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A MICROSCOPIC MODEL OF AIR POLLUTANT CONCENTRATIONS: COMPARISON OF SIMULATED RESULTS WITH MEASURED AND MACROSCOPIC ESTIMATES

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ABSTRACT

Road traffic is a major source of air pollution and substantial effort is currently being devoted to the development of both technological and transport policy measures to reduce these impacts. It is well established that the emission of certain pollutants is closely related to both traffic speed and fluctuations in traffic speed. However, conventional transport emission models are largely based on average traffic conditions, and thus they cannot properly represent the effects of policy measures, such as automatic speed control or traffic calming, that directly affect the speed dynamics of the traffic stream. Given the prevalence of such policies, there has been considerable effort to develop improved emissions modelling capabilities.

This paper describes a new approach to the microscopic modelling of air pollution from road traffic. This approach can represent detailed speed fluctuations in the flow of traffic and it is applied to a local network in Maidstone, Kent, in the UK. We combine a stochastic microscopic traffic flow simulation model (VISSIM), an existing speed-based emission database (MODEM) and a Gaussian dispersion model. Simulated results are compared with a macroscopic model of air pollutant concentrations (DMRB method) and roadside pollutant measurements. Results are encouraging and show a good comparison with the DMRB method and with some exceptions, good comparisons with trends in measured pollutant concentrations. Statistical differences in the methods, however, suggest that either measurement error or other inaccuracies are present.

INTRODUCTION

Transport, and road traffic in particular, is a major contributor to pollutant emissions. Of the total UK emissions of various pollutants, transport accounts for 26 per cent of carbon dioxide, 61 per cent of nitrogen oxides, 91 per cent of carbon monoxide, 42 per cent of volatile organic compounds and 59 per cent of black smoke *(1)*. Considerable effort has been devoted to the development of models to describe air pollution from road traffic. Macroscopic models based on average travel speed are the most common method used for estimating vehicle emissions. However, macroscopic models *(2, 3, 4)* entail enormous simplification of physical processes involved in pollution emission, and the effects of the simplification on the accuracy of the analysis is largely unknown. Although the trip speed is the most important factor influencing emissions, speed fluctuation is also an important factor *(5, 6, 7)*. Currently, significant effort is being devoted to the development of models that can account for speed fluctuations and more realistically model vehicle emissions *(8, 9, 10, 11)*.

The objective of this research is to develop and investigate the advantages of an air pollution emissions model that can describe the detailed movement of vehicles and analyze alternative traffic scenarios. To accomplish this, we combine the VISSIM stochastic microscopic traffic flow simulation model *(12)* with the MODEM emission inventory database *(6)*. This is further integrated with a simple air pollution dispersion model. We apply the model using local network data derived from the SCOOT urban traffic control system for Maidstone, Kent, in the UK. We evaluate the results against measured pollutant concentrations and with standard UK procedures for air quality assessment, as outlined in the *Design Manual for Roads and Bridges* (DMRB) *(13)*.

In the next section we briefly describe the modelling process. This includes a description of the VISSIM traffic flow simulation model and the MODEM emission inventory. We then present an analysis of simulating emissions using a hypothetical signalised junction with various traffic parameters, primarily to verify that the simulation outputs provide expected results when parameters are varied. The third section then discusses the implementation of the model to a local downtown road network in Maidstone, Kent. Following this we use the UK DMRB method to determine pollutant concentrations and compare this with the more detailed microsimulation method. Results are also compared against actual pollution concentrations. These results are discussed and we conclude with recommendations for future research in this area.

MODELLING PROCEDURES

To characterize the emissions for motor-vehicles we first need information on the traffic flow characteristics within the network to be modelled. This information includes the speed and acceleration of every vehicle in the system. Network information needed for VISSIM includes roads, junctions, signal systems, vehicle types (e.g. cars versus heavy duty vehicles), and traffic volumes. The latter are exogenous to the system and we make no assumptions about how demand patterns may change with different scenarios. Microscopic simulation models provide vehicle speeds on a second-by-second basis, allowing detailed characterization of vehicle accelerations and decelerations.

To obtain this information, we use the VISSIM traffic simulation model. These type of models often are imperfect versions of actual traffic behaviour due to their limited modelling of actual human behaviour *(14)*. The VISSIM model provides some advantages over many other traffic simulation models since it is based on human psychology and behaviour. The actual movement of the vehicles in VISSIM are based on behavioural assumptions regarding the desired speed and gap acceptance of drivers. As an initial assumption, vehicles follow each other with the same speed. If a vehicle is below the desired speed it will accelerate to that speed using the maximum possible acceleration for the given speed and vehicle type. As the vehicle closes on any vehicle in front, the vehicle will, after a slight reaction delay, decelerate to match the speed of the vehicle being followed. Should the desired gap distance be too small, then the vehicle will react to avoid an accident by a sharp reduction in speed. Lane changing movements are also based on human decisions that are influenced by perceptions of surrounding vehicles in a similar fashion.

These movements are based upon a natural distribution of various behavioural elements. These include differences in driving abilities, human perception, desired safety and speed, and the relative levels of driver aggressiveness characterized by different maximum values for accelerations and decelerations. These phenomena are normally distributed within the model allowing random selection of various values during the simulation process *(15)*.

The outputs from the VISSIM model are the instantaneous vehicle position, the vehicle speed, and vehicle acceleration. These are then used to determine estimated emissions as well as providing a point input source for the pollutant dispersion model. Emission volumes are calculated at each link segment. Each link segment is treated as a single point source to be input into a Gaussian dispersion model.

The MODEM microscopic emission database was developed as a part of the European Commission's DRIVE II research program. It is a microscopic modal emissions database based on the results of chassis dynamometer driving cycle measurements. Fourteen different cycles were used in the development of the MODEM emissions database based upon a large-scale survey of the operating characteristics of vehicles used in urban areas across Europe with the aim of representing real-world driving conditions.

