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 a case study area in Antwerp, Belgium. For this purpose, an integrated model that combines the microscopic traffic simulation model Paramics with the CO₂ and NO_x emission model VERSIT+ is constructed and validated. On the one hand, reductions in CO₂ and NO_x emissions in the order of 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.

Keywords: Microscopic traffic simulation, CO₂, NO_x, Speed limits, Traffic light synchronization, Green wave

1. Introduction

With the increasing amount of road traffic in urban areas in the last few decades, 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 air pollutants. Next to this, the rise of

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6 atmospheric carbon dioxide, which is a major greenhouse gas, has become a matter of
7 concern. A number of traffic management measures are therefore considered in vari-
8 ous cities, such as diverting traffic from peak hours to off-peak hours using congestion
9 pricing, reducing speed limits, coordinating traffic lights along major arterials, replac-
10 ing signalized intersections with roundabouts, or even adding additional lanes where
11 expanding the road network is feasible.

12 It is widely acknowledged that if the number of acceleration and deceleration events,
13 associated with stop-and-go traffic, is reduced, fuel efficiency increases and emissions
14 are reduced (El-Shawarby et al., 2005; Int Panis et al., 2006). On the one hand, op-
15 timized signal timing (Li et al., 2004; Pandian et al., 2009) and coordinated traffic
16 lights (Zito, 2009) are increasingly applied along major arterials, in order to smoothen
17 traffic flow. Usually, systems are designed to create green waves along arterial roads
18 facing high demands. On the other hand, speed reductions, such as through the in-
19 troduction of zones with a 30 km/h speed limit, are becoming popular for protecting
20 residential areas, as they provide benefits in terms of road safety, traffic diversion, as
21 well as smoother flows and reduced emissions (Int Panis et al., 2006).

22 Because it is often infeasible to employ a trial-and-error method for assessing the
23 environmental effects of traffic management measures, microscopic simulation models
24 are increasingly employed for this purpose; see e.g. De Coensel et al. (2007) for the
25 case of noise emissions or Smit and McBroom (2009) for the case of air pollutant emis-
26 sions. Microscopic traffic models consider the behavior of individual vehicles, which
27 are modelled to obey empirically based rules for car following, lane changing and
28 overtaking (Helbing, 2001). They allow to estimate the impact of detailed measures,
29 because the influence of braking and acceleration is taken into account. However,
30 they require a large amount of detail in input data (road layout, signal timings, traffic
31 counts, etc.), and are therefore mainly useful to study traffic management measures
32 within small to medium sized areas, such as a part of a city. Next to this, compu-
33 tational models for estimating pollutant emissions that return realistic results for the
34 stop-and-go behavior of vehicles in urban environment have not been available until
35 recently.

36 In the present paper, the effects of traffic management measures on the CO₂ and

37 NO_x emissions in a part of the city of Antwerp, Belgium, are evaluated. For this
38 purpose, a microscopic traffic model in combination with a state-of-the-art air pollutant
39 emission model is employed. In Section 2, the construction of the traffic network model
40 for the case study area is presented, together with a validation of the integrated model.
41 In Section 3, the effects of a speed limit reduction and of traffic signal coordination
42 on emissions are presented. The approach presented could be of inspiration for the
43 construction of guidance tools for urban planning practice.

44 **2. Methodology and validation**

45 *2.1. Case study area*

46 The case study area, called “Zurenborg”, is located in the southeastern part of the
47 19th century city belt of Antwerp, Belgium. Figure 1 shows a map of the region. In
48 the east, the area is bounded by the R1 freeway, on which a speed limit of 100 km/h
49 holds, and a major road (the R10 or “Singel”), with a speed limit of 70 km/h. In the
50 southwest, the area is bounded by a railway track. In the north, the area is bounded by
51 a major arterial road (the N184 or “Plantin en Moretuslei”), which connects the city of
52 Antwerp (situated at the west side of the area) with suburban areas in the east. This
53 road has 2 lanes in each direction, and implements traffic signal coordination. More
54 in particular, during morning rush hour, all signals along this road operate at the same
55 cycle time (60 s to 90 s, depending on the presence of pedestrians or buses), and the
56 temporal offset of the cycle of each intersection is set such that vehicles travelling from
57 east to west encounter only green lights, when driving at the desired speed of 50 km/h.
58 A similar traffic signal setting is applied in the reverse direction during the evening rush
59 hour. Traffic intensity during morning rush hour, from east to west, varies between 700
60 and 1000 vehicles/hour, depending on the segment that is considered (vehicles also
61 enter along the side streets). The triangular area within the eastern, southwestern and
62 northern borders is mainly residential, with an overall speed limit of 50 km/h.

