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A strategy for pollution control in european cities

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1. Introduction

Anti-pollution regulations are promulgated on the basis of far-too-little factual information both in Europe and the U.S. Though there was perhaps justification for this in the early days due to lack of time, a scientific review of the air quality situation is long overdue. This lack of information was appreciated but too clearly by the motor industry which has had to suffer from the effects of too hasty legislation.

It is the purpose of this paper to try to set in perspective the present air quality situation in respect to present and proposed legislation for Europe. The paper relies heavily on work in this field undertaken on behalf of the Committee of Common Market Automobile Constructors (CCMC) by British Leyland (BL Technology Ltd) and Fiat who collected most of the experimental data with some assistance from BL.

All are agreed that we need air clean enough to have minimal adverse effect on health. So we need first to define Air Quality Standards and then to regulate the pollutants from all sources to ensure that these standards are at least reached with a margin of safety. Of course this aim is much easier to state than achieve. To insist on excessively clean air means great expense to owners and what is worse the wastage of dwindling liquid fossil fuel supplies. Already in the United States some 5-10% of fuel has probably been wasted unnecessarily due to a misunderstanding of the true needs. For instance most manufacturers fitted oxidation catalysts to meet the 1975 Californian regulations to achieve 9.0 gm/mile carbon monoxide while it is well known that California has a smog problem from hydrocarbon and nitric oxide but no real carbon monoxide problem. From this start the whole of the U.S. adopted regulations demanding catalysts hence lead free fuel and lower compression ratios and a sacrifice of some 5-10% in fuel economy, perhaps more.

2. Defining the problem

We must consult the medical experts for a definition of "clean air". Unfortunately there is a paucity of information on this subject. Nevertheless Air Standards exist in the U.S. and are proposed for Europe. The pollutants considered in this paper are, carbon monoxide, nitrogen dioxide, and ozone. Nitric oxide, the principle oxide of nitrogen emitted from the exhaust, is not itself harmful in the concentrations in the atmosphere; it does however play a major part in photochemical smog formation.

Table 1 shows the current situation of Air Quality Standards. We need to know what regulations we require for vehicles and industrial sources to meet these standards.

To link required regulations to Air Quality Standards we require a mathematical model which simulates as closely as possible what is actually

Table 1 Air Quality Standards.

U.S.A.			E.E.C. Proposed	
Pollutant	Concentration ppm	Averaging/Time Frequency	Concentration ppm	Averaging/Time Frequency
CO	35	1 hour 1)	40	1 hour
	9.6	9 hour 1)	15	8 hour
SO_2 2)	.05	Annual Mean	.05	Annual Mean
			.16	1 hour/95% of hourly values to be less than given value
			.50	1 hour/All hourly values to be less than given value
O_3	.12	Number of days in excess to be averaged with previous 2 years. Mean number of days ≤1.		

1) Not to be exceeded more than once per year.

2) SO_x as SO_2 (US regulations).

happening to the pollutants as they are emitted from the various sources. For such a model we need accurate input data and require to know details of the city, its typical meteorology, the industrial and mobile sources of pollution, the vehicle population and density, and driving patterns.

3. Choice of Modelled Region

Turin has been chosen for the first application of the mathematical model as it represents in the authors' view, the city with one of the most extreme conditions in Europe. It is surrounded on three sides by mountains or hills and due to its latitude has a relatively high intensity of solar radiation. Secondary pollutants such as ozone and nitrogen dioxide are likely to be higher than other European towns. Hence regulations that are satisfactory for Turin should be more than adequate for the rest of Europe.

Additionally Turin was suitable from a practical standpoint as Fiat has a substantial monitoring network available for pollutant and meteorological measurements.

4. Choice of Model

Two major types of model were available. First a trajectory model, which considers a column of air as it passes into the city from outside (i.e. a Lagrangian-type model) or secondly a grid model obtained by postulating a grid covering the city, establishing the mixing depth and dividing this into strata thus forming boxes (i.e. a Eulerian-type model).

The trajectory model was rejected as in Turin winds are light and variable and it was considered that a column would not maintain its integrity and may be blown well away from its predicted course.

A grid model was kindly provided by the Environmental Protection Agency U.S.A. (E.P.A.). This model was written by Systems Applications Inc. of San Francisco (S.A.I.)(1).
It has several advantages over a trajectory model as it covers the whole city, may be increased in resolution and being Eulerian allows more easy comparison with a fixed monitoring network. The SAI model was originally written for Los Angeles and required modifying for Turin, a much smaller city. The major change was to reduce the grid size from two miles to 600 metres square.

