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Modelling instantaneous traffic emission and the influence of traffic speed limits

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Abstract

This paper considers the effect of active speed management on traffic-induced emissions. In particular, the traffic emissions caused by acceleration and deceleration of vehicles are modelled based on an instantaneous emission model integrated with a microscopic traffic simulation model. The emission model is based on empirical measurements which relate vehicle emission to the type, the instantaneous speed and acceleration of the vehicle. The traffic model captures the second-by-second speed and acceleration of individual vehicles travelling in a road network based on their individual driving style, the vehicle mechanics, and their interaction with other traffic and with traffic control in the network. The integrated model is applied to test a new technology to actively manage the driving speed of the vehicles in an urban network. Their impacts on vehicle emission in the network are assessed to give an indication of the relative effectiveness of the different technological designs and different levels of driver responses. The results show that, while the speed management has effectively reduced the average speed of the traffic, their impact on vehicle emissions is complex. For the study network, the frequent acceleration and deceleration movements in the network has significantly reduced the effect of the reduced average speed on emission. The net results are that the active speed management has no significant impact on pollutant emissions. The study suggests that the analysis of the environmental impacts of any traffic management and control policies is a complex issue and requires detailed analysis of not only their impact on average speeds but also on other aspects of vehicle operation such as acceleration and deceleration.

Keywords: Instantaneous emission; Integrated traffic and emission modelling; Traffic speed management; Microsimulation

1. Background

In recent decades, air quality at the local, regional and even worldwide level has received great attention from scientists, policy makers and the general public alike. As the negative impacts of NO_x and SO_2 have become clear, measures have been taken to try to reverse the trend. The most important contributing emission sources at the time (e.g. NO_x emission from the traffic) have been targeted with policy measures at the European level necessitating the implementation of novel technical features such as 3-way catalysts in new petrol cars in the early 1990s. More recently attention reverted to public health effects with a focus on urban air quality and fine particle emissions from traffic which are now believed to be the most toxic component of a complicated mixture given the efficient abatement of the earlier culprits CO, SO_2, NO_x and Pb (Hoek et al., 2002). Particles in the PM2.5 range are found to cause

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the most damage to health. In addition health effects are persistently found in new epidemiological studies at low ambient concentrations (Pope et al., 2002).

Policy makers and engineers have again turned to technical solutions such as tighter fuel specifications to reduce the amount of sulphur in automotive fuels even more. Particulate filters and traps have become available at a pace much faster than policy makers expected, but are not yet mandatory. Despite the fact that fuel specifications as well as the end-of-pipe technologies have reduced the emissions per kilometre by several orders of magnitude for some pollutants (with the exception of CO_2), increased travel demand and traffic congestion have severely offset the expected beneficial effect on air quality.

Vehicle emissions are known to correlate strongly with driving behaviour, even though direct measurements of such type of effects are very difficult. De Vlieger (1997) and De Vlieger et al. (2000) used instrumented vehicles to demonstrate that emissions in real traffic conditions differed considerably between different drivers. They found that aggressive driving resulted in a sharp increase in fuel consumption and emissions compared to normal driving. Fuel consumption rose by 12–40% and CO emissions increased by a factor of 1–8 for an aggressive driver compared to those of a normal driver. For VOC and NO_x the increase in emissions due to aggressive driving ranged from 15–400% to 20–150% respectively. Ericsson (2000) showed a significant difference between urban driving patterns in different street types and drivers and suggested that knowledge of this variability would help to devise policy to change driving behaviour and thus reduce exhaust emissions from vehicles.

In recent years, a wide range of real-time transport policy measures has been developed and some implemented to try to manage travel demand (such as congestion-based road pricing, pedestrian-only zones, automatic highway systems) and to influence driver behaviour (such as dynamic route guidance, variable message signs, automatic cruise control). Although they are designed primarily to reduce congestion and improve network efficiency, these measures were also expected to have a significant impact on urban traffic pollution (Chiquetto, 1997). It is not always feasible to directly measure the effect of the policy measures on vehicle emissions and air pollution. Most policies have impacts that are much smaller than the noise in the data from fixed site monitoring stations. The full effect is often only felt after several years as the fleet is gradually renewed. Considerable effort has therefore been devoted to develop models to describe emissions and air pollution resulting from the implementation of policy measures in real-life traffic (e.g. Sturm et al., 1996; Trozzi et al., 1996; Int Panis et al., 2005).

For many years, macroscopic models based on average travel speed have been the most common methodology used for estimating vehicle emissions. In Europe, for example, most inventories of exhaust emissions at the fleet level or for a city as a whole are still calculated according to the COPERT methodology developed from the European MEET project (EC, 1999).

These macroscopic models entail enormous simplifications on the accuracy of physical processes involved in pollutant emissions. An important drawback of this methodology is that it calculates emissions per kilometre for vehicle trajectories using primarily the average speed. Although the overall trip speed is an important factor influencing emissions, instantaneous speed fluctuation plays a greater part. For the same average speed, one can observe widely different instantaneous speed and acceleration profiles, each resulting in very different fuel consumption and emission levels. For the compilation of emission inventories of large areas and over long time periods, this microscopic effect may be ignored and the results from the macroscopic models may give reasonably good estimates. Models taking traffic dynamics partially into account by partitioning the traffic situations in several classes such as the Infras methodology have been less widely used (BUWAL/INFRAS, 1995). More sophisticated hybrid approaches such as ARTEMIS are still in their infancy (André, 2004).

For smaller scale and real-time applications, however, one needs to develop models that take into account vehicle operation conditions. This is especially the case when the policy to be evaluated is real-time traffic management and results in changes in driving behaviour such as those mentioned above. In order to effectively measure the behavioural changes on exhaust emission, it is crucial that the models fully incorporate the new technology employed by the policy measures, the behavioural responses of the drivers and the real-time vehicle operations. Joumard et al. (1995) correlated their emission measures with vehicle speeds and the product of speed and acceleration. They showed that the emission rates increased not only with increasing speed, but also with increasing acceleration. Currently, significant effort is being devoted to the development of models that can account for speed fluctuations and allow instantaneous emission modelling, such as the Comprehensive Modal Emission Model developed at the University of California (An et al., 1997; Barth et al., 2000) and many others around the world (e.g. Rakha et al., 2004; Pelkmans et al., 2004; Cornelis et al., 2005; El-Sgawarby et al., 2005).

In parallel, recent years have seen a tremendous interest in the transport field in the use of microsimulation techniques to model traffic on road networks through which to represent the real-time, behaviourally-based policy measures (e.g. Ben-Akiva et al., 1997; Hu and Mahmassani, 1997; Liu et al., 2006). Traffic microsimulation models are based on the explicit representation of the individual driver behaviour and individual vehicles' real-time space-time trajectories. They offer detailed vehicle operation and instantaneous speed and acceleration of vehicles required by the microscopic emission models.

This paper presents a methodology to make instantaneous emission modelling compatible with traffic microsimulation models. The paper shows the basic functionality of both the microscopic emission model and the traffic microsimulation model. The methodology is demonstrated through its implementation in the DRACULA microsimulation suite of models developed and used intensively in transport research and practice (Liu et al., 2006). The methodology itself is, however, generic and can be incorporated with other traffic microsimulation models (Int Panis et al., 2005). Section 2 of the paper describes in brief the DRACULA traffic microsimulation model and presents the microscopic emission model and the data sources used in its development. Section 3 presents an application of the integrated microscopic traffic emission model to evaluate a new technology to control driving speed. Discussion and suggestions for further research are presented in Section 4.