A total of 150 vehicles of 12 different vehicle types sampled from the vehicle population of different European Union countries were selected and tested. Pollutant emissions and fuel consumption are derived as a function of the instantaneous speed and acceleration. The emissions of HC, CO, CO_2, and NO_x, are aggregated for the 12 different vehicle types and can be calculated within the speed range between 0 km/h to 90 km/h with an acceleration times speed range of –15 to +15 (m^2/s^3). Outputs from VISSIM, in combination with fleet vehicle types are input into the MODEM model to produce estimates of emissions.

We then link these outputs based on aggregated link level emission outputs to a Gaussian dispersion model. We select the model developed by Hickman *(3)* for this purpose. The dispersion model provides an estimate of actual pollutant concentration at selected receptor locations. More detailed and advanced dispersion models could also be used, but was beyond the scope of the current study.

The overall modelling structure is depicted graphically in Figure 1.

MODEL CALIBRATION ON A SIMPLE NETWORK

To test and calibrate the model we first applied it using a simple junction network with various traffic parameters. First we describe basic relationships between emissions and traffic parameters at an unsignalized junction. Then we examine the relationships at a signalised junction.

We define a network that consists of three directly connected links that have no junction or curve. The first link is about 300m, the second is 1000m, and the last link is 400m in length. Each link has two lanes. We assign 1000 vehicles per hour to the network and the capacity of the network is enough to allow free flow speeds for each vehicle. Five percent of the vehicles are heavy-goods vehicles (HGV) which have a different length than the cars within the VISSIM simulation. We executed the simulation for a one hour period using a constant random seed to maintain the same stochastic characteristics for each simulation run. Link lengths were divided into 10m lengths and we divided the simulation period into 5 minute intervals. From this we calculate CO, HC, NO_x and CO_2 emissions in grams per metre per second.

We analysed differences in emissions based upon changes in average speed, vehicle type, and different traffic volumes (the latter with a signalised network). Figures 2 and 3 show CO and NOx emissions as a function of increasing average speed and for four different vehicle classes. These vehicle classes include ECE 15/03 and ECE 15/04 which are vehicles without catalytic convertors (see Table 1). We also show results for a vehicle equipped with a catalytic convertor and for a diesel powered vehicle.

CO tends to decrease with increases in average speed for vehicles not equipped with catalytic convertors. However, for catalyst equipped cars and diesel vehicles, CO emissions appear to not change with average speed as well as being quite low (compared to those vehicles without catalysts). Results for NO_x emissions show an increase in emissions for vehicles without catalysts as average speeds increase. For those vehicles with catalysts there is no discernible change in emissions with increases in average speed. NO_x emissions tend to decrease for diesel vehicles and stabilize at about 50 km/h.

Next, we tested the model with a network with two signalized junctions. Using the same network we add a junction at a distance of 1000m from the start point, and the second at a distance of 300m from the first signalized junction. The cycle length is set at 90 seconds with 50% green time.

We set the car type to ECE 15/04, which is a vehicle without a catalytic convertor and the engine size is set between 1400cc and 2000cc. We found the magnitude of results not to vary by engine size to the same extent as they do for other factors, such as vehicle vintage and whether they have a catalytic convertor (we omit these results for brevity). The desired speed of the traffic is 55 - 65 km/h. HGVs are diesel vehicles with engine size more than 2000cc. The desired speed of HGVs is 45 - 55 km/h.

Figure 4 shows CO emissions from the network with different levels of traffic volume ranging from 500 – 2500 vehicles per hour. As the traffic volume increases, capacity of the junction is overwhelmed and we show congestion in the network. As the length of the queue grows, stop-and-go actions of the vehicles are simulated. Not surprisingly, we find that CO emissions increase as the network becomes more congested (traffic volumes increase). The increase in total emissions is roughly proportional to the number of vehicles in the network until it reaches about 1800 vehicles per hour. Then we find that emissions increase more than proportionally. At a traffic volume of 2500 vehicles per hour we find that CO emissions are high even at the starting point. This is due to the long queue lengths which are generated by this level of demand. At lower levels of traffic volumes we see a peak in CO emissions only at the signalised junctions due to queuing.

Figure 5 shows NO_x emission for the same network and traffic volumes. As can be seen, emissions again tend to increase in proportion to total traffic volumes. However, beyond 1700-2500 vehicles per hour we actually see a decrease in average vehicle emissions. That is, in this range as we add more vehicles to the network, total emissions do not increase significantly. While there is a peak in emissions at the signalised junctions, the congested network appears to reduce NO_x emissions due to the slowing of the traffic. The peak at the junctions is likely due to hard accelerations upon leaving the junction.

These results suggest that for vehicles without catalysts, congestion will tend to increase CO emissions per vehicle but decrease NO_x emissions per vehicle. While we did not test the effects with catalyst-equipped vehicles, it is likely that the variation in emissions from congested conditions would be much less when vehicles are equipped with catalysts (and assuming they are not operating under cold start conditions). In the next section we apply the model to a real world network and compare results with both macroscopic and measured estimates of air pollutant concentration.

APPLICATION OF THE MODEL TO A REAL NETWORK AND COMPARISON WITH MEASURED AND MACROSCOPIC ESTIMATES

In this section we discuss the application of the model to a real local traffic network in the town centre of Maidstone, Kent, in the UK. Maidstone is a small free-standing town with a population of about 150,000 approximately 30 miles from London and 30 miles from channel ports.

Network traffic data has been collected from the SCOOT urban traffic control system. SCOOT (the Split, Cycle and Offset Optimisation Technique) is a traffic-responsive urban traffic control system developed in the UK for optimising network traffic performance *(16)*. The main objective of SCOOT is to provide optimum real time network control. The information obtained from a SCOOT system, such as traffic flows, delays and levels of congestion is also of considerable value. The availability of SCOOT data has lead to a number of attempts to develop modelling or predictive tools *(17, 18, 19, 20, 21)*. Figure 6 illustrates the SCOOT system of the network. 13 links and 5 junctions are included in this study network.

