QUANTIFYING THE POTENTIAL IMPACTS OF ATMS ON AIR QUALITY

Bruce Hellinga
Department of Civil Engineering
University of Waterloo, Waterloo, ON Canada
Phone: 519-885-1211
Fax: 519-888-6197
Email: bhellinga@uwaterloo.ca

Presented at the

Canadian Society of Mechanical Engineers Forum 98

Symposium on Recent Advances in Transportation Systems and Technologies

Held at:

Ryerson Polytechnic University,

Toronto, Ontario, Canada

May 19-22, 1998

QUANTIFYING THE POTENTIAL IMPACTS OF ATMS ON AIR QUALITY

Bruce Hellinga
Department of Civil Engineering, University of Waterloo, Waterloo, ON Canada
Phone: 519-885-1211 Fax: 519-888-6197 Email: bhellinga@uwaterloo.ca

ABSTRACT

Many people expect that the anticipated near and medium term deployment of intelligent transportation systems (ITS) will produce significant benefits in terms of reduced congestion, increased safety, reduced emissions, and reduced fuel consumption. While these expectations may be realised, limited research has been conducted to-date to explicitly quantify these benefits, particularly in terms of the environmental benefits. Furthermore, there is the expectation that these ITS will enable traffic engineers to implement traffic control strategies that satisfy legislated air quality standards. Unfortunately, the relationships between various traffic management options and the resulting air quality impacts are generally poorly understood.

This paper describes the use of a traffic network simulation model to quantify the impact of traffic management strategies on network traffic conditions. The model is capable of estimating spatially and temporally correlated pollutant emissions on the basis of a drive mode elemental emissions sub-model. These emissions are used as input to a Eulerian air quality standards model, in which the dispersion of the pollutants is modelled. In this way, the air quality estimates are sensitive to the implemented traffic management strategies. This approach provides a mechanism by which the impact of different ATMS/ATIS strategies on air quality can be quantified and considered when selecting the desired strategy. The approach is demonstrated on an urban network representative of Detroit, Michigan. The traffic and air quality impacts of a typical ATMS strategy is quantified and discussed.

1. INTRODUCTION

Public concern for the condition of the environment has been continuing to increase over the past decade. Issues of global warming, ozone depletion, and increasing concentrations of greenhouse gases, have been presented and discussed extensively, both within the scientific community and the general public. This heightened awareness of, and concern for, the environment has also placed increased focus on the significant role that automobile traffic plays in contributing to these environmental problems.

Existing literature indicates that motor vehicles are major contributors to air pollution. Currently, in the United States, motor vehicles release up to 90% of the carbon monoxide (CO) found in urban air; up to 50% of smog forming volatile organic compounds (VOCs) and nitrogen oxides (NO_x); and more than 50% of the hazardous air pollutants [1]. Many of the air pollutants emitted by motor vehicles are known to have adverse health effects, including breathing problems, reduced lung function, bronchitis, reproductive and neurological problems, and cancer [1,2].

The concentration of air-borne pollutants in a given area is generally a function of the location and emission rates of all pollution sources, and the mixing, reaction, advection and dispersion of these pollutants in the atmosphere.

Substantial research efforts, particularly in Europe, have been directed at modelling the movement and reaction of air-borne emissions. These models can consider many factors impacting the atmospheric reaction, dispersion, and advection of pollutants, including the impact of wind direction and speed, local topology, air temperature, reactivity of the pollutant, and mixing height. However, while sophisticated air quality models have been developed, they all rely on the prior knowledge of the emission source locations and emission rates.

The emission rates of motor vehicles are primarily a function of the vehicle's physical characteristics, (e.g. vehicle weight, engine size, engine design, emission controls, gear ratios, tire size and pressure, etc.), environmental conditions (e.g. ambient air temperature), and driving conditions (e.g. stop and go traffic, constant speed, hilly terrain, etc.).