2. Methodology

Fig. 1 shows the interplay among transport policy, road traffic congestion, traffic emission and air pollution. The proposed methodology is to integrate models of these various factors, policy effects and behavioural responses together as a tool which allows direct evaluation of the impacts of real-time transport policy on the environment. The methodology proposed here attempts to develop an integrated modelling approach that represents traffic and emission at the same level of detail. It links the real-time traffic conditions directly with models of emissions which are based on the instantaneous driving speed and acceleration, and through which to provide direct estimates of exhaust emissions.

There are two main components in this methodology: a microscopic traffic simulation model and a microscopic emission model. The former can be based on any existing traffic microsimulation model software which has the ability to provide measures of *real-time* driving conditions in terms of driving speed and acceleration (e.g. Barcelo and Casas, 2004; Fellendorf and Vortisch, 2000; Liu, 2005a). The latter is an emission model developed based on a wealth of measurement data that had not previously been analyzed for this purpose. The emission data are analyzed and a model is formulated with the specific objective to link with real-life data or model results that represent real-time driving rather than with laboratory-based driving cycle conditions. In this paper, we describe the integration of the new emission model with the DRACULA traffic microsimulation model during a collaborative EU-funded project PROSPER (Liu et al., 2005). The choice of the traffic model is made simply because that project has access to the software and is able to incorporate the new emission model within its simulation framework.

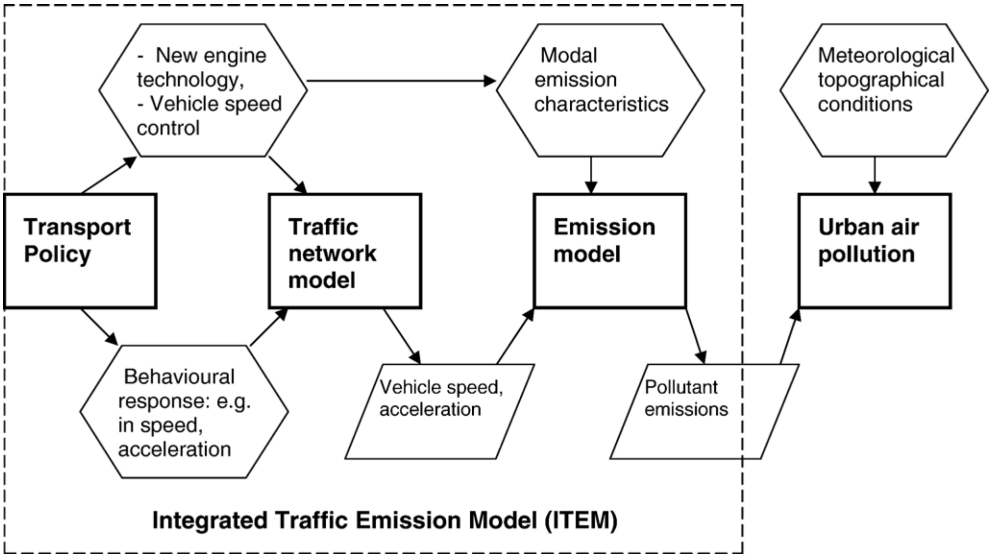

Fig. 1. The proposed model framework to analyze the relationship between transport policy, traffic network conditions, vehicle emissions and urban air pollution.

2.1. The traffic microsimulation model

The traffic model used here is based on an explicit simulation of the movements of individual vehicles through a network. En route, they interact with other drivers/vehicles and with traffic controls (e.g. traffic lights, speed limits). A large number of such microscopic vehicle models have been developed in the past at varying levels of complexity and network size (e.g. in some the network size is effectively limited to only a single intersection) (see a review in Algers et al., 1997). The essential property of all such models is that the vehicles move *in real time* and that their *space-time* trajectories are determined by e.g. car-following models, lane-changing models, and obvious network controls such as stop on red and speed limits.

The DRACULA (Dynamic Route Assignment Combining User Learning and microsimulAtion) model is a network-wide traffic microsimulation model package. It can represent a wide range of road types (including urban, rural as well motorway networks) and intersection controls. The traffic model represents individual vehicle movements through a network and records and updates individual drivers' experiences and perceptions of the network. The traffic model is combined with a modelling of the day-to-day evolution of individual drivers' route choices based on their own experiences of congestion on previous days, making it particularly suited for the realistic modelling of real-time policies as those listed in Section 1 (Liu et al., 2006). The main simulation component of the model is described briefly below. More detailed description of the model can be found in Liu (2005a,b).

2.1.1. Network representation

The road network is represented by nodes, links and lanes. Different types of intersections are represented, including signal controlled, priority give-way, roundabout, motorway merge and diverge. Public transport network and services are modelled, including regular bus services, bus lanes, bus stops or bus laybys and guideway. Incidents are modelled with fixed duration and locations set prior to the simulation.

2.1.2. Vehicle representation

Vehicles are individually represented, each having a set of individual characteristics to give the technical description of the vehicle and to represent the behaviour of the driver. These include:

- vehicle type (such as car, bus, guided bus, taxi, goods vehicles);
- vehicle length;
- maximum acceleration the driver can use;
- maximum deceleration driver uses in emergency braking conditions;
- reaction time of the driver;
- minimum safety distance the driver prefers to keep from the vehicle in front;
- normal acceleration the driver uses in normal car-following conditions;
- desired speed factor; and
- a risk factor related to the gap that the driver regards as safe to accept.

A driver's desired speed is not only a behavioural characteristic of the driver but also influenced by the speed limit on the road. For example, a faster or a more aggressive driver may always want to drive fast at 90 mph, but on an urban 30 mph road, he/she may have to adjust his/her desired speed accordingly. So in DRACULA, a "desired speed factor" is modelled, instead of the desired speed itself, to represent the different level of aggressive behaviour in drivers' choice of speed. These characteristics are randomly sampled from normal distributed representations of the type of vehicle, with means and coefficients of variation defined by the user.

Because of the flexibility of the microsimulation approach, it is possible to introduce additional driver/vehicle types, such as whether one has a speed control device installed or not, an example of which is presented in Section 3.

2.1.3. Vehicle movement

In the DRACULA traffic model, the speeds and positions of individual vehicles are updated at a fixed time increment of 1 s. Vehicles are generated at their origins and arrive at the border of the network at random intervals according to some observed headway distributions (e.g. shifted negative exponential distribution). Vehicles are then moved through the network along the routes they have chosen according to a car-following model, a gap-acceptance model, the lane-changing rules and traffic regulations at intersections.

The direct effect on vehicle emission comes from the vehicle's speed and acceleration determined in the simulation by the car-following model which is described briefly below. Description of the lane-changing and gap-acceptance models can be found in, e.g. Gipps (1986), Liu (2005a), Toledo et al. (2003) and references therein.

