A simulation framework for modelling the impacts of an integrated road-vehicle system on local air quality

TRAIL Research School, Delft, October 2008

Authors
Mohamed Morsi Mahmod MSc, Prof. dr. Bart van Arem
Centre for Transport Studies, University of Twente, the Netherlands

© 2008 by M. Mahmod, B. van Arem and TRAIL Research School
Abstract
Traffic-induced emission is a major source of air pollution in urban areas. Today while demand for environmental aspects has increased and is expected to increase even further, a new development has occurred in the applications of co-operative road-vehicle systems. Co-operative systems use vehicle-to-vehicle and vehicle-to-infrastructure communications to influence traffic flow in real-time and help improve safety, efficiency as well as air quality. However, new modelling tools are needed to assess the impact of such systems on the environment. A simulation framework for modelling the impacts of an integrated road-vehicle system on local air quality has been presented. Choices for models to be used have been made carefully according to the special requirements and level of details needed for our system. The simulation framework will be used to evaluate various measures which use roadside and in-vehicle systems.

Keywords
Traffic modelling, traffic emission modelling, dispersion modelling, air quality, integrated road-vehicle system.
1 Introduction

In many urban areas, traffic transport has become a major source of air pollutants, particularly nitrogen oxide (NOx), particulate matter (PM), volatile organic compound (VOC) and carbon monoxide as well as carbon dioxide (CO2). This is due to the increased usage of road transport (especially freight and passenger transports) which is expected to double in Western Europe between 1990 and 2010 (Kitwiroon et al., 2007). Air pollutants can have serious health impacts if the ambient concentrations exceed certain limits. This increases death risks, where in the Netherlands around 1,700 – 5,000 people died in 2001 due to air pollution (VROM, 2004). In order to reduce the concentration levels of air pollutants, the EU directives (EU, 1999) (EU, 2000) have set threshold values for pollutants concentrations levels. Actions must be taken where these threshold values are breached. Breached already occurred in a large number of Dutch municipalities and without further measures these situation will just worsen.

The recent developments in information and communication technologies have paved the way for the development of co-operative systems in intelligent transportation systems (ITS). Co-operative systems use vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication to increase road safety and efficiency. Moreover, co-operative systems can be used to reduce traffic emissions and improve air quality. This is through influencing traffic flow in real-time to optimize traffic flow, traffic safety and air quality. To reduce traffic emission, co-operative systems can aim at reducing traffic volumes, the number of heavy vehicles and traffic dynamics (acceleration and deceleration) as well as obtaining optimal speeds (emission is high when speeds are very high or very low) (Wilmink & op de Beek, 2007). In this regard, a PhD project of ‘‘environmentally friendly traffic management using integrated road-vehicle system’’ (Mahmod & van Arem, 2008) has been launched at the AIDA centre (Application of Integrated Driver Assistance), which was founded by the University of Twente and TNO (AIDA, 2003).

To be able to assess the effectiveness of the measures, traffic and environmental models are used. Traffic models are used to simulate the real traffic situation before and after the implementation of the measure. Environmental models such as emission and dispersion models are used to estimate the effect of the measure on emission and concentration levels of air pollutants. However, in order to increase the accuracy of the calculations, these different models can be linked together (Wilmink & op de Beek, 2007). The choices of models should be made based on the required level of detail and accuracy needed by the application. This is because no model can be the best for all situations. In the OSCAR project, a multi-model approach has been used to develop an Air Quality modelling system which can be used in different level of complexity. The system integrates a suite of models which can be selected by the user to study air quality at street level (Sokhi et al., 2008). In (Costabile & Allegrini, 2008) a new approach to link transport emissions and air quality has been presented. The methodology is based on having a communication between transport emissions and air quality, which has been used to design a system for the Beijing ITS-TAP project (Intelligent Transport System-Traffic Air Pollution). The main advantage of this system is the runtime integration of modelling with measurements to provide high time/space resolution of measurements of both air pollutants concentrations and
traffic emissions. The same methodology of combining measurements with modelling is being used in the MESSAGE project in the UK (MESSAGE, 2006).

This paper presents a simulation framework for modelling the impacts of an integrated road-vehicle system on the environment. This includes different models for traffic flow, traffic emission and dispersion. The models have been selected according to the special requirements of our project taken into account the need for representing intelligent roadside and in-vehicle systems and the interaction between them. The paper is organized as follows: Section 2 defines the goal and approach of the project. Section 3 describes our simulation framework. Finally, the paper ends up with the conclusion in Section 4.