During the past 25 years, regulatory agencies, such as the US EPA, have tended to concentrate on quantifying the relationships between motor vehicle emission rates and the physical characteristics of the vehicle. These efforts have led to reduced pollutant emissions primarily from improvements to the physical characteristics of the vehicle fleet's combustion and emission systems, including engine design improvements (e.g. improved fuel economies), emission control devices (e.g. positive crankcase ventilation, catalytic converter), reformulated fuels (e.g. unleaded gasoline, propane, compressed natural gas, volatility limits), and more recently, the development of electric and hybrid vehicles.

While significant reductions in emissions have been achieved through these efforts, which have been focused on the physical characteristics of the vehicle fleet, much less effort has been directed at developing methods for understanding and quantifying the relationships between emissions and environmental conditions and between emissions and driving conditions.

With the current development and expected near-term deployment of advanced traffic management systems (ATMS) and advanced traveller information systems (ATIS), there exists the opportunity for transportation system managers to have unprecedented influence on the traffic network conditions. These traffic management and control strategies can also have significant impact on the resultant air quality. While some research has been conducted [3,4,5], in general little work has been done directly linking air quality models with models that can accurately estimate vehicle emissions as a function of driving conditions.

This paper demonstrates the potential for assessing the impact of ATMS on air quality through the linking of a traffic simulation model and a simple multi-box air quality model. The impact on CO of a typical advanced traffic signal control system is demonstrated for a 100 square km potion of Detroit, Michigan.

Nomenclature

CO carbon monoxide
HC hydrocarbon
NO_x oxides of nitrogen
$w_{n,t}$ wind speed in box *n* during time period *t* (km/h)
$q_{n,t}$ direction of wind in box *n*, during time period *t* (degrees clockwise from due North)
$c_{n,t}$ concentration of pollutant in box *n* at time period *t* (kg/km^3)
$c_{n,t-1}$ concentration of pollutant in box *n* at time period *t*-1 (kg/km^3)
V_n volume of box *n* (km^3)
$f_{n,t}$ mass of pollutant advected into box *n* during time period *t* (kg)
$g_{n,t}$ mass of pollutant advected out of box *n* during time period *t* (kg)
$e_{n,t}$ mass of pollutant emitted in box *n* during time period *t* (kg)

Organisation of Paper

Section 2 of this paper describes the existing categories of air quality models, and the typical modelling approaches. The Eulerian based AQM, that is used within this study, is described. Model requirements are specified, as are the limitations and assumptions of the model.

In Section 3, approaches to traffic emissions modelling are identified and described. The capabilities of the traffic simulation model INTEGRATION, are briefly described, followed by a description of the emission submodels incorporated within INTEGRATION.

Section 4 describes the application of the linked traffic and emissions model to a sample network. The characteristics of the network are described, followed by a description of the ATMS evaluated and the air quality modelling parameters. Finally, results from this sample application are presented and discussed.

In Section 5, conclusions and recommendations are made on the basis of the results obtained.

2. AIR QUALITY MODELLING

An increasing concern of traffic engineers and transportation engineers is the monitoring and control of air-borne traffic pollutants [5]. This concern has been heightened by the signing of the Kyoto Protocol to the 1992 Climate Change Treaty in December of 1997, in which 38 industrialised countries have agreed to reduce the emission of greenhouse gases to 1990 levels by the year 2010. Furthermore, in the United States, the Clean Air Act Amendments, passed in 1990, and the

Intermodal Transportation Efficiency Act, passed in 1991, link federal funding for highway projects with the successful demonstration that the proposed projects will meet the legislated emission requirements. These Acts and agreements now require that a procedure must be utilised which allows for the evaluation of the expected pollutant levels associated with the subsequent traffic operations.