The car-following models represent the longitudinal interactions among vehicles in a single stream of traffic and model the response of a following vehicle to a stimulus from the vehicle or vehicles in front. The most common form of car-following models represents the response of the following vehicle as a product of the stimulus and the sensitivity of the following vehicle as:

$$\text{Response} = \text{Sensitivity} \times \text{Stimulus}$$

where the response is typically represented by the acceleration of the following vehicle, and the stimulus is represented in terms of space and speed differences. The simplest form of the above car-following model was developed in the early 1950s based on the data collected by General Motors using their test track (e.g. Chandler et al., 1958). The formulation is shown in Eq. (1):

$$a_n(t+\tau) = C_0[v_{n-1}(t) - v_n(t)] \tag{1}$$

where the stimulus, $[v_{n-1}(t) - v_n(t)]$, is the difference between the speed of the following vehicle n and its preceding vehicle $n-1$. The response, $a_n(t+\tau)$, is the acceleration of the following vehicle n after some initial perception reaction time τ. In this model, a constant sensitivity C_0 was fitted here.

$$v_n(t+\tau) = \min\left\{\begin{array}{c} v_n(t) + 2.5a_n^{\max}\tau[1-v_n(t)]/v_n^{des}[0.025 + v_n(t)/v_n^{des}]^{1/2} \\ c_1 v_n(t) + c_2 v_{n-1}(t) + c_3[s_n(t) - s_n^{\min}] \\ d_n\tau + [d_n^2\tau^2 - d_n\{2[s_n(t) - s_n^{\min}] - v_n(t)\tau - v_{n-1}^2(t)/\hat{d}]^{1/2} \end{array}\right\} \begin{array}{c} (2a) \\ (2b) \\ (2c) \end{array} \tag{2}$$

The car-following model implemented in DRACULA considers vehicle following in three different traffic conditions: free-flow, comfortable-following and close-following condition. The mathematical formulation of the car-following models is shown in Eq. (2). A complete list of the notations used in the paper is given in the Appendix.

Eq. (2a) represents the *free-flow condition* (Gipps, 1981) where vehicle n is the lead vehicle in a platoon of traffic and its driver will use its maximum acceleration ($a_n^{\max}$) to reach and maintain his/her desired speed v_n^{des}. When the vehicle has caught up with the tail of the preceding platoon of the traffic but is not yet too close to it, it is considered to be in a *comfortable (normal) car-following condition* and its following speed is determined by Eq. (2b). When the vehicle gets very near to the *close-following condition* (Gipps, 1981), its driver becomes ready to apply emergency brake with a maximum deceleration (d_n) should the vehicle in front brake suddenly at a rate $\hat{d}$. The speed of the close-following vehicle is determined by Eq. (2c). The speed of vehicle n at time $t+\tau$ is chosen as the minimum of the above three speeds derived from Eq. (2a–c). The acceleration of vehicle n is then calculated as:

$$a_n(t+\tau) = [v_n(t+\tau) - v_n(t)]/\tau \tag{3}$$

2.1.4. Simulation outputs

There is a wide range of traffic performance measures that a traffic model can provide. These are generally represented in terms of spatially and temporally aggregated measures of journey time, delays, queues, etc. The traffic microsimulation models can output, for each individual vehicle, the second-by-second space-time trajectory, speed and acceleration of the vehicle from its origin through to its destination. The latter information can then be coupled with a modal emission model to calculate the second-by-second exhaust emissions produced by the vehicle. But a more efficient way would be to calculate the instantaneous emission in-situ within the traffic simulation loop (see Section 2.3).

2.2. The new modal emission measurements and modelling

The following pollutants were modelled: nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon dioxide (CO_2) and particulate matter (PM). These particular pollutants were chosen based on their potential health impacts and external costs. For other pollutants, the potential health impacts are much smaller and their contribution to the total burden of exposure to pollutants is expected to be minimal. This is for example the case for carbon monoxide (CO) which, though a very toxic gas, hardly causes any negative effects at low levels in the open air.

Carbon dioxide is modelled because of its effect on global climate change and its immediate link with fuel consumption. It is known that 1 kg CO_2 corresponds, on average, to 0.4 l of fuel, although there is a small difference between petrol and diesel in our model. Emissions of SO_2 could also be easily calculated from the sulphur content of the fuel (50 ppm) and fuel consumption. It is omitted from this study because external costs of SO_2 and sulphates have become almost negligible due to the increased use of low sulphur and sulphur-free fuels.

New second-by-second emission functions were developed for use with traffic microsimulation models. They are based on actual measurements with several instrumented vehicles driving in real urban traffic situations. Measurements were made with the VOEM system (De Vlieger et al., 1994; Lenaers, 1996, 2000; Lenaers et al., 2003). Table 1 gives an overview of all vehicles measured and the amount of measurements analyzed to derive the emission functions. In total, measurements of twenty-five vehicles have been used, of which six are buses and two trucks. From the seventeen cars, data from twelve petrol and five diesel cars complying with different emissions standards (Uncontrolled, EURO-1, EURO-2 and EURO-3) have been analyzed.

Table 1
The instrumented vehicles and the measurements used to derive the emission functions

Vehicle	Type	Fuel	EURO-type	Measurements (s) analyzed
Toyota Yaris	Car	Petrol	3	2634
Volkswagen Polo	Car	Petrol	3	5461
Skoda Octavia	Car	Diesel	3	4819
Alfa Romeo 156	Car	Diesel	2	2365
Citroën Jumper	Car	Diesel	3	10,074
Ford Escort	Car	Petrol	1	11,398
Toyota Corolla	Car	Petrol	1	2517
Ford Fiësta	Car	Petrol	1	13,209
Opel Corsa	Car	Petrol	1	12,782
Renault Clio	Car	Petrol	1	13,194
Peugeot 205	Car	Petrol	0	14,055
Toyota Celica	Car	Petrol	1	8704
Opel Astra	Car	Petrol	1	9318
VW Golf	Car	Petrol	1	10,747
VW Golf	Car	Diesel	1	5302
Renault Mégane	Car	Petrol	2	11,642
Volvo 850	Car	Diesel	1	6831
Van Hool A600	Bus	Diesel	2	1154
MAN A12	Bus	Diesel	2	7803
MAN A12	Bus	Diesel	2	5066
MAN NL202F	Bus	Diesel	1	9978
Van Hool A300D	Bus	Diesel	1	6654
Van Hool 3154	Bus	Diesel	2	5449
Iveco Eurocargo	Truck	Diesel	2	1638
Volvo FH12-420	Truck	Diesel	2	4514

Euro-type: 0 = uncontrolled, 1 = EURO-1, 2 = EURO-2, 3 = EURO-3.

From this data, emission functions for each vehicle are derived with instantaneous speed and acceleration as parameters using non-linear multiple regression techniques. A general function is found for all pollutant emission and is shown in Eq. (4):

$$E_n(t) = \max[E_0, f_1 + f_2 v_n(t) + f_3 v_n(t)^2 + f_4 a_n(t) + f_5 a_n(t)^2 + f_6 v_n(t) a_n(t)] \tag{4}$$

where $v_n(t)$ and $a_n(t)$ are the instantaneous speed and acceleration of vehicle n at time t as calculated from Eqs. (2) and (3). E_0 is a lower limit of emission (g/s) specified for each vehicle and pollutant type, and f_1 to f_6 are emission constants specific for each vehicle and pollutant type determined by the regression analysis.

For certain pollutants different functional forms are derived for acceleration (defined as $a_n(t) \geq -0.5$ m/s^2) and deceleration (with $a_n(t) < -0.5$ m/s^2). This approach is used whenever visual inspection of the data plot reveals a clear distinction in the scatter for acceleration and deceleration. Fig. 2 shows an example of a function derived through non-linear regression and its comparison with the measurements.