The SCOOT system controls the signal cycle length and green time using real-time traffic information. Cycle lengths increase with increasing traffic volume. The minimum cycle length is 72 seconds, and maximum length is over 120 seconds. Figure 7 depicts the variation in cycle length for both a low traffic and a high traffic day of the week.

Two weeks of data from 18th July 1999 to 31st July 1999 were collected from this area. 15 minute average traffic flows for each link and signal data, cycle lengths and green times for each junction were collected from the SCOOT ASTRID module *(22)*. We also collected actual measurement of pollutant concentrations from roadside pollution monitors every 15 minutes (the location of these is shown in Figure 6). Figure 8 depicts the traffic volumes for Monday and Sunday for two of the intersections in the study area.

While it would be desirable to know the actual vehicle types that use the simulated network, this information was not available. Therefore we use estimates of typical UK fleet averages of the type of vehicles listed in Table 1 (and compatible with the MODEM emissions database). As shown previously, the key determinant of total vehicle emissions is the fraction of vehicles that are fitted with catalytic convertors. These have been required on all new passenger cars in the European Union only since January 1993. Using various assumptions on average fleet turnover we estimate that 42% of the simulated vehicles are equipped with catalysts based on an average fleet age of 6 years as reported in DETR *(23)*.

For the VISSIM component of the model we defined the desired speed of the vehicles as a distribution of speed between 60 km/h (about 40 mile/h) and 80 km/h (about 50 mile/h). As trucks and buses have different vehicle lengths, the length of HGVs entering the network are defined by a vehicle length distribution between 8m and 12m, while passenger vehicles are modelled with a constant length of 4.5m (14.8ft). Traffic volumes are entered in vehicles per hour for a specific link and time period. Within this time period vehicles enter the link based on a Poison distribution. In this study, there are four traffic volume input links, N05111d, N05111a, N05121b and N05131a (see Figure 7). Traffic volumes are input as 15 minute averages of each input link.

Signals are controlled by the signal controller of VISSIM. One controller allows up to 125 signal groups. A signal group is the smallest entity on the control level. Each signal head on the road has a unique identification number and is controlled as a group with adjacent signal heads. One signal group has its own cycle length and pattern. Signal groups have a fixed sequence of green – amber (yellow) – red – red/amber. During the period between Red End and Green End, vehicles are allowed to pass the junction. There are five signal-controlled junctions in the study network, and except one Pelican pedestrian crossing, they require two different signal groups for cross direction traffic flow.

Estimated emissions were calculated for the entire period for which we had SCOOT data. Results for CO pollutant concentrations are shown graphically for one week in Figure 9. We also graph actual measured CO concentrations collected from the roadside pollution monitors over the same time period. While this would likely contain CO emissions from other sources, the vast majority of urban CO emissions (>95%) are generated by motor-vehicles, so we expect the monitors to be a good estimate of actual vehicle CO emissions (our measured results for other pollutants are less reliable due partly to the presence of other sources of emissions; we omit these from our discussion for brevity). The trends in the measured values appear to correspond with results from our simulated concentrations with several notable exceptions. Weekend day measurements of emissions appear to be much larger than those simulated. Likewise, Thursday and Friday afternoon measured emissions exceed the simulated values. While it is not known why measured emissions were higher in the afternoon on these two days, it is possible that various weather conditions may have led to CO accumulation and persistence in the area over time, which would not be picked up by a Gaussian dispersion model *(24)*.

Table 2 displays the mean and 95% confidence intervals for the estimated and measured emissions for weekdays, weekends, and the entire two weeks. As can be seen, comparing the measured and the microscopic estimates shows a significant difference (i.e., no overlap between confidence intervals). Our measured pollutant concentrations are definitely higher than our simulated estimates with 95% confidence. We also see that weekend measurements are significantly higher both for our microscopic estimation and the measured values.

We also compare our estimates with the standard macroscopic air pollution model used in the UK. This is specified in the *Design Manual for Roads and Bridges* (DMRB) *(13)*. The DMRB method involves estimating air quality levels at selected locations near a road network. The inputs it uses are vehicle flow and speed, percent of HGVs, the distance of the recipient from the roads carrying the traffic and changes in tailpipe emissions due to legislation or regulations scheduled to take effect in the future. Therefore this method is characterized as a macroscopic model that does not take microscopic changes in acceleration patterns into account. It also encapsulates an air dispersion model to derive estimates of the average pollutant concentrations at specified receptor locations.

Figure 9 graphically compares estimates calculated with the DMRB method with both our measured and simulated pollutant concentrations. The DMRB method closely matches our detailed microscopic simulation of pollutant concentrations. This is quite an interesting result. First, it gives us confidence that the system of models we have developed is comparable to existing practice for estimating pollutant concentrations. On the other hand, it may suggest that detailed microscopic modelling may not be necessary for the assessment of pollution concentrations. However, we did not compare these methods for a policy scenario that may involve major changes in speed and acceleration characteristics. It is likely that the results would diverge substantially and possibly give inconsistent answers as to the preferable policy for reducing pollutants.

Table 2 also shows the mean and 95% confidence interval for our DMRB estimates. We see that while the graphic presentation tends not to show a difference between this estimate and our microscopic estimate, statistically we can discern a difference in the mean with 95% confidence. The total mean DMRB estimate is higher but is also lower for weekend estimates relative to our microscopic estimate. Despite their statistically significant difference, both are closer in value to each other than they are to our mean measured estimates.

At this point we cannot conclusively say why these differences are occurring. Obviously many possible sources of error can be introduced in emissions estimates. For one, we do not know the actual vehicle fleet that we are measuring in the Maidstone network. Whether this alone can introduce a 50% difference in pollutant concentrations is not known. Another potential source of error is that the stage of the driving cycle that each vehicle is engaged in is unknown. How long have the vehicles been operating? Are they still under cold start conditions? If this is the case we could expect the greater measured concentrations that we found. Also, measurement devices may also be subject to error in their measurements and we do not take this into account in our comparisons.