The standard method of solving this problem is to utilise Air Quality Standards (AQS) models, which, given emission source data, estimate the spatial variation in pollutant concentrations over a given area of study. Depending on the complexity of the AQS, these concentration estimates are computed on the basis of some, or all, of the following factors: wind speed and direction, temperature and humidity, turbulence, atmospheric stability, and topographic effects on meteorology [6].

Scale categories of models

Most AQS models can be loosely divided into three categories based on the resolution of their modelling scale.

- Microscale models examine the dispersion impacts for regions in the order of magnitude of 1 km^2, and are typically used to evaluate the impacts of a single source, such as a chimney plume over a time scale of minutes to hours.
- Mesoscale models are used to examine regions up to several hundred square km (such as an urban area) over a period of hours to days.
- Macroscale models are applied to regions in the order of thousands of square km over periods of days to weeks.

In this paper, the mesoscale, or urban scale models are of most interest.

Dispersion modelling approaches

In general, three techniques for the modelling of pollutant dispersion can be identified, namely Eulerian, statistical, and Lagrangian [7].

The Eulerian approach uses the continuity equation (i.e. conservation of mass) to derive expressions for the movements of pollutants over space and time. These models can be formulated to include advection, dispersion, chemical reaction, and deposition.

Statistical approaches attempt to establish relationships between pollutant concentrations and emissions on the basis of field observations. The accuracy and reliability of these models are highly dependent on the quantity and quality of the observed data.

The Lagrangian method consists of using a probabilistic description of the dispersion of pollutants to estimate pollutant concentrations. The most widely used Lagrangian model is the Gaussian plume model, in which the downwind concentration of a pollutant along the vertical and cross wind axes of a plume are assumed to be normally distributed. The Gaussian model is widely used primarily for its simplicity, however, it imposes several limitations and simplifying assumptions, such as:

1. There is no variation in wind speed between the source and the location for which a concentration is being estimated.
2. All pollutant remains in the atmosphere. There is no provision for deposition or chemical reaction.
3. Dispersion does not occur in the downwind direction. It only occurs in the vertical and cross wind directions.
4. Emission rates are assumed constant and continuous.

In this study, the Eulerian method is adopted to estimate pollutant dispersion. The next section describes the adopted Eulerian method in detail.

Eulerian dispersion modelling

In urban scale regions there typically exists many thousands of individual pollutant point sources. The modelling of individual sources independently is usually not practical, so the common approach is to combine the emissions from all sources within a pre-defined area. Following the Eulerian approach, the principles of dispersion, advection, and reaction are then applied to this aggregated emission concentration [8].

Eulerian, or multi-box models, overlay a series of square grids or boxes over the horizontal surface area to be considered. The mixing ceiling is defined, often as a function of local atmospheric conditions. The model then calculates the change in concentration of the pollutant levels in the box during each time period *Dt*. This calculation is performed by considering both the net flow of pollutant through the sides, as defined by meteorological inputs, and by emissions entered directly into the box. This process can be further refined by allowing for variable horizontal resolution, so as to reflect the relative strengths of different emission inputs. Larger grids may be selected for low emission areas and smaller grids for larger emission areas, such as busy intersections and malls.

The multi-box model adopted for this study can be described by Equation (1).

$$c_{n,t} = \tfrac{1}{V_n}\left(f_{n,t} - g_{n,t} + e_{n,t}\right) + c_{n,t-1} \qquad (1)$$

The objective of this paper is to demonstrate the potential for quantifying air quality impacts of various ATIS and ATMS strategies. As such, a relatively simple air quality model has been adopted. More comprehensive AQMs exist, and could readily be used within the same framework that has been used within this study.

Required inputs

The multi-box dispersion model described by Equation 1 requires that the mass of a pollutant emitted within each box of the grid (n), during each period (t), be known. Furthermore, wind speed (w) and wind direction (q) are required in order to determine the amount of pollutant advected into (f) and out of (g) each cell during each time period. Unique wind speed and direction values can be provided for each box in the grid.