5. Description of Model

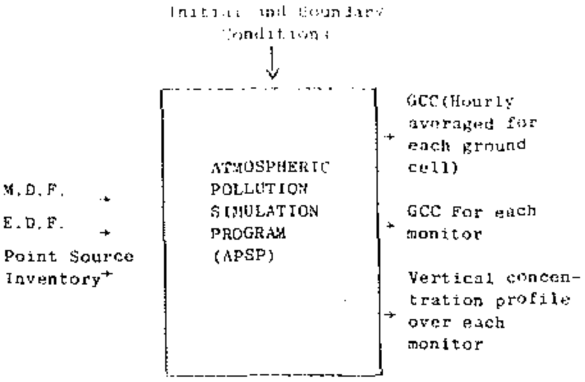
The Systems Application Model is a mathematical representation of the transport and chemical reactions of pollutants over the city to which it is applied. It consists of a set of non-linear coupled partial differential equations which express the conservation of mass of each pollutant.

The computer program, which embodies the model, obtains a finite difference solution of the equations by the method of fractional steps. The output is the spatial and temporal variation of the ground cell concentration of each primary and each secondary pollutant. The inputs to the model are numerical representations of the meteorological and emission conditions as a function of the time of day. The initial concentration conditions and the inflow boundary conditions have to be specified also.

For the computation, the plan of the city is divided by a square grid. The mixing depth is an input and the atmosphere may be divided vertically into as many as six layers, giving a grid of cells. Within each cell the conditions are assumed to be uniform. Time also is divided into small steps. The program simulates the behaviour of the atmospheric pollution by simulating the chemical and transport processes in each grid cell for each time step. This results in an implicit time and space averaging of the concentrations of the pollutants.

The simulation program predicts the ground cell concentration (hourly averaged) of each pollutant in each square as a function of time. It also predicts the vertical concentration profile at each monitor station.

The simulation package consists of four main programs (See Figure 1).
(1) The Atmospheric Pollution Simulation Program (APSP), which performs the tasks described above.
(2) The Emission Data Preparation Program, which takes the emissions inventory data and prepares the Emissions Data File, from which the APSP takes the input.
(3) The Meteorology Data Preparation Program, which takes the meteorological data and prepares the Meteorology Data File.
(4) The Data Plotting Program which plots the results of the simulation together with the monitor station data.



EDF - Emissions Data File

MDF - Meteorology Data File

GCC - Ground cell concentration

Fig 1 The Simulation package.

6. The Kinetic Mechanism

The chemical kinetics consists of fifteen reactions involving ten chemical species.

The mathematical representation includes four differential equations permitting the prediction of the change in concentration with time of NO, NO_2, ozone and hydrocarbons. Five of the species, all radicals, react rapidly to establish equilibrium concentrations and can thus be represented by algebraic equations. These species are O, OH, HO_2, $RO_2$1) and NO_3. The tenth species HNO_2 has been treated as if the steady state approximation were valid for its reaction, although this is known not to be the case. The generalized mechanism is given in Table 2.

7. Emissions input data

Elevated sources are treated individually; they are treated as volume sources being distributed in several cells downwind of the sources.

Near ground sources include domestic heating and automobile emissions; these are considered as distributed uniformly at the ground within each cell. There are 33,000 boilers providing domestic heating within Turin. Typical emissions of the boilers are taken to calculate their contribution to each grid square. They are weighted to allow for seasonal and diural variations.

For the vehicle inventory the city is divided into three zones - central, urban and sub-urban. Driving modes were established for each area and measurements of specific emissions were made on a chassis dynamometer for four weight classes of vehicles. Traffic flow densities were obtained and from these, weighted average emissions were calculated.

Table 2. The Generalized Photochemical Kinetic Mechanism.