Based on the fleet-specific shares of vehicle types concerning fuel type, engine capacity and EURO-type, an average function is then calculated for each pollutant. The functions (including the lower emission limit and the constants) are determined for the four pollutants and for cars, heavy duty vehicles (HDV, diesel) and buses (diesel). The results are presented in Table 2. Each function is then used to predict the emissions of a car and a trip not included in the data set used for the regression analysis to check the accuracy of the predicted value. Second-by-second comparisons have revealed a very good match for the timing of the peak emissions. Predictions for total trip CO_2 are within the 95% confidence limits (based on the cars used). Comparisons for other pollutants are not possible because of the large variation between individual brands and types.

We have primarily used measurements made in urban traffic (with low speeds) in getting the functional forms and the variables in Eq. (4). This is considered sufficient for the purpose of evaluating the effects of speed management in urban networks (see Section 3). It is possible that the emission functions for highway traffic (at higher speed) differ from those for urban traffic. The traffic on highways is insufficiently represented in the data set used here. This means that the typical U-shaped profile of emissions per kilometre as a function of speed is reproduced very well at high speeds. In general, emissions continue to decrease with speed. As more data on highway traffic are included, this pattern changes (Broekx and Int Panis, personal communication).

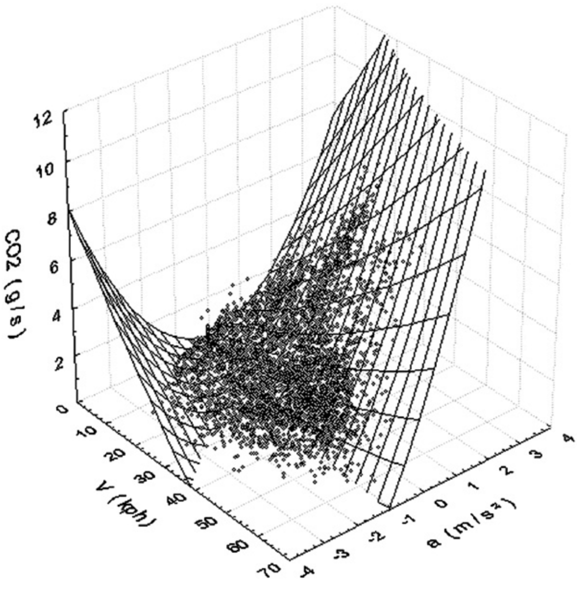

Fig. 2. CO_2 emission as a function of speed and acceleration (the surface) versus measurements (points) for a EURO-3 diesel car (Skoda Octavia).

Table 2
Emission functions for the 2010 fleet of urban traffic

Pollutant	Vehicle type	E_0	f_1	f_2	f_3	f_4	f_5	f_6
CO_2	Petrol car	0	5.53e−01	1.61e−01	−2.89e−03	2.66e−01	5.11e−01	1.83e−01
	Diesel car	0	3.24e−01	8.59e−02	4.96e−03	−5.86e−02	4.48e−01	2.30e−01
	LPG car	0	6.00e−01	2.19e−01	−7.74e−03	3.57e−01	5.14e−01	1.70e−01
	HDV	0	1.52e+00	1.88e+00	−6.95e−02	4.71e+00	5.88e+00	2.09e+00
	Bus	0	9.04e−01	1.13e+00	−4.27e−02	2.81e+00	3.45e+00	1.22e+00
NO_x	Petrol car ($a \geq -0.5$ m/s^2)	0	6.19e−04	8.00e−05	−4.03e−06	−4.13e−04	3.80e−04	1.77e−04
	Petrol car ($a < -0.5$ m/s^2)	0	2.17e−04	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
	Diesel car ($a \geq -0.5$ m/s^2)	0	2.41e−03	−4.11e−04	6.73e−05	−3.07e−03	2.14e−03	1.50e−03
	Diesel car ($a < -0.5$ m/s^2)	0	1.68e−03	−6.62e−05	9.00e−06	2.50e−04	2.91e−04	1.20e−04
	LPG car ($a \geq -0.5$ m/s^2)	0	8.92e−04	1.61e−05	−8.06e−07	−8.23e−05	7.60e−05	3.54e−05
	LPG car ($a < -0.5$ m/s^2)	0	3.43e−04	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
	HDV	0	3.56e−02	9.71e−03	−2.40e−04	3.26e−02	1.33e−02	1.15e−02
	Bus	0	2.36e−02	6.51e−03	−1.70e−04	2.17e−02	8.94e−03	7.57e−03
VOC	Petrol car ($a \geq -0.5$ m/s^2)	0	4.47e−03	7.32e−07	−2.87e−08	−3.41e−06	4.94e−06	1.66e−06
	Petrol car ($a < -0.5$ m/s^2)	0	2.63e−03	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
	Diesel car ($a \geq -0.5$ m/s^2)	0	9.22e−05	9.09e−06	−2.29e−07	−2.20e−05	1.69e−05	3.75e−06
	Diesel car ($a < -0.5$ m/s^2)	0	5.25e−05	7.22e−06	−1.87e−07	0.00e+00	−1.02e−05	−4.22e−06
	LPG car ($a \geq -0.5$ m/s^2)	0	1.44e−02	1.74e−07	−6.82e−09	−8.11e−07	1.18e−06	3.96e−07
	LPG car ($a < -0.5$ m/s^2)	0	8.42e−03	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00
	HDV	0	1.04e−03	4.87e−04	−1.49e−05	1.27e−03	2.10e−04	1.00e−04
	Bus	0	1.55e−03	8.20e−04	−2.42e−05	1.86e−03	3.21e−04	1.36e−04
PM	Petrol car	0	0.00e+00	1.57e−05	−9.21e−07	0.00e+00	3.75e−05	1.89e−05
	Diesel car	0	0.00e+00	3.13e−04	−1.84e−05	0.00e+00	7.50e−04	3.78e−04
	LPG car	0	0.00e+00	1.57e−05	−9.21e−07	0.00e+00	3.75e−05	1.89e−05
	HDV	0	2.14e−04	3.35e−04	−2.22e−05	2.07e−03	1.80e−03	2.27e−04
	Bus	0	2.23e−04	3.47e−04	−2.38e−05	2.08e−03	1.76e−03	2.23e−04

Nevertheless the functions are considered sufficiently accurate for use in the urban networks discussed in this paper.

To validate the results of our instantaneous emission functions, total emissions for the morning peak period at an urban study site in the city of Ghent are estimated and compared with three validated emission models (COPERT III, MEET and HBEFA). The results show that there are large differences among the results from these well-established models which could not be explained by the operator choices or parameter settings used. The MEET model produces higher estimates of emission than the other two models. The estimates using our new emission functions are found comparable with those from the MEET model for NO_x (Fig. 3) but are higher than MEET estimates for CO_2, PM and VOC.

A new emission module is then developed to integrate the emission functions of Eq. (4) and associated parameter values of Table 2 in DRACULA. The basic structure distinguishes four driving modes: acceleration, deceleration, cruising and idling. We allow a small margin of acceleration in defining the mode of cruising. A vehicle is considered in cruising mode if its acceleration is within the range of $[-0.5\ \mathrm{m/s^2}, 0.5\ \mathrm{m/s^2})$. Emissions in cruising are calculated as the emission at that specific discrete speed with a zero acceleration. Emissions at idling are calculated by setting both speed and acceleration to zero in the corresponding emission functions.