Relationships of geometry are used to determine the mass of pollutant advected into (f) and out (g) of each box on the basis of wind speed, wind direction, box dimensions, and box location within the grid.

Assumptions and limitations

The adopted multi-box model incorporates the following assumptions:

1. The model does not consider the effect of chemical reactions, and as such is most appropriate for non-reactive pollutants such as CO.
2. Dispersion resulting only from wind is considered, diffusion is ignored.
3. While wind direction and speed can be unique for each box within the grid (n), and for each time period (t), they are deterministic and remain fixed throughout the analysis period (t).
4. Complete mixing of pollutant occurs within each box.

3. TRAFFIC EMISSIONS AND ATMS/ATIS MODELLING

As indicated previously, a critical factor in the estimation of air quality impacts is the accurate estimation of expected emissions. Not only must the magnitude of these emissions be estimated, but the location at which they are emitted, and the time at which they are emitted, are also required.

Approaches for estimating emissions

A number of approaches have been developed for the estimation of emission rates. These methods can be generally classified into three categories, namely macroscopic, mesoscopic, and microscopic.

Approaches classified as macroscopic typically estimate emissions on the basis of aggregate traffic measures, such as vehicle kilometres travelled. An average emission rate per kilometre is used to transform the traffic measure into an estimate of total emissions. Unfortunately, this approach is only able to distinguish between those ATIS and ATMS strategies that influence the vehicle kilometres travelled. They are insensitive to any changes in the level of congestion experienced.

Mesoscopic approaches typically utilise traffic measures that reflect, in at least a limited manner, the characteristics of the trip. Typically, average speed, roadway type, and average trip length, are used in conjunction with average emission rates (which are functions of roadway type and average speed), to estimate emission quantities.

While mesoscopic approaches provide some additional capability to distinguish between the impacts of different ATMS/ATIS strategies, their benefits are limited by the difficulty in accurately estimating the average speed expected to result from the implementation of a given ATMS or ATIS strategy. Furthermore, the assumption that there exists a sufficiently strong correlation between emissions and average speed has been shown to be untrue for certain pollutants, including CO [9].

Microscopic methods typically rely on the development of relationships that are functions of vehicle type, instantaneous speed, instantaneous acceleration, engine temperature, ambient air temperature, etc. These relationships are applied on the basis of the second-by-second performance of the vehicle to estimate emissions.

Microscopic approaches are able to most accurately reflect the impact of the ATMS or ATIS strategy on emissions. However, these methods are also computationally intensive, and require the provision of a significant quantity of input data.

Description of the INTEGRATION model

The INTEGRATION model is a microscopic routing-oriented simulation model of integrated freeway and surface street networks. Individual vehicle movements are traced through the network as they interact with traffic control devices, such as traffic signals, and with other vehicles. Each vehicle's identity is unique, such that its routing decisions are based on its trip origin, trip destination, departure time, link/lane use permissions (e.g. high occupancy vehicle), and real-time and historical knowledge of network travel conditions.

The ability to concurrently represent ATMS/ATIS impacts, and to provide second-by-second individual vehicle position by co-ordinate, yields a significant opportunity to perform environmental assessment of ATMS/ATIS strategies.

The INTEGRATION model incorporates a mode elemental emissions model which is directly associated with the traffic simulation model. A brief description of this emission model follows. A complete description of the development and application of the emission model is available in the literature [10,11].

Description of emission submodels within INTEGRATION

The emission submodels incorporated within INTEGRATION were developed on the basis of the US EPA developed MOBILE model [12], the current accepted standard in North America for assessing the emission impacts of transportation planning or traffic engineering proposals. These derived models estimate the emissions of individual vehicles as a function of the traffic flow characteristics and management strategies associated with the driven route.