2 Goal and approach

The main goal of the project is to improve the local air quality in an urban corridor using integrated road-vehicle systems. To achieve this goal a simulation framework will be developed and applied to investigate the impact of the system on the environment. The project will make use of measures which are based on roadside and vehicle systems. Special attention will be given to the use of in-vehicle systems such as Adaptive Cruise Control (ACC) and Intelligent Speed Adaptation (ISA). This is by comparing different scenarios with and without equipped vehicles in order to study the added value of such systems.

Although several methods exist to improve air quality near roads, the focus in our project is only on measures that use road-based and vehicle-based systems to influence traffic flow and change drivers’ behavior in real-time. An example of these measures is traffic light and vehicle coordination, where in case of a high emission level traffic lights will aim at reducing stops, delays and vehicles dynamic at an intersection (acceleration and deceleration). Another example is dynamic access control, where the infrastructure can admit or deny access depending on traffic conditions and the air quality level inside the defined area. This is through the communication with approaching vehicles so as to assess their characteristics (e.g., vehicle type, speed). In this case the measure is intended to be more flexible than the standard access control, in which certain vehicles are prohibited all the time.

![Integrated road-vehicle system image](image-url)

Figure 1: Integrated road-vehicle system
The overall approach of the project consists of the following work packages:

1. develop an indicator for the momentary local air quality;
2. develop an algorithm to influence traffic flow and improve the local air quality;
3. study the operation and the side-effects of the algorithm in a simulated environment;
4. demonstrate the system using a test vehicle.

The development of the air quality indicator is important for the development of environmentally friendly traffic management systems. Based on the indicator the air quality can be marked as poor or good and hence it can be decided whether or not the measure should be activated. The indicator will be based on concentration levels since they are more relevant than emission levels for judging the actual air quality with respect to human health and comparing to the EU limit values. Moreover, short term and local traffic measures should be related to concentration levels. The indicator will also help to switch between different scenarios e.g., efficiency or environmentally.

The algorithm will be developed to influence the traffic flow in real-time and improve local air quality. Various measures which are based on roadside and in-vehicle systems will be simulated. The impact of combination of different measures will also be tested. The effect of driver support systems (e.g., speed assistance), particularly the co-operative implementation, will be evaluated using different percentage of equipped vehicles.

The modelling study of the developed algorithm will be carried out using our simulation framework. The development of our simulation framework together with choices of the models to be used is discussed in section 3. During the modelling study, the side effects on traffic flow and safety as well as greenhouse gases emission will be investigated.

Finally, the system will be demonstrated in a test site using one test vehicle equipped with driver support system. This in a connection with the Dutch test site for integrated road-vehicle system developed for the CVIS and SAFESPOT European project. The demonstration is considered as a show case in order to prove the technical feasibility of the system.

### 3 Simulation framework

To able to evaluate the impact of an integrated road-vehicle system, a simulation framework needs to be developed. This includes different models such as traffic model, emission model and dispersion model. The main building blocks of the simulation framework are shown in figure (2) below.
A literature study of traffic modelling, emission modelling as well as dispersion modelling has been carried out. A summary and the conclusion drawn from each is given next.

3.1 Traffic modelling

The most commonly used microscopic simulation models were reviewed keeping in mind the special requirements of our project. These models include AIMSUN, PARAMICS and VISSIM. ITS modeler has also been considered as a modeling environment for intelligent road-sides and vehicles units and the interaction between them. First, a list of selection criteria has been set up to help deciding the most suitable model to be used. These are:

1. We have to be able to simulate the co-operation between the vehicle and roadside units (e.g., traffic light).
2. The microscopic model should be able to model an urban environment i.e. one or more intersections with the possibility to put some ITS measures on top of it.
3. Also the model should be flexible in programming traffic signal control and could be linkable to external signal state generator software.
4. The microscopic model must be able to produce valid driving patterns to account for the emission calculation.
5. The microscopic model needs to be available (practical choice).

With regards to the simulation of the intelligent road-vehicle systems and the interaction between them, the ITS modeler has been selected. The ITS modeler was developed at TNO (the Netherlands Organization for Applied Scientific Research) as a modeling environment to simulate intelligent road-side and vehicle systems and the interaction between them. The architecture of the ITS modeler has been divided into network architecture, intelligent vehicle architecture, evaluation modules architecture, and ITS system architecture. Currently, the ITS modeler is used in conjunction with Paramics, while linking to other models has been taken into account during the development. The users can define their own algorithms, which represent the ITS system, to control the behavior of drivers and vehicles. In this way, the ITS modeler can be used to evaluate and assess the impacts of the new ITS system (Versteegt et al., 2005). However, we need to decide which microscopic model will be the best to link...
to the ITS modeler. An important point to consider here, was to look at the situations in ITS modeler where vehicles are not controlled by the ITS modeler. These are: braking for intersection and traffic light, lane-changing at intersection and traffic signal control at intersection.