2.3. The integrated traffic and emission model

For each individual vehicle that travels during the period studied, DRACULA simulates their second-by-second movements through the network following their chosen routes. The basic modelling structure is as follows:

1. [Initialization] Set up the network. Set the study time period of the day. Set up the traffic policy measures.
2. [Global supply conditions] For each link in the network, set the link free flow speed randomly, with means representing annual averages and a user defined variance to represent daily variability due to weather and lighting for example.
3. [Local supply conditions] For any incident occurring on the day, allocate the incident on the link/lane affected and give its start and finish time.
4. [Start simulation] Set simulation clock at $t=0$.
5. [Vehicle generation] Each individual that is to travel on the day enters the network at their origin node. Each vehicle is given a set of individual

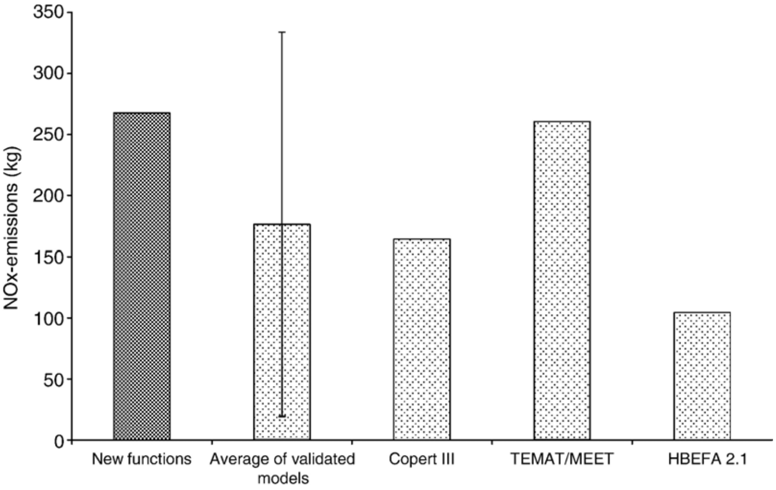

Fig. 3. Comparison between the results of the new emission functions and three frequently used emission models in total NO_x.

characteristics drawn randomly from pre-specified distributions.

6. [Vehicle movement] Each vehicle is moved along their chosen route from origin to destination. Their speeds and positions are updated according to car-following, lane-changing and gap acceptance rules, and traffic regulations at intersections.
7. [Emission calculation] Calculate emissions and fuel consumption for each individual vehicle according to their instantaneous speed and acceleration, and the modal emission functions of Eq. (4) and Table 2.
8. [Data collection] Collect statistics on travel time, delays, speed, flow, queue length, emissions and fuel consumption.
9. [Traffic control update] For each signalized junction, update the stage change-over clock according to desired signal plans (fixed plans or responsive). Check if other traffic management measures (such as variable speed message signs) are to be updated, if so, change accordingly.
10. [Time increment] Increment simulation clock at $t=t+1$. Return to step 5, until some condition is satisfied such as the simulation period is reached.

The new modal emission model is incorporated in the structure as Step [7], hence making it an integral part of the simulation iteration process. It is also possible to output the second-by-second trajectories of each individual vehicles and then make the emission calculation subsequently (e.g. Noland and Quddus, 2006), but it is clearly not as efficient as having the calculation embedded in the simulation iteration and only output the relevant aggregated measures of emission. In the case shown in Section 3, for a medium-sized network with a demand of 10,000 trips over the morning peak period and average journey time of approximately 30 min, the data to output from one simulation run would amount to 72 MByte—which is made up by the four essential measures (time, location, speed and acceleration) for emission calculation, per trip per second.

In order for such a model to be used to provide reliable predictions, it is important that the model is calibrated and validated against real-life observations. It is desirable to have a two-step approach to calibrate and validate an integrated model such as the one described here. Initially, the individual models (e.g. traffic simulation model and modal emission model) are calibrated independently (see description in Section 2.2). In the second step, the integrated model as a whole is calibrated and validated with simultaneous observation of traffic dynamics and pollutant emission. In this study, only the first step has been carried out. The values of the key parameters in the traffic model (e.g. those representing the driver–vehicle characteristics and the car-following behaviour) are chosen from calibrated source (Gipps, 1981) and published literature (ITE, 1982; May, 1990). For other parameter values used in the DRACULA traffic model, see Liu (2005a) and Bonsall et al. (2005). The overall traffic model of the case study network in Section 3 is calibrated using the observed aggregated traffic flow and average travel speed. The results of the calibration are presented in Section 3.2. As discussed in Section 4, greater effort is required to further develop and calibrate traffic emission models. Continued study of traffic dynamics and microscopic emission modelling features strongly in our future research plans.

3. Evaluation of an advanced speed control system

While in theory the above microscopic traffic emission model could be applied to studies of long-term average trends in traffic emissions, it is in the evaluation of the environmental impacts of real-time, new technology-based transport policies that their application is most useful. In this section, we present an application of the methodology in evaluating a new technology to control driving speed, namely the Intelligent Speed Adaptation (ISA) system.

ISA is an in-vehicle electronic system which enables the speed of the vehicle to be regulated. Most often it is used to cap the maximum speed of the vehicle or to inform the driver of the prevailing speed limit of the road. It works by using a combination of the GPS navigation system to pinpoint the location of a vehicle on a digital road map with the speed limits for each street in the area and a device to choke off the fuel supply if the speed limit is exceeded.

The system will do away with the need for road humps and speed cameras. It also allows for different control speeds to be set for different times of day, roadway, traffic and weather conditions. On-road trials of various forms of ISA have been conducted in the UK, Sweden, the Netherlands, Spain and Belgium (Almquist et al., 1991; Duynstee et al., 2001; Várhelyi et al., 2004; Broekx et al., 2005) and in simulation studies (Liu and Tate, 2004). The studies have shown the potential of ISA to secure large reductions in accidents and injuries. In this experiment, we examine the effect of ISA on exhaust emissions and fuel consumption in an urban network.

3.1. Modelling of ISA

There are two main categories of ISA implementations in which vehicle speed is managed:

1. “Mandatory systems” which automatically limit a vehicle’s maximum speed to the prevailing speed limit on the road;
2. “Voluntary systems” which provide speed limit warnings to the driver and allow drivers to make their own decision as to whether to act upon the warning.

It is quite clear that only an individual vehicle-based microscopic simulation model such as DRACULA can fully represent the technology envisaged for ISA. Models of ISA are developed based both on the system design parameters and driver behavioural adaptation. The design parameters modelled are the prevailing speed limits on each road in the network, and the maximum deceleration put on a vehicle whose speed exceeds the speed limit.

The DRACULA model has been enhanced to represent:

- ISA-equipped vehicles, as a unique vehicle type which will respond to ISA speed control (in a mandatory system) or receive speed limit information (in a voluntary system);

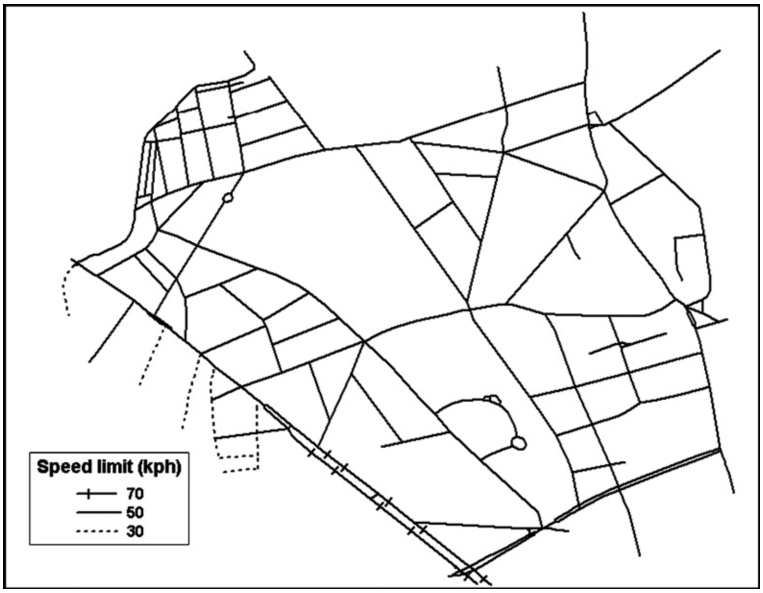

Fig. 4. ISA speed limits in the Ghentbrugge network.