$NO_2 + h\nu \rightarrow NO + O$	$HO_2 + NO \rightarrow OH + NO_2$
$O + O_2 + M \rightarrow O_3 + M$	$HO_2 + NO_2 \rightarrow HNO_2 + O_2$
$O_3 + NO \rightarrow NO_2 + O_2$	$HC + O \rightarrow \alpha RO_2$
$O_3 + NO_2 \rightarrow NO_3 + O_2$	$HC + OH \rightarrow \beta RO_2$
$NO_3 + NO_2 \xrightarrow[H_2O]{} 2\ HNO_3$	$HC + O_3 \rightarrow \gamma RO_2$
$NO + NO_2 \xrightarrow[H_2O]{} 2\ HNO_2$	$RO_2 + NO \rightarrow NO_2 + \delta OH$
$HNO_2 + h\nu \rightarrow OH + NO$	$RO_2 + NO_2 \rightarrow PAN$1)
$CO + OH \xrightarrow[O_2]{} CO_2 + HO_2$	

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1) Peroxyacetyl Nitrate (PAN)

8. Validation of the Model.

The value of the model will depend entirely on how well it does indeed represent the physical and chemical phenomena that actually take place and it is therefore essential to validate the model as comprehensively as possible. This is done by selecting a day on which as many measurements as possible are made. These measurements cover the taking of all the input data and monitoring station records. This enables predictions and measurements to be compared.

The low wind speeds, typical of the region, and mixing depth measurements give rise to most of the problems. The low wind velocities make it particularly difficult to define the wind field over the city from a limited number of wind observations. Also under low wind conditions during the Summer (the time when photochemical activity is most likely) thermally induced mixing (convection) becomes important and this has had to be introduced into the model. An acoustic sounder was at first used to establish the mixing depth but this proved inadequate for large depths due to its low power. Subsequently a helicopter was commissioned to make measurements of the mixing depth In addition the helicopter was instrumented to measure nitrogen dioxide and ozone both across and around the city. It will be appreciated that this model does not predict kerbside concentrations but the average concentration in ground level cells For this reason monitoring probes need to be away from the kerbside

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1) R is an Alkyl group (C_2H_{2n+1})

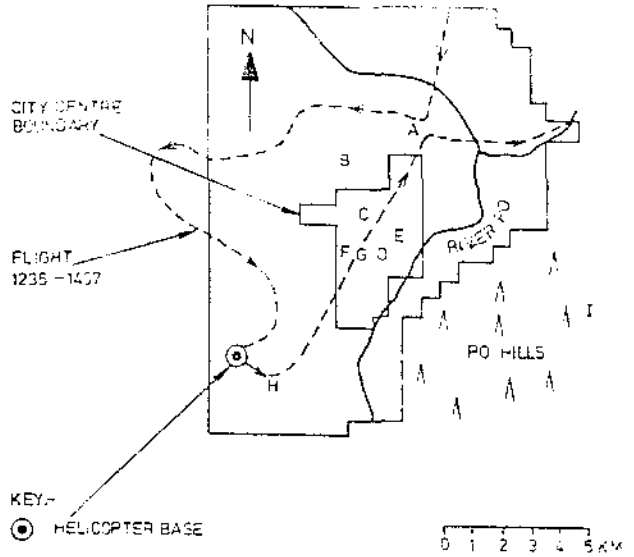

Fig 2

The city of Turin. The outer boundary delineates the modelled region.The inner boundary delineates the central city zone containing the highest traffic densities. Monitoring stations A to I are indicated. Part of a helicopter flight path executed on the 27 July 1979 is also shown.

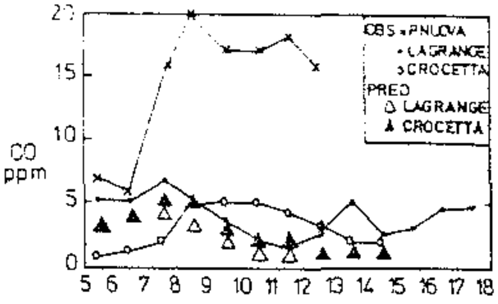

Fig 3a

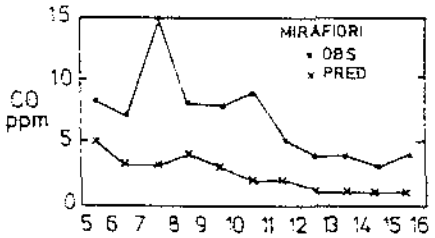

Fig 3b

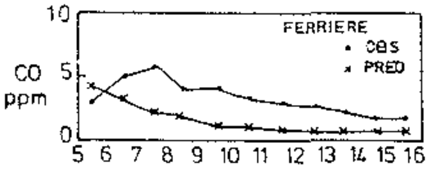

Fig 3c

Fig 3(a-c)Predicted and observed CO concentrations for 27 July 1979.