63 *2.2. Microscopic traffic simulation model*

64 In this work, Quadstone Paramics, a commercially available microscopic traffic
65 simulation tool, is used as the modelling software. A simulation network of the tri-

Figure 1: Map of the case study area “Zurenborg” in Antwerp, Belgium. The triangular area bounded by the R1, the N184 and the railway forms the outline of the traffic simulation network. The circles along the N184 mark signalized intersections with coordinated traffic lights.

66 angular case study area was constructed on the basis of GIS (Geographic Information
 67 System) data and aerial photographs, which supplied the detailed positions of all roads
 68 and buildings in the study area. Network wide traffic demands were calibrated for the
 69 morning rush-hour, based on traffic counts made available by the Flemish Department
 70 of Mobility and Public Works. Traffic signal parameters (cycle times, signal offsets
 71 between intersections etc.) were set according to the actual situation, based on data
 72 obtained from the Antwerp police department. Two types of vehicles (light and heavy
 73 duty) were considered, which were linked to the respective emission classes of the
 74 emission model (see Section 2.3). The railway passing through the study area was not
 75 modelled. The simulation time considered was 1 h, with a timestep of 0.5 s. Vehicles
 76 are loaded onto the network at the edge roads along the sides of the network, according
 77 to the traffic demands. During simulation, the position, speed and acceleration of each
 78 vehicle is recorded at each timestep, for subsequent calculation of emissions.

79 It should be noted that, although the microscopic traffic model is able to take into

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

92 2.3. *Emission model*

93 The instantaneous CO₂ and NO_x emission of each vehicle in the simulation is cal-
94 culated using the VERSIT+ vehicle exhaust emission model, based on the speeds and
95 accelerations extracted from the traffic model. The VERSIT+ model, developed by
96 TNO (Smit et al., 2007), is based on more than 12,500 measurements on vehicles of
97 a wide range of makes and models, fuel types, Euro class, fuel injection technology,
98 types of transmission etc. The model uses multivariate regression techniques to de-
99 termine emission factors for different vehicle classes. As the model requires actual
100 driving pattern data as input, it is fully capable of accounting for the effects of con-
101 gestion on emission. A derived model was recently developed by TNO (Ligterink and
102 De Lange, 2009), specifically targeted at a coupling with microscopic traffic simula-
103 tion models. For this, emission parameters of different vehicles (with varying age, fuel
104 type etc.) were aggregated into a prototypical vehicle emission model representing the
105 average emission of the Dutch vehicle fleet. While there may be differences between
106 individual vehicles, the model is aimed at predicting measurement results aggregated
107 over a sufficiently large number of vehicles sampled from the Dutch vehicle fleet. In
108 this work, the VERSIT+ light and heavy duty vehicle classes representing the fleet in
109 Dutch urban environments during the year 2009 was used. Finally, it has to be noted

that only emissions are considered in this paper; the dispersion of air pollutants is not modelled.

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, CO₂ and NO_x emissions were carried out using 4 different 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 CO₂ and NO_x emissions based on measured speeds and accelerations. Finally, both measured and estimated emission time series were compared. In general, a good dynamic agreement was found, with temporal correlation factors $r^2 = 0.90 \pm 0.03$ for CO₂ and $r^2 = 0.72 \pm 0.10$ for NO_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_x may be explained by the presence of an Exhaust Gas Recirculation (EGR) system in some of the vehicles considered. More details on this validation can be found in Trachet et al. (2010).

2.4. Validation of the integrated model

The accuracy of the integrated model (combination of traffic and emission models) concerning the estimation of emissions is examined using data from a series of actual vehicle trips through the case study area. On the one hand, 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. On the other hand, trip data for all (light duty) vehicles driving along the N184 was extracted from the microsimulation model. In both cases, only the part of the trip along the N184 was considered. Subsequently, instantaneous emissions were calculated using the emission model, for both measured and simulated vehicle trips. Figure 2 shows the normalized distribution of calculated CO₂ and NO_x emissions per km, for the measured and simulated vehicle trips. In general, a good agreement was found between both, suggesting that the accuracy of the

Figure 2: Normalized distributions of CO₂ and NO_x emissions per km, for both measured and simulated vehicle trips along the N184.

integrated model is sufficient for estimating the effects of traffic management measures on emissions.