According to the functional evaluation carried out by Hidas (2005) for the three microscopic models, here are some of the differences that make one of the models less or more suitable for specific situations:

1. For bicycle, motorcycle, and pedestrian modeling, VISSIM has more realistic models than AIMSUN and PARAMICS.
2. The gap acceptance model in VISSIM has found to be more flexible and more detailed. This helps in modeling complex and unusual traffic situation more realistic than in AIMSUN and PARAMICS.
3. For traffic signal control, AIMSUN can simulate fixed time signal control, while adaptive signal control can be modeled through linking to an external software (using GETRAM). PARAMICS has an enhanced vehicle actuated signal control and can also be linked to external adaptive signal control. VISSIM has the optional VAP (vehicle actuated programming) add-on module which can be used for simulating programmable, phase (stage) based, traffic actuated controls. It can also be used for interfacing VISSIM with external signal state generator softwares.
4. VISSIM has a more detailed network and traffic models allowing for the consideration of vehicle widths, lateral movement between the lanes, and modeling two-wheeled vehicles (motorcycles and cycles).
5. Compared to AIMSUN and PARAMICS, VISSIM is less suitable and convenient for simulating large networks with significant route choices options and ITS applications. However, VISSIM is more suitable for small-scale networks with complex geometry, and/or unusual difficult networks, traffic, and control conditions.

It is important to mention that this evaluation of the three models was based on the following version of the models: AIMSUN V4.2 (2003), PARAMICS V4.2 (2003), and VISSIM V3.7 (2003).

Accordingly, VISSIM has been selected to be linked with the ITS modeler. This is because of the features of VISSIM especially for the situations where vehicles are not controlled by the ITS modeler modules. For example, VISSIM has been found to have high quality and more detailed traffic control model including user behavior at traffic signals. Furthermore, VISSIM has the ability to model adaptive signal control and link to external signal state generator softwares (VAP tool). Finally, VISSIM is considered to have better method for simulating traffic at intersection. This is because of the many modeling parameters for intersections that can be controlled by the user (Poska, 2002).

### 3.2 Emission modeling

Various approaches for traffic emission modeling have been reviewed. The advantages and limitations of each approach have been studied with regards to the required level of detail (i.e. street level) for our project. The classification systems for vehicle emission models can be based on a combination of the following:
1. The geographical scale of application (macro-scale, meso-scale, and micro-scale)
2. The generic model type (aggregation emission factors, average speed, adjusted average speed, modal, instantaneous, traffic situation, multiple regression)
3. The nature of emission calculation approach (discrete, continuous, discrete/continuous)

Some examples of emissions models based on the generic types are discussed in table (1) below together with their advantages and limitations (Boulter, Barlow et. Al., 2002).

**Table 1: Emission models**

<table>
<thead>
<tr>
<th>Generic Type</th>
<th>Definition</th>
<th>Examples</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregated emission factor models</td>
<td>Emission factor calculated from laboratory test on a number of vehicles using a given driving cycle. A single emission factor is used to represent a particular type of vehicle and a general type of driving</td>
<td>MOBILE</td>
<td>Appropriate for large scale applications (national &amp; regional emission inventories) Relatively large number of measurements</td>
<td>Can not use to determine emissions for situations which are not explicitly covered by the emission factors e.g. effect of traffic measures</td>
</tr>
<tr>
<td>Average speed models</td>
<td>Calculate average vehicle emission over a trip as a function of average speed</td>
<td>COPERT</td>
<td>Suitable for large scale Relatively large number of measurements</td>
<td>Can not account for the variability in driving dynamics at particular speed. With new vehicles, average speed is not a reliable indicator for the high amount of emission during short peaks</td>
</tr>
<tr>
<td>Modal models</td>
<td>Modal models relate vehicle operation modes (steady state, acceleration, deceleration, and idling mode) to the emissions produced during these modes Instantaneous emission models are complex extensions of modal models, where emission rates are calculated on a second-by-second basis from instantaneous speed &amp; acceleration An advanced instantaneous modeling approach is another extension of instantaneous models. It is used for estimating emissions from individual vehicles over short time scales</td>
<td>UROPOL MODEM model</td>
<td>Better than in emission factor approach as they reflect the effects of vehicle-operating modes, so higher resolution is possible</td>
<td>Lack in the tools for forecasting the vehicle activity modes Time lag and damping of the signal being sampled. Can not take into account factors like road gradient Difficult to extend to the entire fleet Required information is expensive to collect</td>
</tr>
<tr>
<td>Traffic situation models</td>
<td>Correlate cycle average emission rates with various driving cycle parameters, which are referenced to specific traffic situations</td>
<td>Handbook for Emission Factors (HBEFA)</td>
<td>Suited for local applications (road links)</td>
<td>How to define the road and conditions leading to a given driving pattern? No commonly accepted definitions of universal traffic situations</td>
</tr>
<tr>
<td>Multiple linear regression models</td>
<td>Multiple linear regression models the relationship between two or more explanatory variables and emission rates by fitting a linear equation to observed data</td>
<td>VERSIT+</td>
<td>Based on statistic method, can estimate accuracy</td>
<td>Need very large database</td>
</tr>
</tbody>
</table>