Kerbside concentrations are of course relevant for carbon monoxide as this is non reactive and emitted at kerbside levels. The geometry of kerbside areas however are so complex that a separate micro model is necessitated. Knowing the average ground cell concentration however enables this model to be comparatively simple. The secondary pollutants are formed after longer periods of time and the average cell concentrations predicted by the model are appropriate

Some results for an experiment conducted on 27 July 1979 are presented here. Figure 2 shows the location of the monitoring stations Background concentrations were obtained by the helicopter outside the city. Radiation intensity was measured at Lagrange. A meteorological description for this day was given in a previous paper(2).

Predictions for CO provide a means of examining model performance without the complication of photochemistry - i.e. predictions are largely influenced by the emission and meteorological inputs of the model. Figure 3 shows the predicted against measured values for all stations. In Figure 3a predictions for Lagrange and Crocetta are shown. These stations (see Figure 2) are located in the city centre. Model predictions for the maximum concentrations show fair agreement with observations except at P Nuova where the sampling point was at the kerbside The correlations on an hour to hour basis between predicted and observed values can be seen to be no worse than the correlations ordinarily encountered between monitoring stations situated in close proximity in a complex urban environment. Differences due to local effects of emissions,meteorology and other factors on a scale finer than the resolution of the model will provide for such variations.

The model underpredicts at Mirafiori but this is consistent with the expected influence of the local heavy traffic close by.

Validation results for photochemical species were presented in a previous paper(2). Since then further information concerning the hydrocarbon composition both in the air (as measured from bag samples taken 27 July 1979) and from a vehicle exhaust study have been incorporated into the model and the model simulations for this day repeated. A more refined chemical kinetic mechanism is currently being introduced into the basic model and hence a more rigorous validation exercise will be conducted at a future date.

With this in mind it is still of interest to explore some of the consequences of a few control strategy exercises to gain an appreciation of some of the issues involved.

9. Discussion of Results for Validation Day

Figure 4 shows the results of the simulation for 27 July 1979 for selected hours for CO, NO_2 and O_3. The simulation hours represent the hours for which the highest concentrations of the respective species were predicted to occur in the city. The wind vector for each hour is shown on the diagrams. During the morning the wind was from the NE sector and hence the concentration isopleths are aligned along a NE-SW axis for each figure.

Note that maximum concentrations are predicted to occur downwind of the city but the position and time of maximum concentration varies between species.

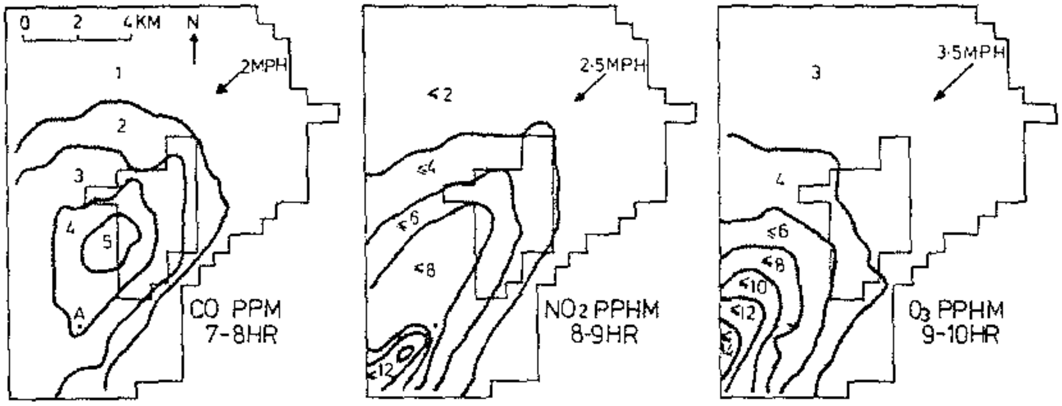

Fig. 4a Fig 4b Fig 4c

Fig 4(a-c) Predicted concentrations of CO, NO_2 and O_3 for the simulation with present vehicles.

