Assessment of the impact of speed limit reduction and traffic signal coordination on vehicle emissions using an integrated approach

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ABSTRACT

This paper examines the effects of two traffic management measures, speed limit reduction and coordinated traffic lights, in an area of Antwerp, Belgium. An integrated model is deployed that combines the microscopic traffic simulation model Paramics with the CO2 and NOx emission model VERSIT+. On the one hand, reductions in CO2 and NOx emissions of about 25% were found if speed limits are lowered from 50 to 30 km/h in the residential part of the case study area. On the other hand, reductions in the order of 10% can be expected from the implementation of a green wave signal coordination scheme along an urban arterial road.

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1. Introduction

The increased amount of road traffic in urban areas over the last few decades has meant that controlling congestion and vehicle related emissions have become major challenges for city planners. Congestion increases travel times and idling, and because of this, urban regions are facing increasing concentrations of local air pollutants. Related to this, there has also been an increase in atmospheric carbon dioxide. A number of traffic management measures have been considered and some implemented in cities, such as diverting traffic from peak hours to off-peak hours using congestion pricing, reducing speed limits, coordinating traffic lights along major arterials, replacing signalized intersections with roundabouts, or even adding additional lanes where expanding the road network is feasible.

It is widely accepted that if the number of acceleration and deceleration events associated with stop-and-go traffic is reduced, fuel efficiency increases and emissions are reduced. One action has been that optimized signal timing and coordinated traffic lights are increasingly applied along major arterials, in order to smoothen traffic flow. Usually, systems are designed to create green waves along arterial roads facing high demands. Alternatively, speed reductions, such as through the introduction of zones with a 30 km/h speed limit, are becoming popular for protecting residential areas, as they provide benefits in terms of road safety, traffic diversion, as well as smoother flows and reduced emissions.

Because it is often not feasible to employ a trial-and-error method for assessing the environmental effects of traffic management measures, microscopic simulation models are increasingly employed for this purpose.1 Microscopic traffic models consider the behavior of individual vehicles, which are modeled to follow empirically based rules for car following, lane changing and overtaking (Helbing, 2001). They allow to estimate the impact of detailed measures, because the influence of braking and acceleration is taken into account. However, they require a large amount of detail in input data on road layout, signal tim-

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1 De Coensel et al. (2007), for example, examined the case of noise emissions and Smit and McBroom (2009) air pollutants.

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ings, traffic counts, etc., and are therefore mainly useful to study traffic management measures within small to medium sized areas, such as a part of a city. Computational models for estimating pollutant emissions that return realistic results for the stop-and-go behavior of vehicles in urban environment have not been available until recently. Here we examine the potential environmental impacts of traffic management measures in Antwerp using a microscopic traffic model in combination with a state-of-the-art air pollution model.

2. Methodology

2.1. The study area

The study area, “Zurenborg”, is located in the southeastern part of the 19th century city belt of Antwerp, Belgium. Fig. 1 shows a map of the region. In the east, the area is bounded by the R1 freeway that has a speed limit of 100 km/h, and a major road, the R10 or “Singel”, with a speed limit of 70 km/h. In the southwest, the area is bounded by a railway track. In the north, the area is bounded by a major arterial road, the N184 or “Plantin en Moretuslei”, which connects the city of Antwerp to the west side of the area with suburban areas in the east. This road has two lanes in each direction, and implements traffic signal coordination. More in particular, during morning rush hour, all signals along this road operate at the same cycle time (60–90 s intervals, depending on the presence of pedestrians or buses), and the temporal offset of the cycle of each intersection is set such that vehicles traveling from east to west encounter only green lights, when driving at the desired speed of 50 km/h. A similar traffic signal setting is applied in the reverse direction during the evening rush hour. Traffic intensity during morning rush hour, from east to west, varies between 700 and 1000 vehicles/hour, depending on the segment that is considered (vehicles also enter along the side streets). The triangular area within the eastern, southwestern and northern borders is mainly residential, with an overall speed limit of 50 km/h.