Specifically, three driving modes are captured by a coupled elemental fuel consumption model and emission model, that considers idling, cruising at constant speed and acceleration/deceleration manoeuvres. The fuel consumption model is linked to a series of equations which predict the quantity of HC, CO and NO_x for a given volume of fuel consumed. These emission and fuel consumption estimates are sensitive to the ambient air temperature, each individual vehicle’s speed profile, and the presence of engine cold starts, an effect which dissipates as the vehicle is driven.

The derived emission models have been validated by comparing the results offered by the MOBILE standard and the proposed equations for comparable scenarios. This comparison yielded a correlation coefficient (r^2) of approximately 90 percent. A complete description of the calibration findings can be can be found in elsewhere in the literature [11].

4. SAMPLE APPLICATION

The ability to evaluate potential ATMS or ATIS strategies on the basis of environmental measures, including air quality impacts, is demonstrated for a region of Detroit, Michigan. This section describes the network characteristics, the ATMS strategy evaluated, the atmospheric conditions considered, and finally the results obtained.

Description of the study network

The network used in this study, and illustrated in Figure 1, represents approximately a 100 km^2 area of Detroit, Michigan. This network was initially created and used in several ITS architecture assessment projects sponsored by the US Federal Highway Administration (FHWA) [13]. Though the network is based on the Detroit area, it does not exactly replicate all aspects of the existing Detroit network. However, the network serves as a representation of a typical urban area.

The network is composed of 1,946 uni-directional links reflecting the highways, major arterials, and arterials, within the study area. Roadway classes are defined on the basis of the free-speed – 120 km/h for highways, 90 km/h for major collectors, and 70 km/h for arterials. The component fraction of these three roadway types are provided in Table 1.

There exists 99 traffic signals in the network, controlling 316 approach links. Traffic demands enter and exit the network via 143 origin and destination zones. Traffic demands are initiated over a 2.5 hour period, representing a portion of the morning peak period. During this time, a total of 146,827 vehicle trips are initiated. The network is simulated for 3.5 hours to ensure that all vehicles complete their trips.

Description of the ATMS strategy evaluated

To demonstrate the feasibility of assessing potential ATMS strategies on the basis of environmental impacts, a typical ATMS and non-ATMS configuration was defined.

The base scenario (or non-ATMS configuration) considered signal timings to be non-responsive fixed

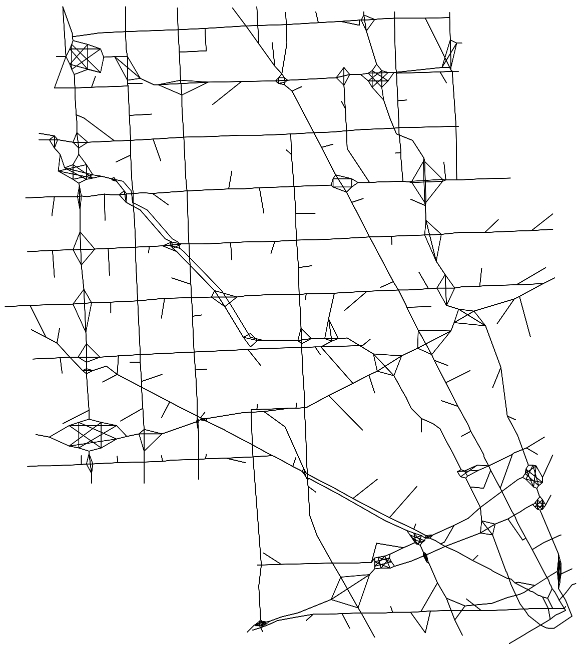

Figure 1: Study network

time of day plans. These timings were developed on the basis of field observations and expected average traffic conditions, and so can be considered to be consistent, in terms of the degree of optimality of the timings, with the fixed timings existing in most urban centres.

The ATMS scenario assumed that all of the 99 traffic signals were controlled by an advanced distributed real-time signal control system. This system re-computed and implemented the optimal cycle lengths and phase splits for each signal at the end of each cycle. The optimisation explicitly considered the impacts of queue spill-back.