To explore the error in measurement, we graphically show the average measured and estimated CO concentrations for all 10 weekdays in Figure 10. The standard deviation of the measured concentrations are also plotted on the graph. As can be seen on the graph, both estimation methods (our simulation and the DMRB method) fall within the range of the standard deviation of the measured concentrations. Therefore, it is likely that part of the discrepancy between our estimated simulation model and the measured pollutant concentrations may be various errors with the measurement equipment. However, one should keep in mind that pollutant concentrations may vary from day to day for other unknown reasons and our sampling of only 10 days is quite small.

CONCLUSIONS

This paper has summarized the development of an air pollution model based on microscopic traffic flow and a modal emissions inventory. The model shows good performance in describing detailed vehicle movements and emissions from local traffic flows. The model was applied to a real local network with traffic data from the SCOOT urban traffic control system. Results were compared both with measured pollutant concentrations and with the DMRB method of assessing vehicle pollutants. Our simulated model showed results comparable to the DMRB method. Measured results were generally similar except for weekend measurements and some afternoon measurements and while total averages appear to be statistically different, it is difficult to separate day to day variability in the measured concentrations from our estimations.

We are continuing to examine other scenarios using the model that has been developed. In particularly, future work will analyze the impact of traffic management schemes, changes in signal timing, increases in road capacity, and traffic calming. Of particular interest is whether the microsimulation model provides a different estimate of emissions than the DMRB model leading to different decisions for infrastructure policies that may reduce emissions.

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Table 1

Vehicle fleet data used in the study

Vehicle type	Per cent (%)	Engine size	Per cent(%)
Gasoline engine car without catalyst (ECE R15/03)	15	Less than 1400cc	8
		Between 1400cc to 2000cc	6
		Greater than 2000cc	1
Gasoline engine car Without catalyst (ECE R15/04)	55	Less than 1400cc	28
		Between 1400cc to 2000cc	24
		Greater than 2000cc	3
Catalyst equipped car	25	Less than 1400cc	13
		Between 1400cc to 2000cc	11
		Greater than 2000cc	1
Diesel vehicle	5	Greater than 2000cc	5
Total	100		100

Table 2

Mean CO concentrations with 95% confidence intervals

	Weekday (ppm)	Weekend (ppm)	Total, all days
Microscopic model	0.82 .±0.03	0.97 ±0.05	0.86 ±0.03
DMRB macroscopic model	0.98 ±0.03	0.83 ±0.04	0.94 ±0.03
Measured concentration	1.41 ±0.05	1.94 ±0.09	1.55 ±0.04