2.2. Microscopic traffic simulation model

We use Quadstone Paramics, a commercially available microscopic traffic simulation tool, to simulate traffic conditions. A network of the triangular case study area is constructed on the basis of geographic information system (GIS) data and aerial photographs, which supply the detailed positions of all roads and buildings in the area. Network wide traffic demands are calibrated for the morning rush-hour, based on traffic counts made available by the Flemish Department of Mobility and Public Works. Traffic signal parameters (cycle times, signal offsets between intersections, etc.) were set according to the actual situation, based on data obtained from the Antwerp police department. Light- and heavy-duty vehicles are considered, which were linked to the respective emission classes of the emission model. The railway passing through the area is not modeled. The simulation period is 1 h, with a timestep of 0.5 s. Vehicles are loaded onto the network at the edge roads along

![Diagram of study area](image_url)

*Fig. 1. Study area of “Zurenborg” in Antwerp, Belgium.*
the sides of the network, according to the traffic demand. During simulation, the position, speed and acceleration of each vehicle is recorded at each timestep, for subsequent calculation of emissions.

Although the microscopic traffic model is able to take into account a wide range of vehicle driving behavior, a number of factors that have an influence on vehicle speeds and accelerations cannot be fully embraced. Among those are the influence of pedestrians crossing the street, cars slowing down to park or cars leaving a parking spot, or the full extent of the stochastic component in driver’s behavior. Next to this, the traffic counts used to calibrate the model reflect the average situation during morning rush hour. Therefore, traffic counts and speed distributions measured at a single instant in time within the simulated region could significantly differ from those that are simulated. Nevertheless, as only average trends are usually considered, microscopic traffic simulation models are increasingly being applied for estimating the emissions from traffic flows. Earlier work has shown that, for emission modeling purposes, a reasonably good agreement between simulated and measured speeds and accelerations can be achieved (De Coensel et al., 2005).

2.3. Emission model

The instantaneous CO\textsubscript{2} and NO\textsubscript{X} emission of each vehicle in the simulation is calculated using the VERSIT+ vehicle exhaust emission model, based on the speeds and accelerations extracted from the traffic model. The latter model (Smit et al., 2007), is based on more than 12,500 measurements on vehicles of a wide range of makes and models, fuel types, Euro class, fuel injection technology, types of transmission, etc. It uses multivariate regression techniques to determine emission factors for different vehicle classes. As the model requires actual driving pattern data as input, it is fully capable of accounting for the effects of congestion on emission. A derived model was recently developed by TNO (Ligterink and De Lange, 2009), specifically targeted at a coupling with microscopic traffic simulation models. For this, emission parameters of vehicles of varying age, fuel type, etc. are aggregated into a prototypical vehicle emission model representing the average emission of the Dutch vehicle fleet. While there may be differences between individual vehicles, the model aims at predicting aggregates over a sufficiently large number of vehicles sampled from the Dutch vehicle fleet. Here the VERSIT+ light and heavy-duty vehicle classes representing the fleet in Dutch urban environments during 2009 are used. Finally, only overall emissions are considered; the dispersion of air pollutants is not modeled.

A small-scale validation of the dynamic properties of the emission model was carried out using VOEM, VITO’s on-road emission and energy measurement system (De Vlieger, 1997). Measurements of instantaneous speed, acceleration, CO\textsubscript{2} and NO\textsubscript{X} emissions were carried out using four diesel vehicles subjected to the MOL30 driving cycle, which is based on real driving behavior in urban, suburban and freeway traffic situations. Subsequently, the emission model was used to estimate the CO\textsubscript{2} and NO\textsubscript{X} emissions based on measured speeds and accelerations. Finally, both measured and estimated emission time series are compared. In general, a good dynamic agreement is found, with temporal correlation factors of 0.90 ± 0.030 for CO\textsubscript{2} and 0.72 ± 0.10 for NO\textsubscript{X} for all test vehicles, indicating that the model is able to capture the dependencies on speed and acceleration well. The somewhat lower correlations for NO\textsubscript{X} may be explained by the presence of an exhaust gas recirculation system in some of the vehicles.\footnote{Details of this validation can be found in Trachet et al. (2010).}

2.4. Validation of the integrated model

The accuracy of the estimated emissions using the combination of traffic and emission models is examined using data from a series of vehicle trips through the study area. A vehicle equipped with data logging devices was driven several times along the N184 on a typical working day. Instantaneous speed, throttle position and fuel consumption were gathered through the CAN-bus interface of the vehicle on a second-by-second basis, while the vehicle location was logged using a GPS device. Trip data for all light duty vehicles driving along the N184 is extracted from the microsimulation model. In both cases, only the part of the trip along the N184 is considered. Instantaneous emissions are calculated using the emission mod-
el, for both measured and simulated vehicle trips (Fig. 2). In general, a good agreement is found between them, suggesting that the accuracy of the integrated model is sufficient for estimating the effects of traffic management measures on emissions.