Air quality modelling

The Eulerian model previous described was used to model the dispersion of the pollutant CO, through time and space. A time period duration of 30 minutes was chosen, resulting in a time series of 7 periods of CO concentrations for each box within the grid. Any time period duration could have been chosen, however, very short period durations result in increasingly violating the assumption of complete mixing within the box. The network was divided into a grid of 20 cells by 20 cells, resulting in each cell covering an area of approximately 0.25 km^2. Again, the grid resolution is user defined and can range from cell dimensions of 100 m to several km.

For the analysis provided in this paper, it is assumed that wind speed is only 1 km/h, reflecting very calm atmospheric conditions. The wind is assumed to be travelling from the north west to the south east (i.e. 135º clockwise from due North) for all cells within the grid. Again, the wind speed and wind direction are user defined values.

Table 1: Network roadway characteristics

Roadway Class	Measure km	Measure lane-km
Highway	222	705
Major Arterial	178	590
Arterial	403	850
Total	**803**	**2,145**

Table 2: Aggregate network level MOP

MOP	Scenario Base	Scenario ATMS	% Δ[1]
Avg. trip time (min)	9.59	7.95	-17.1%
Total fuel (1000 litres)	153.61	144.96	-5.6%
Total NO_x (kg)	3,937.3	3,954.6	0.4%
Total HC (kg)	1,711.4	1,517.8	-11.3%
Total CO (kg)	18,283.8	15,640.8	-14.5%
Total Veh. km (1000 km)	1,482.6	1,482.3	-0.02%

[1] %Δ = (ATMS - Base) / Base × 100%

Results

Table 2 provides a comparison of several aggregate measures of performance that permit a network level of comparison between the Base scenario and the ATMS scenario.

It is evident from the results provided in Table 2, that the implementation of the modelled ATMS configuration results in reductions in all environmental and traffic measures, except for total NO_x emissions, which increased by 0.4%. This increase in not unexpected, as NO_x tends to increase with increases in vehicle speed.

While the values in Table 2 provide an overall comparison between total emissions, fuel consumption, and travel times, from an air quality perspective, it is also important to examine the temporal and spatial variations of these emissions. If, for example, ATMS permits higher throughput in certain areas, only to have more concentrated congestion in another area, the air quality in the local vicinity of the congestion may be poorer than with without ATMS.

Consider first the temporal variation in total network-wide emission of CO, as illustrated in Figure 2. Figure 2 indicates that the mass of CO emitted by

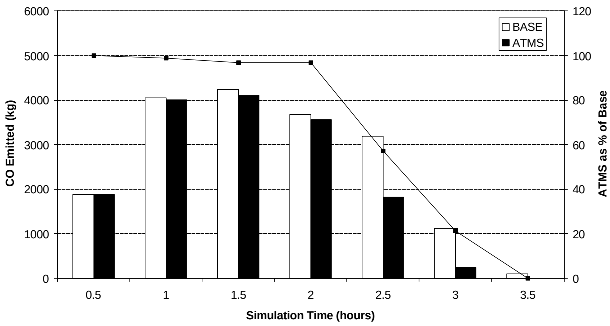

Figure 2: Temporal variation in total CO

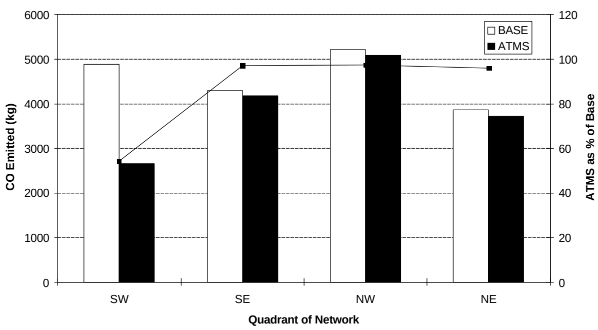

Figure 3: Spatial variation in total CO

vehicles for the ATMS scenario is similar (within 3%) to that of the Base scenario, for the first 2 hours of the simulation. However, from time 2 to 2.5 hours, the mass of CO emitted in the ATMS scenario is only 57% of that emitted in the Base scenario. These results indicate that although the implementation of the evaluated ATMS configuration is expected to reduce total CO emissions by 14.5%, these reductions do not occur uniformly over the simulated time period. Rather, the bulk of the CO reductions occur between time 2 and 2.5 hours.