Figure 1

Structure of the model

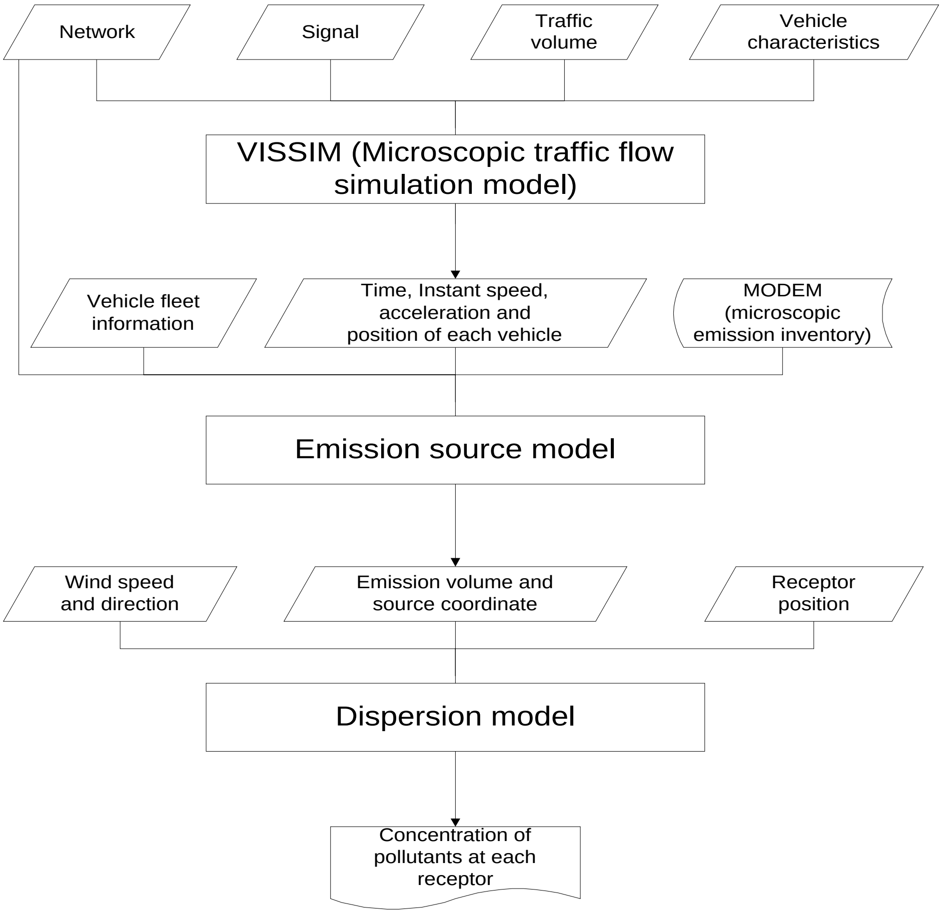


Figure 2

Carbon monoxide emissions at different average speed

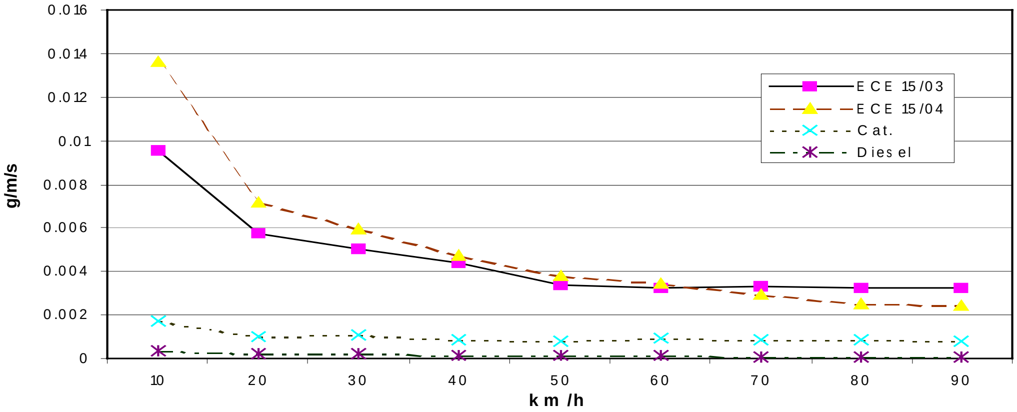


Figure 3

NO$_x$ emissions at different average speed