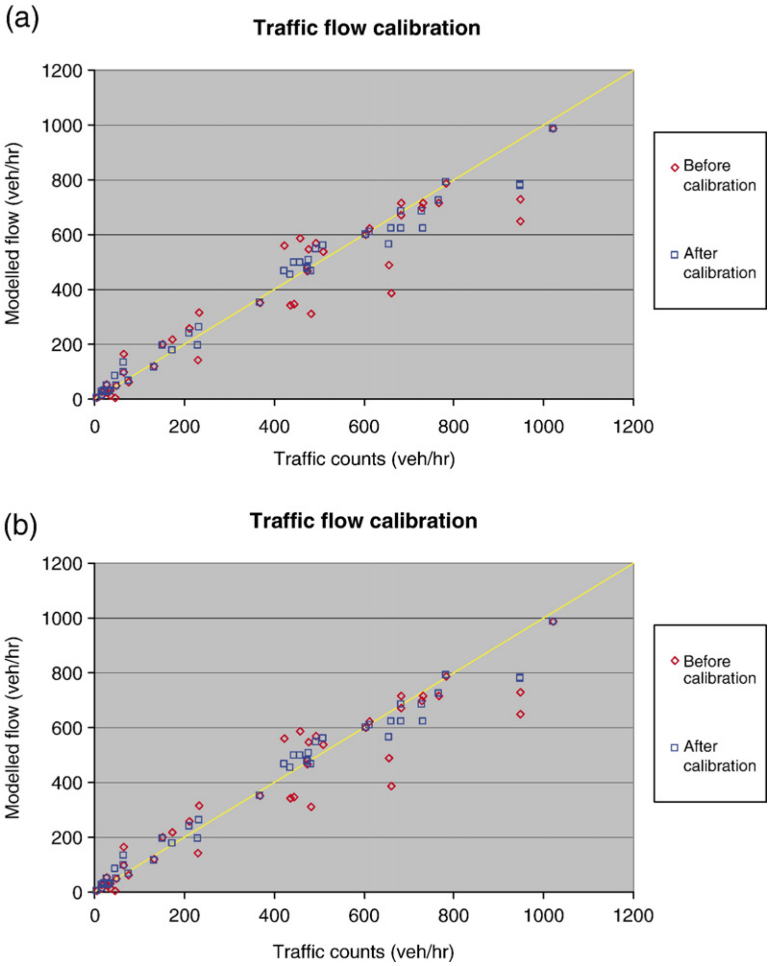

Fig. 5. Results of the model calibration on traffic flows (a) and speeds (b).

- Levels of system penetration (α), represented as a percentage of total fleet equipped with ISA devices;
- Driver compliance rate in a voluntary system (β), represented as a percentage of total ISA-equipped vehicles; and
- ISA speed limits (v_0), which is a function of road links in the network.

In the simulation, when a vehicle is generated, it is randomly selected to be an ISA vehicle or not according to the system penetration level α. In the voluntary system, the driver of an ISA vehicle is then randomly selected to be one who will always comply to the speed limit according to the driver compliance rate β. The detailed description of the models of ISA vehicles and driver compliance can be found in Liu et al. (2005).

Within an ISA controlled area, the speed of an ISA-equipped vehicle is determined not only by the normal car-following rule, but also by the ISA speed limit (in the case of mandatory ISA) and/or how the driver reacts to the speed limit information (in the case of voluntary ISA). Thus the speed of an ISA-equipped vehicle (for mandatory ISA) and a compliant ISA driver (for voluntary system) is calculated according to the following formula:

$$v_n^{\mathrm{ISA}}(t) = \begin{cases} v_n(t) & \text{if } v_n(t) \leq v_0^l \\ v_n(t) - d_0 & \text{else} \end{cases} \tag{5}$$

where $v_n(t)$ is the speed of vehicle n at time t calculated from the car-following Eq. (2), v_0^l is the ISA speed limit on road link l, and d_0 is a constant deceleration (m/s^2) applied to a ISA vehicle to reduce its speed.

Outside the ISA controlled regions, the drivers resume their manual control instantly and drive according to their normal driving behaviour. In the test

Table 3
The test scenarios

ISA scenario	Penetration rate (%)	Number of simulations (with different random speed)
Base (no ISA)	0	5
Mandatory ISA	20, 40, 60, 80, 100	5 of each rate
Voluntary ISA	20, 40, 60, 80, 100	5 of each rate

described in this paper we assume that the whole network is under ISA speed control.

3.2. The test scenario

3.2.1. Ghent network

Ghentbrugge is a suburban area, part of the town of Ghent and close to the city centre. It is a densely populated area. A lot of traffic is generated by local residents. Other traffic in this area is destined for the hospital, the school or shopping areas near the centre and northeast of the area. The majority of traffic, however, is generated by vehicles heading away from the city centre and vehicles heading towards the motorway E17 or neighbouring communities to the west. The network is also part of the ISA field trial area in Ghent and this is one of the reasons why this particular area has been chosen.

The road network of the Ghentbrugge study area as simulated in DRACULA is shown in Fig. 4. It is a small network of 2 by 2 km. It has 2 main roads and several smaller urban roads. A small section of the motorway, which has a legal speed limit of 70 km/h and which passes Gentbrugge at the southwest end of the study area, is included in the model. The legal speed limit for the main part of the network is 50 km/h. A few very short roads leading to external nodes have a speed limit of 30 km/h. Results from this road category are primarily determined by the speed limits of the 50 km/h roads leading to them and therefore cannot be used to show the effect of ISA on 30 km/h roads in general. Results on these roads will therefore not be analyzed in further sections. In this study only the morning peak is presented.

The network is developed based on the network description and origin–destination travel demand data from an existing macroscopic traffic simulation model. Traffic counts and flows on the main roads and speed measurements at twenty-three locations in the network have been collected for the study. The microsimulation model developed is calibrated against the observed flows and speeds. The calibration with speeds is especially important to our estimate of the impacts of ISA in this study. Fig. 5 shows the calibration results. After calibration, the relative difference between observed and modelled flows and speeds are 9% and 6% respectively.

3.2.2. ISA test scenarios

In the simulation, the ISA systems are examined for their effects under different levels of system penetration in order to represent the transition period when only new vehicles will be equipped with ISA and to investigate the interactions between equipped and non-equipped vehicles. The ISA test designs are summarised in Table 3.

The evaluation is made on the effect of ISA on average speed and traffic emissions in the whole network. It was expected that by imposing a maximum speed limit, ISA would reduce the overall average speed which in turn would also reduce emissions from the traffic.

3.3. Test results and analysis

3.3.1. Effects on speed

Average speed reduces by less than 1 km/h for all scenarios tested (Table 4). Effects on 70 km/h roads are smaller than effects on 50 km/h roads because less speeding occurs on 70 km/h roads in the base scenario. Standard deviation of speed reduces slightly for all scenarios compared with the base scenario. This is the effect one can expect as implementation of ISA will reduce not only speeding but also speed variation.