Consider next the spatial distribution of CO, as illustrated in Figure 3. Spatial distribution is reflected by comparing the total emitted CO from each quadrant of the network. From the Base scenario results, it can be observed that total CO emissions from each quadrant of the network range from a high of 5,222 kg in the NW quadrant, to a low of 3,870 kg in the NE quadrant. The results from the ATMS scenario indicate that the largest reduction in CO emissions occurs in the SW network quadrant, in which the ATMS scenario CO emissions are only 54% of the Base scenario CO emissions. It is interesting to note from Figure 1, that the SW quadrant contains the lowest density of roadways, yet in the Base scenario, experiences the second largest quantity of CO emissions.

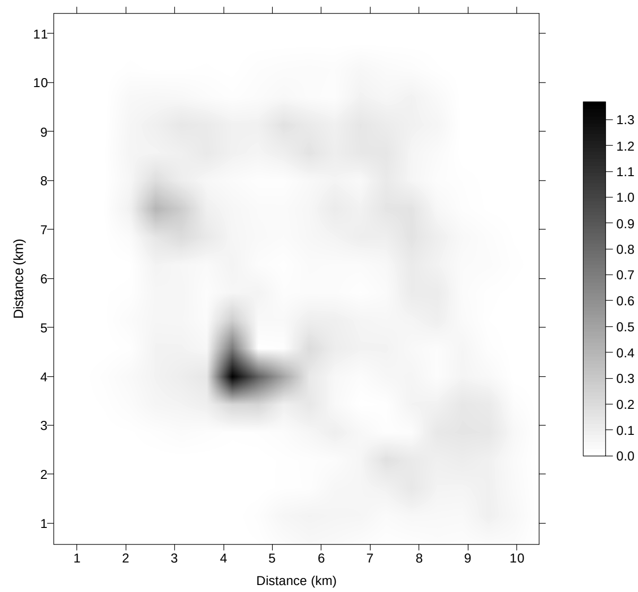

Figure 4: Base scenario CO concentration for period 5 (ppm)

Air quality is generally concerned with the concentration of pollutant, rather than just the mass emitted. The concentration of CO is generally reported in units of parts per million (ppm), which is computed as the ratio of the number of moles of CO to the number of moles of air. Current air quality legislation in the US defines moderate CO non-attainment areas as those areas having CO design values between 9.1 and 16.4 ppm [14]. On the basis of the total CO emitted over the network, and an assumed mixing height of 1 km, the CO concentration resulting from the Base scenario is 1.95 ppm, and from the ATMS scenario is 1.67 ppm. These concentrations are well below the moderate non-attainment area standards.

After applying the Eulerian dispersion model described in Section 2, it is possible to examine the CO concentrations as a function of both space and time. Figure 4 illustrates the concentration of CO observed throughout the network during period 5 (2.5 - 3 hours into the simulation). This figure clearly illustrates that, for this network, the maximum CO concentrations are highly localised to the SW quadrant. This localised concentration may explain why the implementation of ATMS provides such significant CO reductions in the SW quadrant.

Similar figures could be produced for the other time periods and for the ATMS scenario results. The depiction of the air quality in this manner permits the examination of the impacts of a potential ATMS/ATIS strategy on the temporal and spatial variation in air quality.