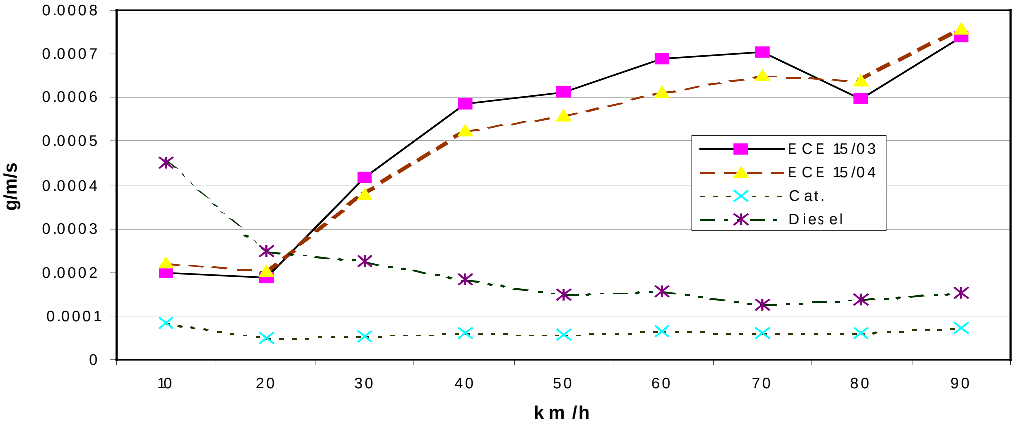


Figure 4

CO emissions from different traffic volumes

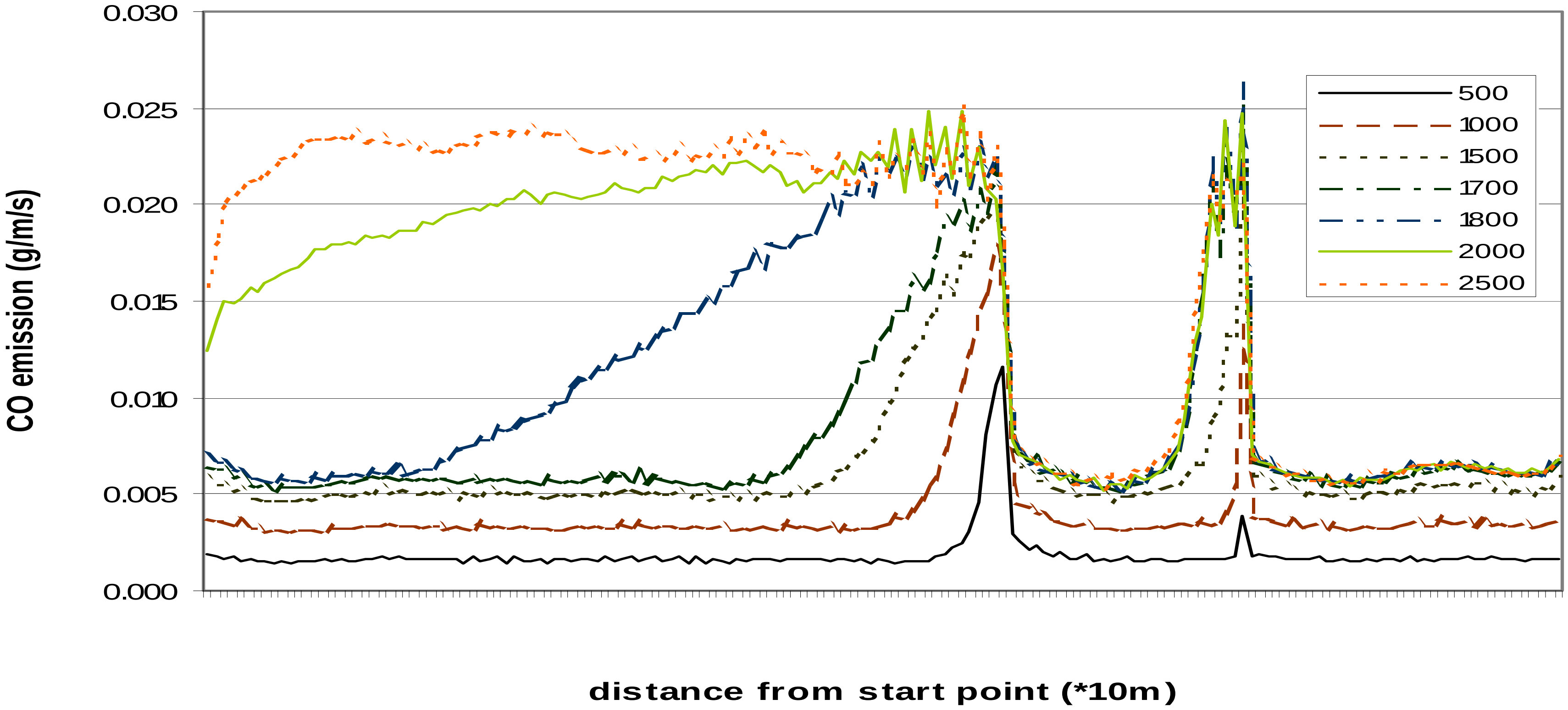


Figure 5

NO_x emissions from different traffic volumes

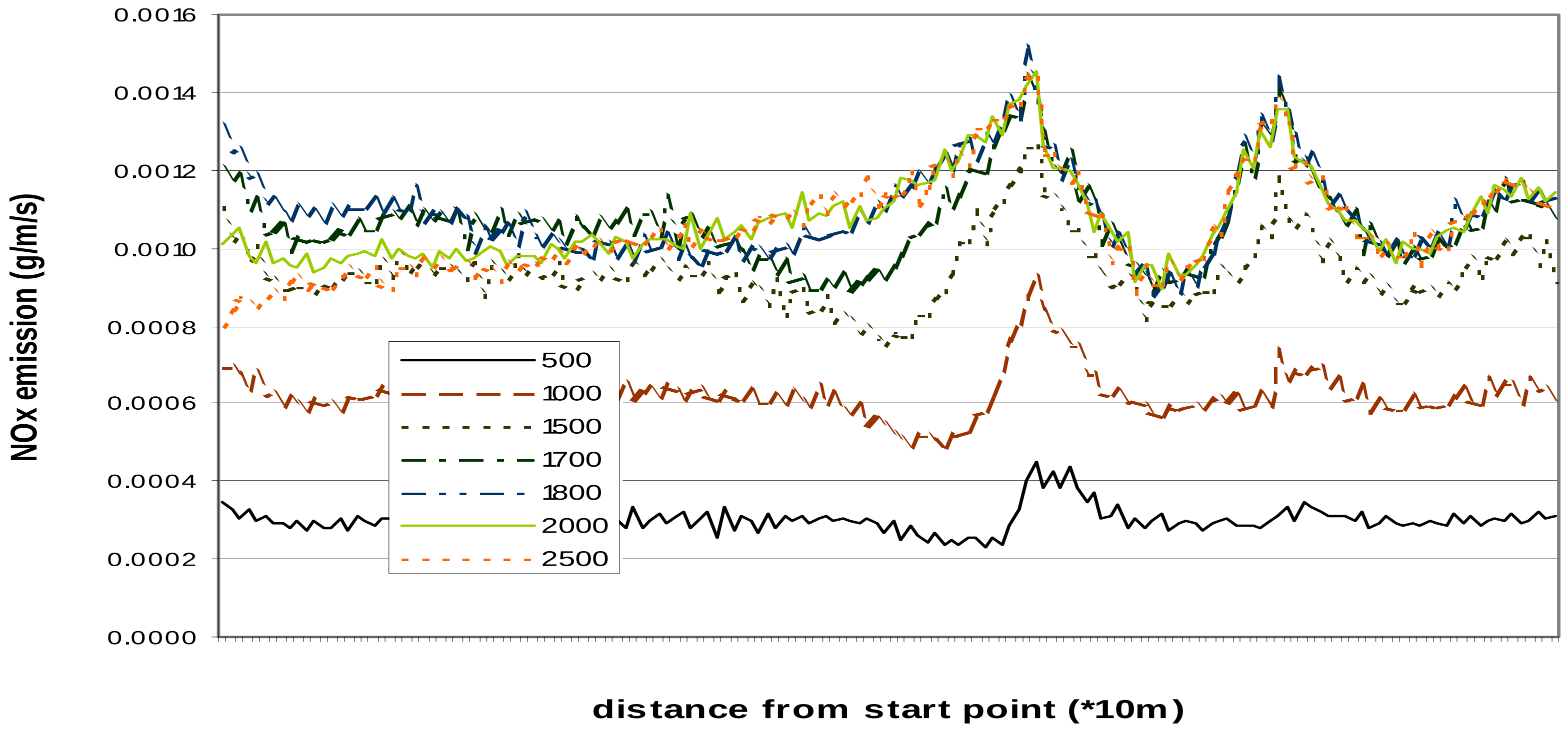
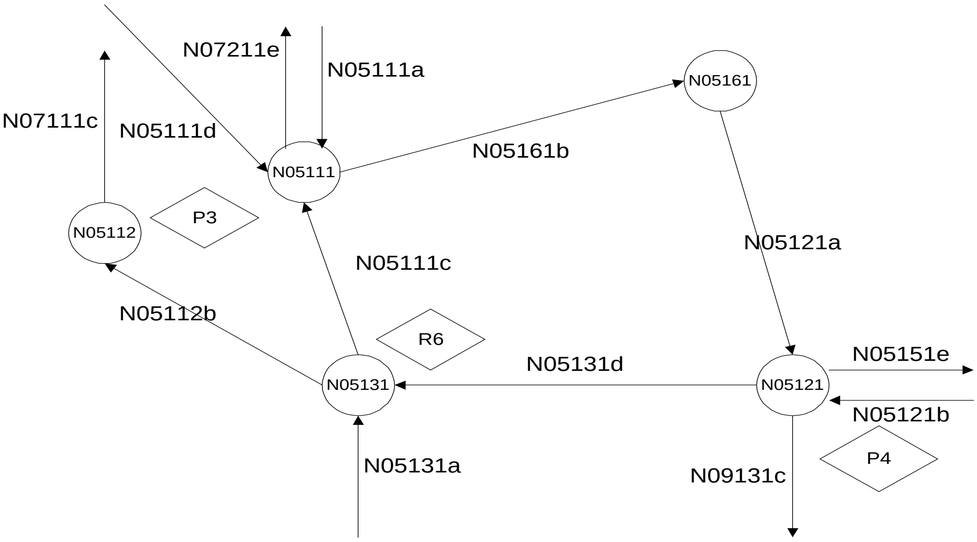


