closure modelling is based on the gradient transport hypotheses and involves application of eddy viscosity-diffusivity concepts. The one-equation model has been adopted for the solution of transport equations: this model utilizing turbulence relates quantities such as turbulent kinetic energy \((K)\) and turbulent energy dissipation \((\varepsilon)\). Turbulent kinetic energy has been obtained through the solution of transport equations, while turbulent energy dissipation \((\varepsilon)\) have been calculated by semi-empirical relations [3]. The temperature variations with height corresponding to neutral stability conditions.

4 Simulation data

As shown in figure 4, the chosen domain of calculus in Cartesian coordinates has dimensions respectively:

<table>
<thead>
<tr>
<th>X direction</th>
<th>Y direction</th>
<th>Z direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>350,0 m</td>
<td>250,0 m</td>
<td>60.0 m</td>
</tr>
</tbody>
</table>
The grid of calculus becomes ticker and ticker inside the urban canyon and close to the ground level. People schematized the continuous linear source, typical for vehicular emission, as seven lined up point sources uniformly distributed along the axis of the canyon. The point sources show the following characteristics:

- Height of sources $h = 0.20$ m, that is about the position above the ground of exhaust pipes.
- Velocity of emission of exhausts ($V = 5.0$ m/s), coming from measurements by portable anemometer (TESTO 452).
- Velocity of exhausts has a vertical component ($i = 5^\circ$) to aim to consider the phenomena of turbulence produced by vehicles along the road.
- Total exhaust flow-rate along the strip of road is $Q = 212.0$ m$^3$/h
- The area of each “jet source” has been obtained from following formula

$$A_i = \frac{Q}{7 \cdot V} = 1.69 \cdot 10^{-3} \text{ m}^2$$

Table 4 shows meteorological data utilised in computer simulation.

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind direction</td>
<td>East</td>
<td>South</td>
<td>S-E</td>
<td>S-E</td>
<td>S-E</td>
<td>S-E</td>
<td>East</td>
<td>South</td>
<td>S-E</td>
</tr>
<tr>
<td>-90°</td>
<td>-90°</td>
<td>-45°</td>
<td>-50°</td>
<td>-60°</td>
<td>-70°</td>
<td>0°</td>
<td>-90°</td>
<td>-45°</td>
<td></td>
</tr>
<tr>
<td>Wind velocity (m/s)</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>
5 Results

For reasons of space, only some results of computer code simulations are shown in the investigated urban canyon in same orthogonal sections of road.

Simulation N°1

From Figure 5, in accord with theoretical studies, notices:

- The air motions into canyon are that ones typical of “skimming flow” for W/H=0.67, that is circulation of air flow in helicoidal shape owing to the forming of one whirlwind carrying polluting gasses from the horizontal plane of road to the leeward side of b-building where there is accumulation of polluting concentrations.
- The forming of one “displacement zone”, which moves the airflow above leeward face of a-building.
- Above the canyon, with levels up to the superior limit of the domain (z=60m), the field of air velocity does not feel the obstacle effect given by the presence of buildings in accord with theories which forecast the presence of effect and maximum for three times the greatest height of building, that is m12.00x3=36 m: in fact air velocity there is about 3.5 m/s.(undisturbed velocity)
- The magnitude of velocity out of whirlwind zone is 0.7 m/sec, that is about 20% of the one at the top of the domain
- The forming w windward side building of a little whirlwind consequent to impact of air fluid on façade.

Figure 6 shows:
- a very little component of wind velocity along the axis of canyon;
- an evident variation of direction of velocity in correspondence to intersection with transversal streets that allows the inlet of air flow coming from zones outside the canyon.

Figures 7 and 8 show:
- the biggest value of pollutants concentration is forecast close to the face of leeward buildings near the jet positions.
- The dispersions of pollutant gases inside the canyon is very small, both in longitudinal and in cross directions; in the longitudinal direction because there is a very negligible component of wind vector, and in the cross direction because the air flow motion forces the pollution between the facades of buildings on both sides.
- There are values of concentrations between 100 and 200 ppm of CO.

Figure 6: Plan section at $z=1.50$ m.- stream traces.

Figure 7: Plan section at $y=163$ m.- CO concentrations.

Figure 8: Section at $z=1$ m – CO concentration.
Simulation N°2

Figures 9 and 10 show the trend of polluting concentrations for different cases of direction of blowing.

Figure 9: CO concentration in function of wind direction.

Figure 10: CO concentration in function of wind direction.

Simulation n°3, 4, 5, 6 and 7

Figure 11 shows:
For direction of wind angles varying from -45° to -70°, the air flow regime inside the canyon are qualitatively like that ones founded for simulation n°1. There is the same strong recirculating vortex and the place of vortex comes up if the angle “α” comes down and vice versa.

Researchers noticed that the images of field of air motion obtained by ADREA–HF code are fully in accord with the theoretical and experimental ones coming from studies by wind tunnel. More, with reference to dispersion of pollutant, researcher noticed small difference between the concentrations forecast by code and those ones measured in situ (30 – 50 ppm).
These differences are not significant for the purposes of research and they show both the reliability of ADREA-HF 3D code as a good tool to evaluate the dispersion of gaseous pollutant and the accuracy of basic hypothesis about the chosen domain and input data too.

Figure 11: Trend of CO concentration.

6 Conclusions

On the basis of the results achieved, coming both from experimental campaign of measurements and the eighteen simulations to take into account different scenarios in function of intensity and direction of wind, and with reference to canyon axis, it has been possible to point out fluid-dynamics profiles so as to maintain the canyon gaseous polluting concentration at levels lower than the ones prescribed by Italian Environmental Legislation. Only in the scenario showing the wind blowing with velocity of 4.00 m/s and in a direction parallel to the street canyon does the value of concentration not exceed law-limits. This last scenario is very unusual, since the velocity of wind during all the year in this canyon seldom comes up to 3.5 m/s and the direction of wind wheels during the day, as happens in all marine cities. As the planning of PUT can determine, in function of the mobility demand, variation of volume of urban car traffic along the main lines of city and it could increase the flow of cars also in sensible zones like the “urban canyon”, “round-a-bouts”, “underpasses” etc. Researchers believe to have demonstrated that it is indispensible that the PUT must be supported by suitable SIA, at least about the environmental component “air” and “noise”, to avoid the detrimental effects to the health of city dwellers that could occur by incorrect choices of planning in environmental matters.
References