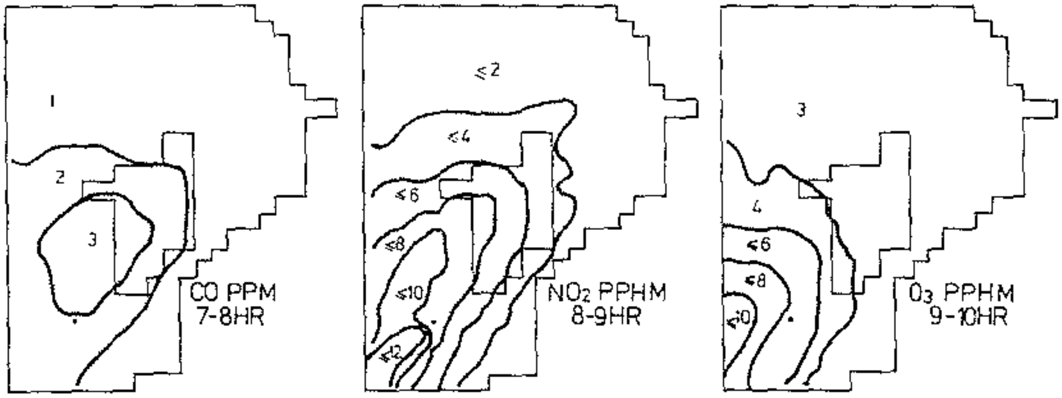

Fig 5a Fig 5b Fig 5c

Fig 5(a-c) Predicted concentrations of CO, NO_2 and O_3 for the simulation with regulated vehicles.

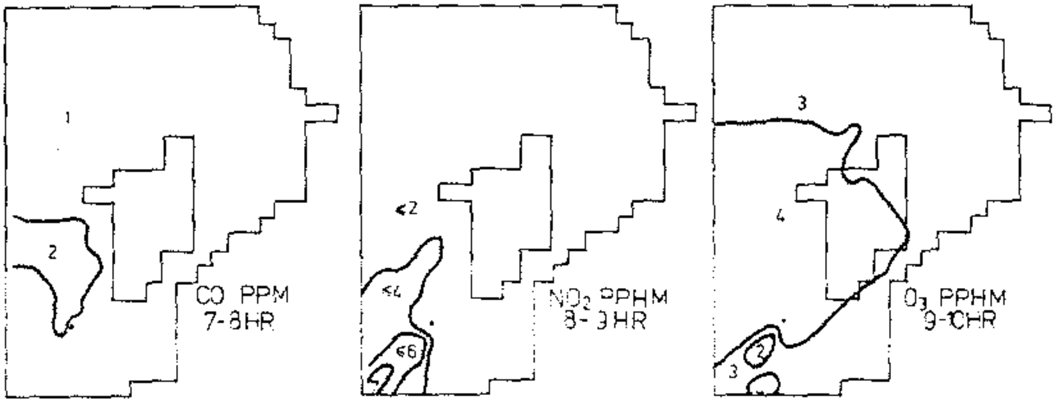

Fig 6a Fig 6b Fig 6c

Fig 6(a-c) Predicted concentrations of CO, NO_2 and O_3 from industrial sources alone.

The maximum concentrations for CO (assumed un-reactive) occur around the time of peak traffic in the city and also when the mixing depth and wind speed are both low. This combination of factors - maximum emissions with low dilution - provides for relatively high CO concentrations. Note that the maximum occurs just downwind of the city centre (See Figure 4a)

Figure 4b shows that maximum NO_2 concentrations occur at a later time and further downwind of the city centre. This is because NO_2 is a secondary pollutant formed through reactions of NO and reactive HC under sufficiently strong insolation. Ozone is formed at an even later time and hence maximum concentrations occur even further downwind (as seen in Figure 4c).

The following general points are worthy of note:

1. Different species provide maximum concentrations at different points in the city. Hence monitoring at a city centre location for example, would not necessarily ensure that compliance with AQS over the whole city will be observed for all species.
2. Clearly the concentrations of secondary pollutants (NO_2 and O_3) within the city will be very sensitive to the wind speed. A higher wind speed would evidently provide for the maximum concentrations to occur well outside the city boundaries. City size (not only with regards to population and emissions) is clearly important when population risk is to be assessed.

10. Application of Model to Existing Regulations.

It will be appreciated that the authors consider that more stringent validation of the model is required before an accurate statement on the adequacy or otherwise of existing pollution legislation for motor vehicles for Europe could be made with confidence. However it is considered that the model at this stage can give valuable indications of the present situation of the pollution pattern in the atmosphere in the city of Turin and the relative contributions of motor vehicles, industrial sources. and the general background situation. In the limited time available for the presentation of the paper, it was decided that a prediction should be made of the effects of 15/03 regulations when fully implemented.