In general, macroscopic emission models based on average speed are un-suitable for emissions calculation, especially for micro- and meso-scaled applications. For small
scale and real-time applications, models that consider vehicle operation conditions (speed fluctuation or vehicle dynamics) are needed i.e. microscopic models.

Consequently, it is clear that models that consider driving pattern (speed-time profiles) will give more accurate emission results and be able to reflect the effect of the congestion, which is very important in emission calculation. Emission models can be divided into four types according to the way they treat the effect of speed-time profiles on emissions. These are described in table (2) below (Smit, Smokers et al., 2006).

**Table 2: Types of emission models**

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Estimate emissions for a few discrete predefined traffic situations (e.g. urban, rural, highway)</td>
<td>The Dutch method (calculating method for estimation of national emission levels)</td>
</tr>
<tr>
<td>B</td>
<td>As type A with large number of predefined traffic situations</td>
<td>Well-known Swiss-German Handbook of emission factors (HBEFA)</td>
</tr>
<tr>
<td>C</td>
<td>Regression model where emission is calculated using continuous emission factors</td>
<td>COPERT</td>
</tr>
<tr>
<td>D</td>
<td>Traffic situations are measured using driving pattern data</td>
<td>VERSIT+</td>
</tr>
</tbody>
</table>

Type D is the most complex models, while type A is the least complex ones. More complex models are more accurate and versatile but they need more detailed input data. No model can be the best option for all situations; this is decided by the level of detail and level of accuracy needed by the application. According to the level of details, the different types of models can be applied as following:

1. Type A can be used for the lowest level of detail i.e. country level
2. Type B and C can be used for medium level of detail i.e. city Area level
3. Type D is used for the highest level of detail i.e. local street level (Smit, Smokers et al., 2006).

Looking to the required level of detail, models of type D are more suitable for our project. An example of type D models is VERSIT+ LD (VERSIT+ - Light Duty). VERSIT+ was also developed at TNO from a largely theoretical and deterministic approach to a fully empirical and statistical framework. The objective of VERSIT+ is to predict accurate traffic stream emissions for any particular traffic situation by using accurate mean emission factors (in grams per Kilometre) for detailed (light-duty) vehicle categories. More than 153 actual speed-time profiles were used to apply 12,000 emission tests to a large number of vehicles (Smit et al., 2007). Therefore, VERSIT+ seems to suit the requirement in our project. Note that in AIDA, TNO and the University of Twente work together on the development of simulation models. Therefore, when several comparable models are available, models were selected on the basis of availability and support by TNO.

### 3.3 Dispersion modeling

The focus here was on line source dispersion models which are used for estimating vehicular pollutant concentrations. In general, atmospheric dispersion models are used to predict the concentrations of pollutants in the air which are emitted from various
sources. They are vital tools in assessing the current and future air quality and hence help to design more effective air pollution control management strategies. The basic concept behind air pollution modeling is the definition of a function $F$ that predicts the concentration of pollutants in time and space i.e. $C(t,x)$ from emission and meteorological data. There are three approaches for defining $F$: deterministic (Analytical or Numerical), statistical and physical (Khare & Sharma, 2002). Table (3) (next page) presents these approaches, their advantages and limitations.

Looking to the descriptions of the different approaches, the following could be mentioned according to the requirements of our project:

- deterministic models (i.e. Analytical) are, in general, unsuitable for our project since they are more suitable for long term planning decision;
- although statistical models seem to be suitable for our project (i.e. used for real-time, short-term assessment), they can not give information on how pollutant levels would respond to emission controls (which is important for our project);
- numerical models seem to be the most promising models for our project and among these is the CARMEN model that is under development by TNO to give the results on an hourly basis. An alternative choice here could be the CAR-FMI model (Contaminants in the Air from a Road - Finnish Meteorological Institute), which give the result also on hourly basis. However, CARMEN has been selected as a practical choice.