3.3.2. Effects on emissions and fuel consumption

Because the effect of implementation of ISA on speed is limited, effects on emissions and fuel consumption are also expected to be limited. Effects could however be more significant as most emissions are highly influenced by acceleration behaviour and this

Table 4
Average and standard deviation in network total travel speed (in km/h)

Scenario	Speed limit							
	50		70		50		70	
	V	S.D.	V	S.D.	ΔV	ΔS.D.	ΔV	ΔS.D.
Base	28.9	16.8	36.7	23.7				
Man 20%	28.6	16.8	36.7	23.7	−0.3	0.0	0.0	0.0
Man 40%	28.6	16.6	36.5	23.6	−0.3	−0.2	−0.2	−0.1
Man 60%	28.5	16.5	36.4	23.6	−0.4	−0.3	−0.3	−0.1
Man 80%	28.4	16.4	36.5	23.5	−0.5	−0.4	−0.2	−0.2
Man 100%	28.2	16.3	36.5	23.5	−0.7	−0.5	−0.2	−0.3
Vol 20%	28.8	16.8	36.6	23.7	−0.1	0.0	−0.1	0.0
Vol 40%	28.6	16.8	36.6	23.7	−0.3	0.0	−0.1	0.0
Vol 60%	28.5	16.7	36.6	23.7	−0.4	−0.1	−0.1	−0.1
Vol 80%	28.4	16.8	36.7	23.7	−0.5	0.0	−0.1	0.0
Vol 100%	28.3	16.7	36.7	23.6	−0.6	−0.1	−0.1	−0.1

V = mean speed, S.D. = standard deviation, Δ = difference to base scenario.

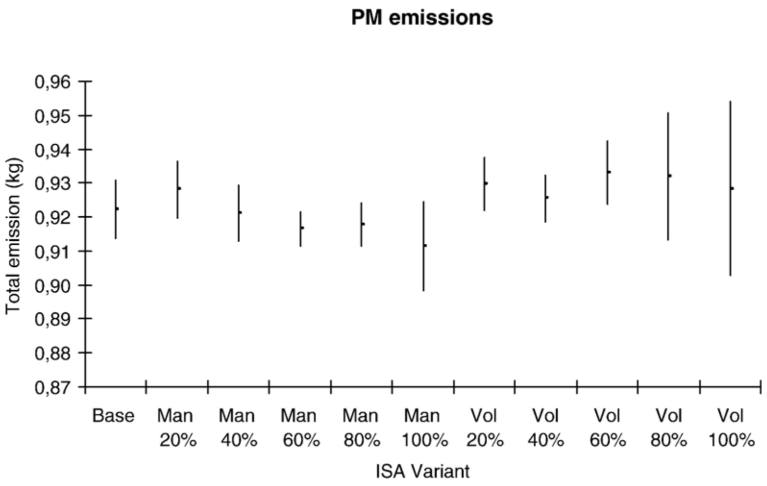

Fig. 6. Emissions of PM of the total network during the morning peak period. The average values are shown in dots and the standard deviations in bars.

behaviour is expected to change more than speed. This is especially the case when the acceleration of aggressive drivers will be influenced by mandatory ISA.

Effects on modelled tailpipe emissions of PM are found to be small (Fig. 6). As stated earlier, high acceleration causes PM emissions to increase significantly. Reducing these high acceleration levels compensates for the fact that emissions per kilometre increase with a decrease in driving speed. The average PM emissions appear to decrease slightly due to the implementation of mandatory ISA. When voluntary ISA systems are implemented, driving behaviour of the aggressive drivers with high acceleration levels is not influenced and the average emissions remain unchanged.

NO_x emissions can also be influenced by acceleration. The simulated effects for this pollutant are more difficult to interpret as functions used for diesel and petrol cars differ considerably (Fig. 7). For diesel cars, emission per kilometre driven decreases until about 30 km/h and then increase at higher speeds. For petrol cars emission per kilometre decreases at higher speeds at all speeds. Because 54% of person cars are diesel cars in the Belgian network, both emission functions influence the results.

There are large variations in the modelled NO_x emissions between the five randomized simulation runs. The variability overlaps and suggests that the differences due to ISA are not significant. However, the mean values of most scenarios appear to be higher than that of the base scenario and emissions from voluntary ISA are higher than emissions from mandatory ISA. There is no clear correlation between the system penetration rates and the emissions.

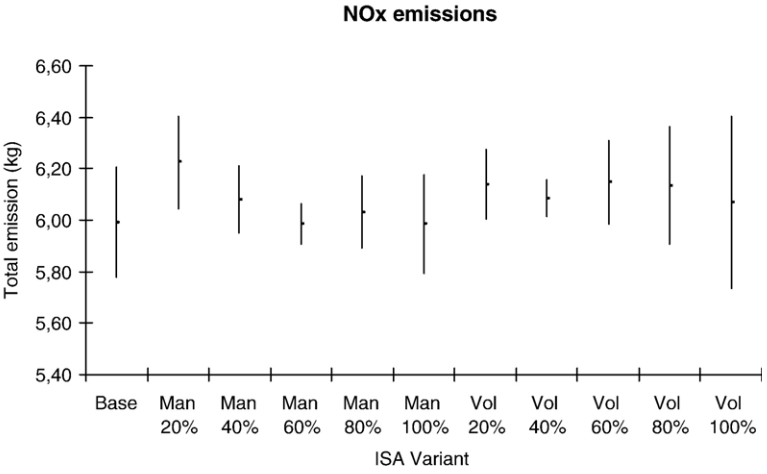

Fig. 7. Emissions of NO_x of the total network. Symbols are as in Fig. 6.

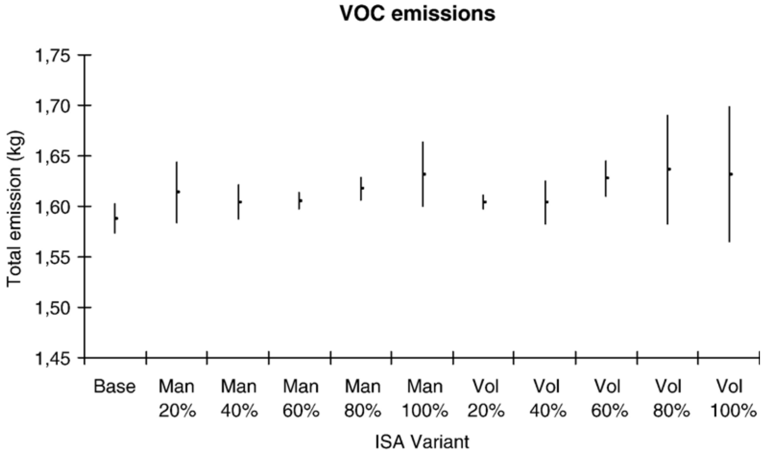

Fig. 8. Emissions of VOC of the total network. Symbols are as in Fig. 6.

The average emissions of VOC are shown to increase with the implementation of ISA (Fig. 8). Emissions of VOC are not significantly influenced by acceleration behaviour. At higher speeds, emissions per kilometre decrease. With increasing ISA penetration, the average travel time increases slightly and the average driving speed decreases. This causes VOC emissions per kilometre to increase. As the total driven distance remains the same, total emissions will rise.