3. Simulation results

3.1. Reduced speed limits

As a first traffic management measure, the effect of a speed limit reduction is studied. Based on measures being considered by the traffic planning authorities of the city of Antwerp, speed limits are reduced from 100 to 70 km/h on the freeway, from 70 to 50 km/h on the Singel, and from 50 to 30 km/h on the other residential roads and the N184. For the latter, the traffic signal coordination is recalibrated for the lower speed limit to have a green wave as in the original scenario. The microscopic traffic simulation model applies dynamic traffic assignment: routes are chosen according to the instantaneous congestion conditions. Traffic demands are kept constant.

The changes in the distribution of instantaneous speeds and accelerations for vehicles driving within the residential part of the network (excluding the N184, R10 and R1) are seen in Fig. 3. Next to a reduction in average speeds, the speed distribution becomes narrower, coupled with a reduction in the occurrence of maximum acceleration events. Hence, the speed limit reduction results in a smoother traffic flow in the residential area. Maximum speeds are about 10% above the speed limits because the traffic model also accounts for speeding to resemble the actual situation as closely as possible.

Fig. 4 shows the corresponding change in distribution of instantaneous distance-based emissions for the light duty vehicles; the results for heavy-duty vehicles show a similar trend. The distance travelled by all vehicles within the residential area fell by 14.1% because of traffic rerouting, but CO₂ and NOₓ emissions fell by 26.8% and 26.7%. Consequently, a reduction in distance-based emissions is also seen in Fig. 4. For the vehicles moving along the N184, similar results are found. Although the distance travelled by all vehicles along the N184 only falls by 0.2%, still, a reduction in CO₂ and NOₓ emissions by 9.9% and 10.4% is recorded.

3.2. Effect of traffic light coordination

As a second traffic management measure, the effect of traffic signal coordination along the N184 is studied. The original situation, with implementation of a green wave from east to west, is compared to a scenario in which coordination is removed. To desynchronize the traffic signals, a small but random number of seconds (≤2) is added or subtracted from the

![Fig. 3. Normalized distributions of instantaneous speed and acceleration, for vehicles driving within the residential part of the network.](image1)

![Fig. 4. Normalized distributions of CO₂ and NOₓ emissions per km, for vehicles driving within the residential part of the network.](image2)
cycle times of all lights along the N184. This results in a wide range of waiting times and queue lengths at each intersection being encountered over the course of the simulation run, with the results representing the average over all possible schemes in which there is no signal coordination. Again, traffic demands were kept constant.

Fig. 5 shows the changes in the distribution of trip emissions for the light duty vehicles that drove along the N184, completing their trips during the simulation run; only that part of the trip along the N184 is considered. When the signal coordination is removed, the combined light and heavy-duty vehicles CO₂ and NOₓ emissions increase by 9.5% and 8.7% because of the more interrupted traffic flow.

4. Conclusions

An integrated approach coupling a microscopic traffic simulation model with a state-of-the-art instantaneous air pollutant emission model reaffirms the environmental benefits of reducing speed limits in residential areas. Reductions in CO₂ and NOₓ emissions of the order of 25% were found if speed limits are lowered from 50 to 30 km/h in residential area, on top of increased road safety that is expected from lower vehicle speeds. The study also finds that a reduction of the order of 10% in CO₂ and NOₓ emissions can be expected from the implementation of a green wave signal coordination scheme. However, traffic signal coordination also decreases travel times, and the effect of facilitating traffic flow may, in the long term, induce additional traffic with the potential side effect of offsetting some of the beneficial environmental consequences of signal coordination.

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References