The validation day simulations shown in Figure 5 provide a baseline against which the effect of various control strategies can be compared. In order to relate to European standards 15/03 the simulation was repeated with the assumption that all vehicles in Turin are tuned to within these standards with a safety factor at approximately 25%. To do this 3 vehicles were selected representing small, medium and large size passenger cars and these were tested on a chassis dynamometer to the driving cycles described in section 7 above, which represent the vehicle journey from the suburbs into the centre of Turin. The vehicle contribution however, was further weighted in accordance with the traffic census already conducted in Turin. Table 3 compares the weighted emissions from vehicles under the assumption that they are all controlled to 15/03 conditions (regulated) to those found with the existing vehicle population in Turin on the validation day. It will be noted noted that carbon monoxide and hydrocarbons emissions are reduced when compared with the validation day. This would be expected and reflects the increased severity of the 15/03 regulations. It will be noted however that nitric oxide is in fact increased. This is unexpected though a major reduction would not have been anticipated as the reduction in NOx from 15/02 is only approximately 15%. There was a difference in the four vehicles tested for 15/03 and those tested as typical for the validation day and this may have had its effect as NOx is very sensitive to the power/weight ratio

Table 3. Weighted average emissions (gm/mile) for the regulated (4 weight classes) and present car population. Values are given for each driving cycle (central, urban and suburban) and for hot and cold started vehicles.

REGULATED CARS 15-03						
	Central		Urban		Suburban	
	Cold	Hot	Cold	Hot	Cold	Hot
CO	45	36	31	23	26	24
RHC	9.0	6.3	5.4	4.6	4.8	4.6
NOx	2.9	2.5	3.0	3.1	3.5	3.5

PRESENT CAR POPULATION (1979)						
	Central		Urban		Suburban	
	Cold	Hot	Cold	Hot	Cold	Hot
CO	97	82	75	38	62	48
RHC	11	13	7.1	6.7	6.7	6.1
NOx	2.5	2.5	2.0	2.0	2.1	2.1

of the vehicles. It would have been desirable, but time was not available, to have tested a far more representative number of vehicles. Also a simulation with all cars excluded is shown in Figure 6.

Figure 5 shows the results of the ECE 15/03 simulation. As noted in Table 3 CO emissions in each zone of the city are less than half of those for the present situation (validation day July 1979). This is reflected in the CO distributions shown in Figure 5a where the CO concentrations have been reduced.

Figure 6 shows the case with emissions from fixed sources only with cars excluded. The distribution mostly reflects that resulting from the initial and boundary conditions for this simulation because a relatively small amount of CO is emitted from industrial sources.

Concentrations of the secondary pollutants NO_2 and O_3 are functions of both NOx and reactive HC emissions. NOx emissions for the regulated cars are generally higher (See Table 3) although reactive HC emissions are some 30-40% lower than the present conditions. Figure 5b shows that predicted NO_2 concentrations are overall slightly higher for the regulated case. The predicted contribution from the power plant A in south west Turin can be deduced from Figure 6a. Figure 5c shows that for the regulated case predicted ozone values have been reduced. Figure 6c shows that the large NO emissions from the power plant have been predicted to deplete the ozone concentrations immediately downwind.

11. Discussion of Model Simulations in Relation to AQS

11.1 Carbon Monoxide

Air Quality Standards proposed by the EEC (Table 1) are 40 ppm for a 1 hour averaging time and 15 ppm for an 8 hour averaging time. It will be noted that for the validation day, even with the present situation predicted and measured values are well within these figures. However increased concentrations will occur at the kerbside; figure 3a showing a maximum of 20 ppm at the kerbside of a high traffic density street. This value is only 50% of the AQS.

11.2 Nitrogen dioxide

The proposed EEC AQS states that all hourly values must be below 50 pphm (parts per hundred million) and 95% of hourly values must be below 16 pphm. Figures 4 and 5 show that predictions for the present situation and with 15.03 fully implemented are within these criteria.

11.3 Ozone

We have only the US AQS available for ozone, where values in excess of 12 pphm are only permitted occasionally (See Table 1).

It will be seen that predicted values for the validation day are at about this level. Predictions with 15/03 reduce concentrations to 10 pphm or less.

It should be borne in mind the days were chosen for high reactivity, at the worst time of the year, in the city which we believe has one of the most extreme conditions.

12. Conclusions

The authors hope that the paper demonstrates that the mathematical model can be a powerful tool to help in the formulation of regulations to ensure clean air.

Validation appears to be reasonable in the limited area examined. It is considered that further refinement and considerably more validation in Turin and other cities is needed and that the model could play an important role in the determination of future regulations

13. Acknowledgements

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