CO_2 emissions per kilometre tend to decrease in urban networks when speed goes up. Acceleration levels also have a large impact on CO_2 emissions. The simulation results show that there appears to be some variation in the average CO_2 emissions with ISA, but again differences are small (Fig. 9). Given the variability in model results due to the stochastic simulation runs, we conclude therefore that there is no significant impact on fuel consumption.

3.4. Discussion of the test results

The simulation tests of the ISA show that, as expected, there is a significant (even though the level is small) reduction in *average* speed with increasing ISA penetration rates. The effect of ISA on emissions is, however, unexpected. There is no statistically significant effect on NO_x and PM emissions, and on fuel consumption (as represented by the CO_2 emissions). There is only a small increase in VOC emissions with increasing ISA penetration rates.

From the emission function in Eq. (4) we can see that the emissions depend not only on vehicle speed, but also

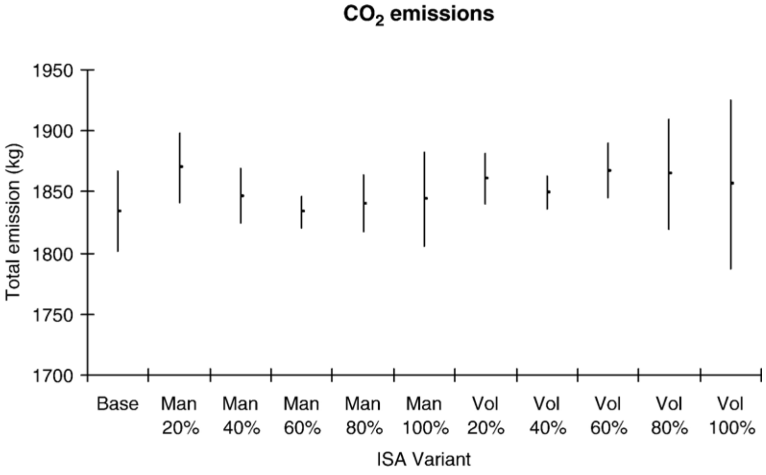

Fig. 9. Emissions of CO_2 of the total network. Symbols are as in Fig. 6.

on acceleration and deceleration of the traffic. The study network is an urban network which contains a number of signalized intersections and minor, residential roads leading to major roads whereby traffic has to stop or slow down either for the traffic signals or to give-way to major road traffic. This implies that acceleration and deceleration occur frequently in this network. The effect of these acceleration and deceleration movements is an increased emission. On the other hand, a decreased average speed with ISA will result in a decreased emission. The two effects may cancel each other out and result in the non-significant or small impact of ISA on emissions concluded from the simulation tests. Similar trade-offs in emission from traffic signal control settings have also been found by Coelho et al. (2005) who showed that on the one hand, signal settings that resulted in stopping a larger fraction of speed violations yields higher emissions. On the other hand, a change in driving behaviour by inducing speed reduction results in decrease in pollutant emissions.

4. Discussion

Macroscopic modelling is used to estimate fleet emissions on large geographical scales (e.g. at regional level or nationwide). This type of models uses the average speed as the main traffic parameter to determine emissions and therefore can only provide a long-term average measure of traffic emission. Microscopic models, on the other hand, are able to estimate the instantaneous emissions, often on a second-by-second basis and are therefore more suited to evaluate the environmental impact of real-time transport policies. Unlike macroscopic models, microscopic models are also able to adequately capture the effects of driving style and vehicle dynamics on emissions. Vehicle dynamics play a very important role when studying the impacts of speed and safety related traffic measures on vehicle emissions and fuel consumption. A traffic microsimulation model is able to provide the necessary estimates of driving behaviour and driver-specific speeds can be simulated in real time. This is an enormous improvement compared with a single average speed for trips and road sections employed in macroscopic emission models. Microscopic emission modelling does however have one significant drawback. The input data required for such models, such as the vehicle characteristics and driving behaviour, are greater than for macroscopic models. In addition, validation of such detailed models is more complicated. Most of the validations to date have been conducted against the measured traffic counts and speeds. Rarely have validations made directly on modelled acceleration and deceleration. Efforts are required to further calibrate and validate the methodologies before they can be reliably used as the basis for emission estimation.

Several authors have found it very difficult or impossible to construct instantaneous emission functions by including acceleration (as the most straightforward variable that describes dynamics) as an input variable for COPERT-like emission functions. The results of multiple non-linear regression techniques (e.g. Cornelis et al., 2005) or even more advanced non-parametric statistics are rather disappointing. From this point of view the methodology used in this study is only a first step in instantaneous emission modelling. Other methodologies such as modelling based on detailed engine characteristics (Pelkmans et al., 2004) and engine-to-wheel relationships may prove to be more suitable in the future to be linked with traffic microsimulation models. Data requirement will however be even greater and much more research effort is needed to predict emissions at a microscopic level. In addition, further emission modelling should also recognise the most appropriate unit of measures for the study of health impact of traffic. For example, studies have shown a strong association between particulate matters (in particular PM2.5) with health (e.g. Pope et al., 2002) and that the important measure is the particle numbers rather than the mass of emission.

The simulation results of ISA speed management show a small but significant reduction in average speed with increasing ISA penetration. However, the analysis of the impact of ISA on pollutant emission and fuel consumption proves to be a more complex issue. For the study network, the frequent acceleration and deceleration movements in the network cancelled out, or significantly reduced, the effect of the reduced average speed on emission. The case study is a clear demonstration that the analysis of the environmental impacts of speed control is very complicated. Simple estimation of the effect of any traffic management and control policies on average speeds is insufficient to determine the effect on emissions. Moreover, vehicle acceleration and deceleration are important factors in determining traffic induced emission.

The effects of ISA on the emissions of a total network appear to be much smaller than had been expected. The preliminary analysis presented here will therefore be repeated on other networks in the future to confirm this result and to identify factors that may contribute to differences between networks and fleets in different countries.

Acknowledgements

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Appendix A. List of notations used in the paper

n	Vehicle number in a single stream of traffic; it is preceded by vehicle number $n-1$
τ	The reaction time of the driver (measured in second)
$v_n(t)$	The speed (m/s) of vehicle n at time t
v_n^{des}	The desired speed (m/s) of the driver of vehicle n
$a_n(t+\tau)$	The acceleration (m/s^2) of vehicle n at time $t+\tau$
$a_n^{\max}$	The maximum acceleration (m/s^2) which the driver of vehicle n wishes to undertake
d_n	The maximum deceleration (m/s^2) that the driver of vehicle n wishes to undertake ($d_{\mathrm{n}}<0$)
$\hat{d}$	An estimate of d_n (m/s^2) employed by the driver of vehicle n ($\hat{\mathrm{d}}<0$)
$x_n(t)$	The location of vehicle n at time t (in metre)
$s_n(t)$	The distance gap (m) between vehicle n and $n-1$, which is calculated as $[x_{n-1}(t)-x_n(t)-L_{n-1}]$
L_{n-1}	The physical length (m) of vehicle $n-1$
$s_n^{\min}$	A minimum distance (m) at which the driver of vehicle n wishes to keep when in stationary
C_0	The sensitivity of the drivers, a constant (s^{-1})
c_1, c_2, and c_3	The car-following parameters
E_0	The lower limit of emission (g/s)
$E_n(t)$	The emission of vehicle n at time t
f_1 to f_6	The emission factors
α	The ISA system penetration rate (%)
β	The driver compliance rate (%) in a voluntary ISA system
v_0^l	The ISA speed limit (m/s) on road link l
d_0	A constant deceleration (m/s^2) applied to the ISA vehicles ($d_0<0$)

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