Figure 6

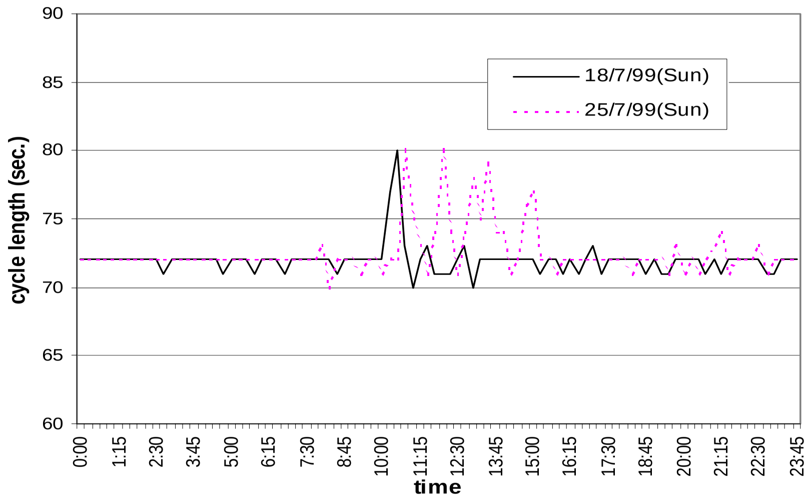
SCOOT network of study area



Note: diamond shape boxes represent roadside pollution monitors.

Figure 7

Daily cycle length changes for junction N05131



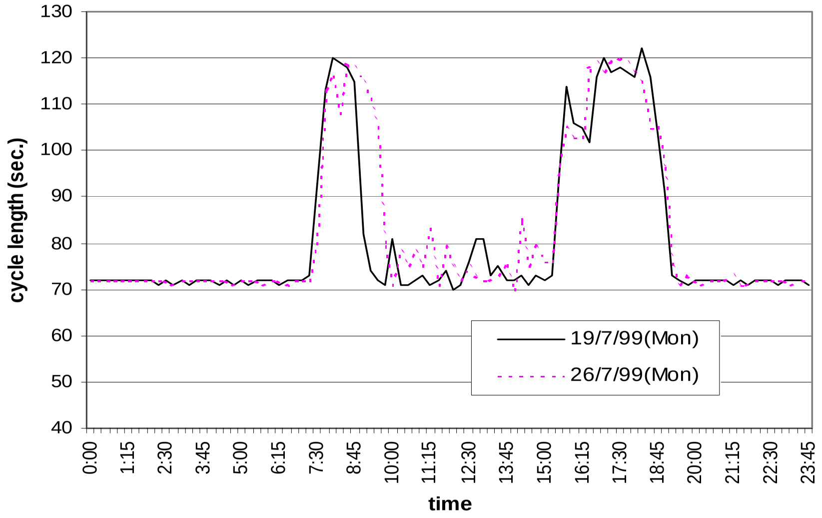
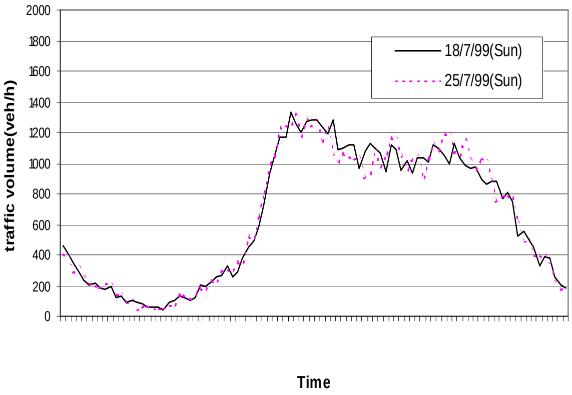
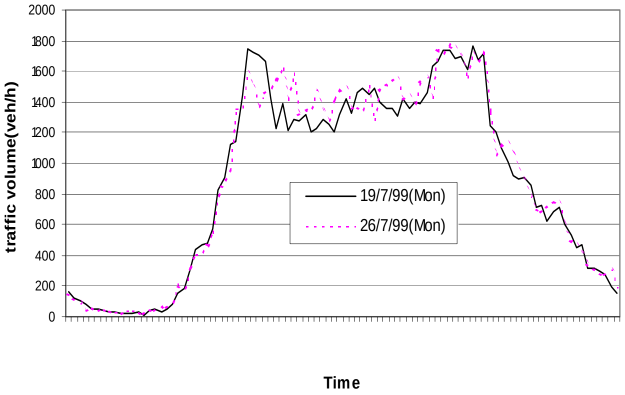


Figure 8

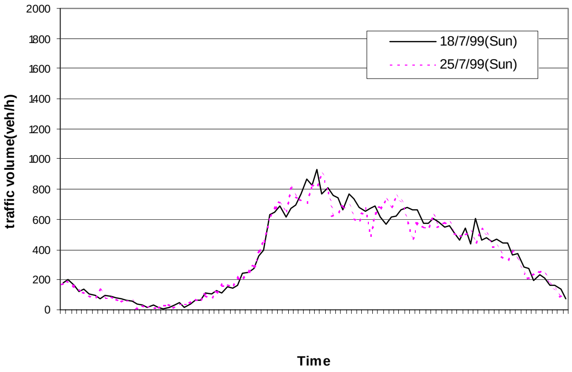
Daily traffic flow of links in the network