3. Simulation results

3.1. Effect of reduced speed limits

As a first traffic management measure, the effect of a speed limit reduction is studied. Based on potential measures that are currently 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 was recalibrated for the lower speed limit, in order to have a green wave as in the original scenario. It should be noted that the microscopic traffic simulation model applies dynamic traffic assignment: routes are chosen according to the instantaneous congestion conditions. Traffic demands were kept constant.

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 presented in Figure 3. It can be seen that, next to a reduction in average speeds, the speed distribution becomes more narrow, coupled with a reduction in the occurrence of maximum acceleration events. Hence, the speed limit reduction resulted in a smoother traffic flow in the residential area. Note that maximum speeds are about 10 % above

Figure 3: Normalized distributions of instantaneous speed and acceleration, for vehicles driving within the residential part of the network.

Figure 4: Normalized distributions of CO₂ and NO_x emissions per km, for vehicles driving within the residential part of the network.

159 the speed limits, as the traffic model also accounts for speeding, in order to resemble
160 the actual situation as close as possible. Figure 4 shows the corresponding change in
161 distribution of instantaneous distance-based emissions for the light duty vehicles; the
162 results for heavy duty vehicles show a similar trend. The total distance travelled by
163 all vehicles within the residential area reduced by 14.1 % because of traffic rerouting.
164 However, total CO₂ and NO_x emissions reduced by resp. 26.8 % and 26.7 %. Con-
165 sequently, also a reduction in distance based emissions was found, as can be seen in
166 Figure 4. For the vehicles driving along the N184, similar results are found. Although
167 the total distance travelled by all vehicles along the N184 was reduced only slightly
168 by 0.2 %, still, a reduction in CO₂ and NO_x emissions by resp. 9.9 % and 10.4 % was
169 found.

Figure 5: Distributions of total CO₂ and NO_x emissions, for (light duty) vehicle trips along the N184.

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 the scenario in which the coordination is removed. In order to desynchronize the traffic signals, a small but random number of seconds (≤ 2 s) is added to or subtracted from the cycle times of all traffic lights along the N184. This way, a wide range of waiting times and queue lengths at each intersection is encountered over the course of the simulation run. The results for this desynchronized scheme will thus represent the average over the results for all possible schemes in which there is no signal coordination. Again, traffic demands were kept constant.

Figure 5 shows the changes in the distribution of total trip emissions for all light duty vehicles that drove along the N184, and that completed their trip during the simulation run (only the part of the trip along the N184 is considered). It was found that CO₂ and NO_x emissions increased by resp. 9.5 % and 8.7 % when the signal coordination was removed (light and heavy duty vehicles combined). Consequently, the implementation of traffic signal coordination along the N184 resulted in a reduction of air pollutant emissions because of a smoother traffic flow.

4. Conclusions

An integrated approach to assess the impact of traffic management measures on CO₂ and NO_x emissions was presented. The methodology consists of coupling a mi-

190 crosopic traffic simulation model with a state-of-the-art instantaneous air pollutant
191 emission model. The latter was validated using a set of vehicles equipped with on-
192 board measurement tools, and a good agreement was found between measurements and
193 simulations. The above described approach differs from earlier work in that modelling
194 results are representative for a complete vehicle fleet (in this case the Dutch fleet), and
195 that this is accomplished through a well-calibrated emission model, instead of using a
196 wide range of different vehicle categories in the traffic simulation model, which makes
197 for an easier calibration of the latter.

198 This study reaffirms the environmental benefits of reducing speed limits in residen-
199 tial areas, which is caused by the combination of traffic rerouting and a smoother traffic
200 flow at lower average speed. Reductions in CO₂ and NO_x emissions in the order of
201 25 % were found if speed limits are lowered from 50 to 30 km/h in residential area,
202 on top of the increased road safety that is expected from lower vehicle speeds. The
203 present study also concludes that a reduction in the order of 10 % in CO₂ and NO_x
204 emissions can be expected from the implementation of a green wave signal coordina-
205 tion scheme. However, it has to be noted that traffic signal coordination also decreases
206 travel times, and the effect of facilitating traffic flow may, in the long term, induce
207 additional traffic ([Kitamura, 2009](#)). This side effect potentially offsets the beneficial
208 environmental consequences of signal coordination, or could even make the situation
209 worse ([Stathopoulos and Noland, 2003](#)).

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