5. CONCLUSIONS AND RECOMMENDATIONS

Achieving current legislated AQS will require the innovative and effective use of ATIS and ATMS strategies, in addition to refining vehicle combustion and emission systems, and improving fuel formulations. Those strategies that can provide both travel time benefits and environmental benefits concurrently, will be sought after. However, the tools used to evaluate these potential strategies must provide traffic and environmental measures of performance that are sensitive to the impacts of the strategy being evaluated. Furthermore, these measures must enable the examination of the temporal and spatial variations.

Air quality modelling requires as input, the magnitude, location, and timing of sources of emissions. The required complexity of the AQM is largely a function of the study purpose, however, it is clear that for the purposes of evaluating ATMS and ATIS strategies, a direct link is required between the traffic modelling and the emission modelling.

The evaluation of a single potential ATMS strategy within this study, indicates that the impact on air quality can vary significantly spatially and temporally.

It is recommended that further investigation be made to quantify the impacts of a greater number of representative ATIS and ATMS strategies have on traffic and air quality MOPs. These strategies should include ramp metering, incident detection systems, additional forms of advanced signal control, and forms of driver information systems.

ACKNOWLEDGEMENTS

The financial support of the Natural Science and Engineering Research Council of Canada is gratefully acknowledged.

REFERENCES

[1] USEPA, 1993, "The Plain English Guide to the Clean Air Act", EPA400-K-93-001.

[2] B. Brunekreef, N. Janssen, J. de Hartog, H. Harssema, M. Knape, and P. van Vliet, 1997, "Air pollution from truck traffic and lung function in children living near motorways", Epidemiology Vol. 8, No. 3. pp. 298 - 303.

[3] A. Sydow, T. Lus, P. Mieth, R-P. Schäfer, 1997, "Simulation of traffic-induced air pollution for mesoscale application", Mathematics and Computers in Simulation, 43. Elsevier Science B.V. pp. 285-290

[4] A.K. Namdeo and J.J. Colls, 1996, "Development and evaluation of SBLINE, a suite of models for the prediction of pollution concentrations from vehicles in urban areas", the Science of the Total Environment 189/190, Elsevier Science B.V. pp. 311-320.

[5] J. Brown, April 1993, "Using computer modelling for transportation air quality analysis," Public Works, pp. 45-46

[6] Gerard Kiely, 1997, "Environmental Engineering", McGraw-Hill. pp. 366 - 381.

[7] Mazen I. Hassounah and Eric J. Miller, 1994, "Modelling air pollution from road traffic: a review", Traffic Engineering and Control Vol. 35 No. 9., pp. 510 - 514.

[8] W.B. Johnson, R.C. Sklarew, and D.B. Turner, 1976, "Urban air quality simulation modelling," in *Air Pollution*, 3rd ed., vol. 1, A.C. Stern, Ed. New York: Academic Press, pp. 503-562.

[9] P.J. Sturm, K. Pucher, C. Sudy, and R.A. Almbauer, 1996, "Determination of traffic emissions - intercomparison of different calculation methods", the Science of the Total Environment 189/190, Elsevier Science B.V. pp. 187-196.

[10] M. Van Aerde, and M. Baker, 1993, "Modeling fuel consumption and vehicle emissions for the TravTek system," VNIS Annual Conference, Ottawa, Canada

[11] M. Baker, and M. Van Aerde, 1995, "Microscopic simulation of EPA fuel and emission rates for conducting IVHS assessments," IVHS America Annual Conference Proceedings, Washington, DC.

[12] US EPA, 1993, "User's Guide to MOBILE5A: Mobile Source Emissions Factor Model"

[13] K. Wunderlich, M. Van Aerde, B. Hellinga, and J. Harding, 1995, "Macro-level traffic simulation and case study development for IVHS system architecture evaluation," IVHS America Annual Conference, Washington, DC.

[14] J.C. Mycock, J.D. McKenna, and L. Theodore, 1995, "Handbook of Air Pollution Control Engineering and Technology" CRC Press, Inc. pp.22