Link N05112b





Link N05121b



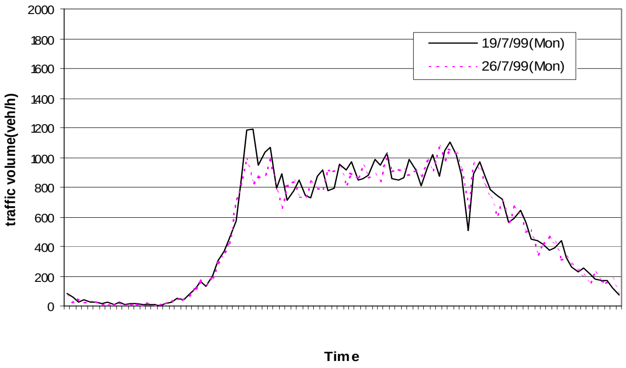
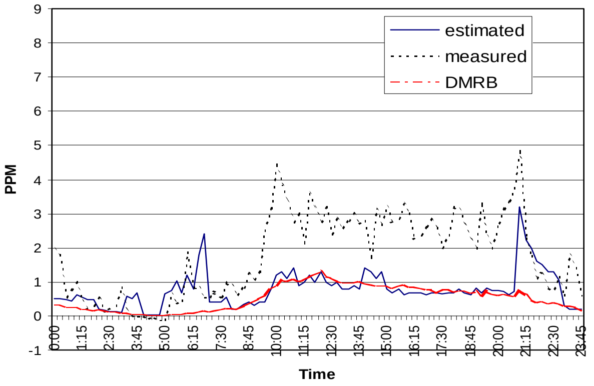


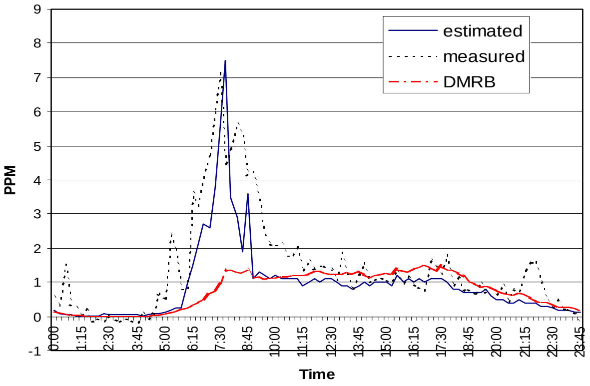
Figure 9

CO concentration at P4 roadside pollution monitor

18/7/99(Sun)



19/7/99(Mon)



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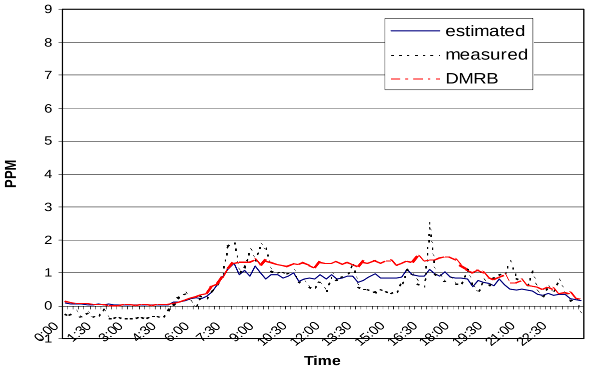
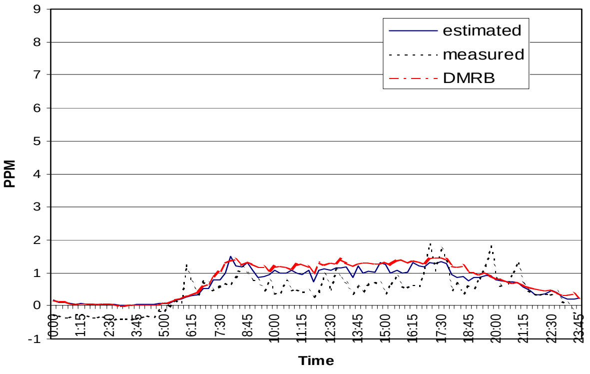
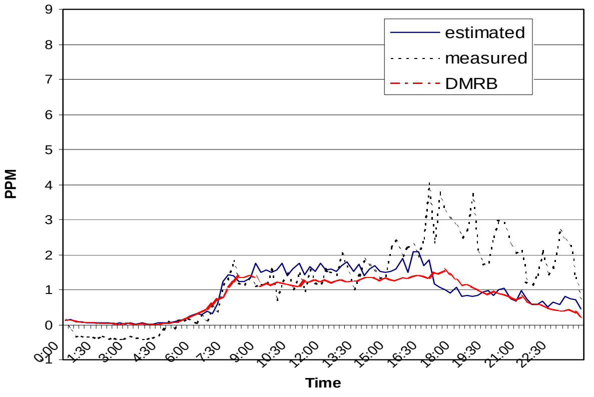


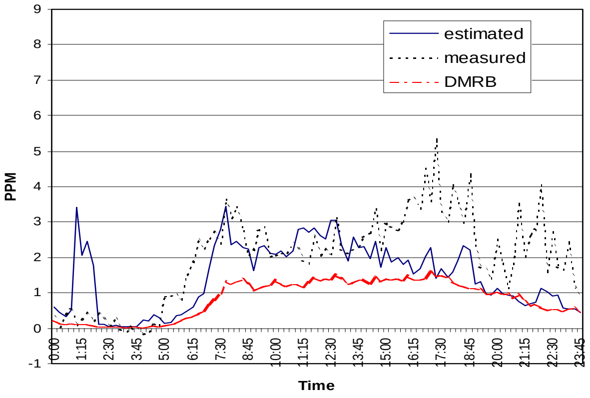
21/7/99(Wed)



22/7/99(Thu)



23/7/99(Fri)



24/7/99 (Sat)

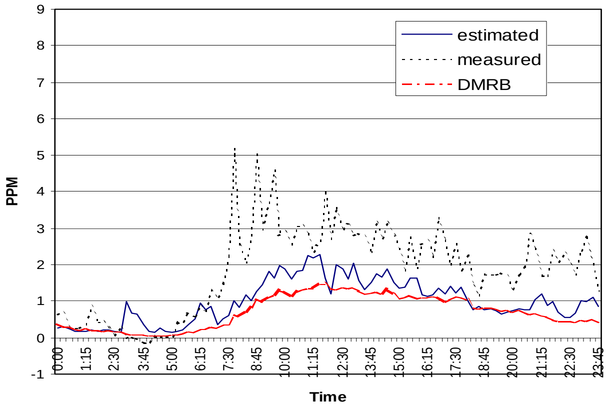


Figure 10

Standard Deviation of Measured CO Emissions versus Averages