Based on the model choices, our detailed simulation framework can be represent schematically in figure (3) below.

![Figure 3: Detailed simulation framework](image)

Figure 3: Detailed simulation framework
### Table 3: Dispersion model approaches

<table>
<thead>
<tr>
<th>Approach</th>
<th>Definition</th>
<th>Examples</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic</td>
<td>Calculate the concentrations from an emission inventory and other independent variables, mostly meteorological variable. Use solution of diffusion equation. Divided into numerical and analytical models</td>
<td>HIWAY General Motor (GM) California (CALINE)</td>
<td>Most suitable for long term planning decisions</td>
<td>Overprediction with parallel wind direction Lack of capability to model the effects of vehicles' heated exhaust on the plume rise Give inaccurate results with very low wind speed</td>
</tr>
<tr>
<td>Numerical</td>
<td>Based on numerical approximation of partial differential equations that described the atmospheric dispersion phenomena</td>
<td>ROADWAY CAR-FMI (Contaminants in the Air from a Road - Finish Meteorological Institute) CAR (Calculation of Air pollution from Road traffic)</td>
<td></td>
<td>Large computational costs Large amount of data</td>
</tr>
<tr>
<td>Analytical</td>
<td>Based on analytical solution of diffusion equation under simple assumption</td>
<td>Gaussian models: Much experience achieved with them Easy to understand and require less computer running time</td>
<td>Due to the assumptions made for the construction of the models: For short time period (i.e. ≤ day) where steady-state assumptions are not met, give inaccurate results Can not account for sudden variations</td>
<td></td>
</tr>
<tr>
<td>Statistical</td>
<td>Use statistical methods to calculate concentrations from meteorological and traffic data after forming a suitable relationship from empirical measurements of the concentrations Useful for real-time, short-term assessment</td>
<td>Methods: Regression models Multiple regression models Time series techniques</td>
<td>Take into consideration the unknown variation Allow all available data to be used in forecasting computations Have adaptive capabilities</td>
<td>Require long historical data sets to give accurate results Lack of physical interpretation Do not reflect the change in pollutant levels due to emission controls</td>
</tr>
<tr>
<td>Physical</td>
<td>Small-scale representation of atmospheric phenomena Used as research tool</td>
<td>Experiments carried out in wind tunnels and water channels</td>
<td>Best approach in case of: Complex air pollution situation When details are required</td>
<td>Expensive and difficult to set up</td>
</tr>
</tbody>
</table>
4 Conclusions

Co-operative systems are a promising solution to help reducing traffic emission and improve air quality. This is by utilizing the communication in-between vehicles and between the vehicles and roadside units in order to obtain a more environmentally friendly traffic flow and driving behaviors. Examples of air quality measures that use co-operative systems are traffic light and vehicle coordination, and dynamic access control. The two main societal objectives that such systems can contribute to are: protecting both human health and natural environment. Moreover, implementation of these systems in the future will help the cities to meet the European objectives on air quality. Accordingly, this will save money since meeting the limit values could cost the Dutch government a lot of money which is socially unacceptable.

Before implementing an environmentally friendly road-vehicle system in real world, one needs to assess and optimize the potential impacts of the system on the environment and study the other side effects. For that a range of models need to be considered. These include traffic model, emission model and dispersion model. These models can be linked together in one simulation framework to increase the accuracy of calculations. Accordingly, a simulation framework has been presented. For traffic modeling, VISSIM has been selected because of its detailed traffic control model including user behavior at traffic signals. Moreover, the ITS modeler has been chosen to simulate the intelligent roadside and in-vehicle systems, and the communication between them. For emission modeling, The VERSIT+ LD model was selected due to the required level of detail (street level). For dispersion modeling, the CARMEN model, which is under development by TNO to give the results on an hourly basis, has been selected according to real-time requirement. The simulation framework will be used in the future stages of our project to study the effectiveness of various air quality measures.

Acknowledgement

This project is part of the AIDA (Application of Integrated Driver Assistance) program of the University of Twente (Transport Research Centre) and TNO. The authors gratefully acknowledge the Cornelis LelyStichting and Vialis for their funding.

References


Boulter, P. G., T Barlow, IS McCare, S latham (TRL), D Elst and E van der Burgwal (TNO) (2005), Road traffic characteristics, driving patterns and emission factors for congested situations, OSCAR project, Deliverable 5.2.


Mahmod M.K.M, B. van Arem (2008), *Environmentally Friendly Traffic Management using Integrated Road-Vehicle Systems*, Accepted for the ITS 15th World Congress on ITS, New York, USA.


