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The Effect of Speed Limits and Traffic Signal Control on Emissions

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Abstract

Traffic signals strongly influence traffic in cities – in terms of delay but also in terms of the emissions emitted by traffic. This work analyzes the effect of different traffic control strategies on emissions like NO_x and PM_x. Simulations of an inner-city arterial show that reducing the speed limit leads to a lower production of NO_x and PM_x, but to an increase in delay. The impact of the traffic signal control on the emissions is less distinct: A carefully designed co-ordination reduces emissions, while a simple actuated control cannot improve traffic flow and therefore increases pollutant production.

Keywords: Traffic control; Emissions; Traffic simulation; Speed limit; Traffic signal control

1. Introduction

Traffic signals increase traffic safety, but do have a strong impact on traffic flow as well. The stopping of vehicles at red lights leads to deceleration and acceleration actions that consume energy, and therefore have an effect on the emissions of various pollutants, too. While a single signalized intersection can be optimized quite well either by an optimal fixed cycle strategy [13, 15], or by an appropriately timed actuated or adaptive signal control strategy, doing so in a network with multiple signalized intersections is more difficult, with presumably smaller gains. Line progression which runs along an arterial in one direction can in principle lead to zero delays; this is no longer possible in general if both directions are taken into account, or with in-flows and out-flows from side roads.

There is an ongoing discussion among stake-holders about the question to what degree pollutant production can be reduced by optimizing the traffic signal control in a network, and how speed limits do affect these gains. Several studies have found that signal control can have a significant effect on emissions. E.g., Chen and Yu [1] show that delay-optimized fixed-time signals in a small real-world network reduce emissions, whereas Stevanovic et al. [11]

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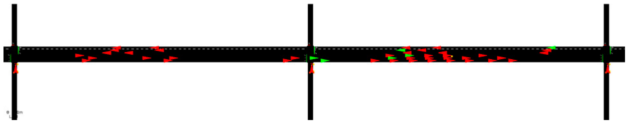

Fig. 1. Screenshot of the simulation of the three node artificial example.

even use emitted emissions as objective function for signal optimization. However, traffic control that improves travel times (e.g. as delay optimizing signal control) generally attracts more traffic which might reduce the gains in emission or even result in higher emissions in the long run, see [12]. The positive effect of reduced speed limits on emissions has been confirmed e.g. by Madireddy et al. [7] who show that reducing the speed limit in an arterial real-world network significantly reduces emissions, whereas a green wave coordination has a lower (but still positive) effect. Also, more complicated dynamical speed-limits decrease emissions [14].

This paper adds to these results by analyzing the effect of speed limits and signal control on emissions in two different simulation studies: One is based on an artificial network (section 3) and one is based on a real-world network in the city center of Berlin, Germany (section 4). It confirms that speed limits are able to reduce emissions (while increasing delay). On the other hand, the simulation studies show that the effect of signal control on emissions is less distinct: Simple delay reducing signal control strategies do not necessarily reduce emissions, while a carefully designed co-ordination is able to do so. The real-world example considered here constitutes an area where the speed limit was experimentally changed recently in the field – aligned with some monitoring of immissions and driven speeds. With this, the present study also adds to the discussion of the effectiveness of this specific speed limit reduction and delimits it to other possible traffic control strategies.

2. Methodology

This study uses the open source microscopic traffic simulation software SUMO [6] (version 1.8.0). SUMO can model the individual movement of all vehicles running in a certain study area, with a large degree of spatio-temporal resolution. Here, the temporal resolution has been set to 0.5 seconds.

A microscopic approach models the acceleration and deceleration of each vehicle, so calculating emitted emissions is straightforward: In each time-step, the vehicle type, the current speed v, and the acceleration a of each vehicle is passed to one of the emission models integrated in SUMO (in this study PHEMlight [5] is used). The emission model computes the corresponding emissions and fuel consumption [9, 15]. Summing them up gives the total production of the pollutants. Here, the focus is on NO_x [2] and PM_x (particulate matter) [4], which are the main source of concern.

3. First simulation study – an artificial network

As a benchmark, this section analyzes a simple set-up that allows for the most likely best possible gains by traffic control. This helps to evaluate the general possibilities of different control strategies.

3.1. Simulation Scenario

All results in this section are based on the same artificial scenario: A three lane, bi-directional road with three intersections as depicted in Fig. 1. Traffic enters in a random manner (by a Poissonian distribution) at the boundaries of this simple network. The main flow enters from the left, while a weaker flow runs in the opposite direction; it is about 40% of the flow in the left-to-right direction. In addition, the horizontal flow is disturbed by a 10%-flow entering from the South (i.e. from the bottom links) and turning right. For each vehicle that enters through one of the three intersections, there is (on average) one leaving the main stream to keep the flow (roughly) constant along the main line. The overall demand level is changed during the simulation from a small value up to a maximum value close to saturation. Each demand level is kept constant for one hour.

The three intersections are controlled by fixed-time signals; in the direction of the main flow, each signal switches by the offset Φ later to green than its upstream signal. This offset Φ is then varied in order to find the difference between

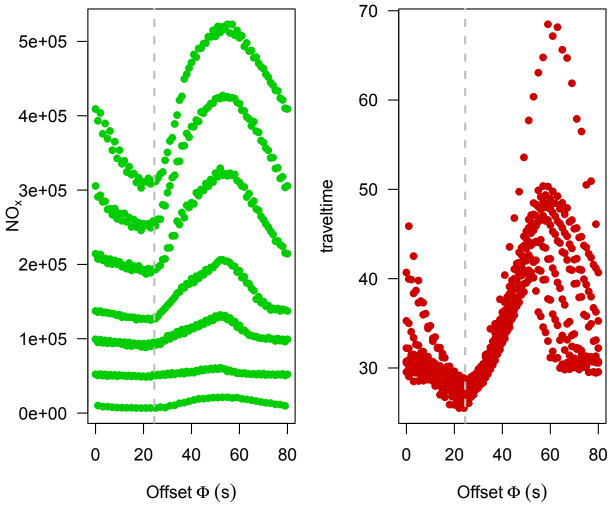

Fig. 2. NO_x and travel time as function of offset Φ. The different curves correspond to seven different levels of demand that where simulated. The one with the largest demand produced over-saturation and was therefore not used in Figs 3, 4.

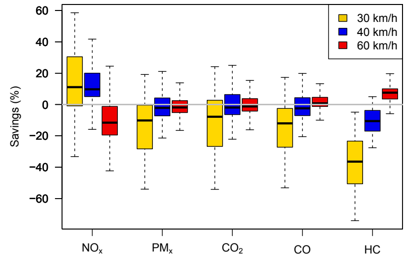

Fig. 3. Difference in various emissions based on the speed limit compared to the base case with a speed limit of 50 km/h.

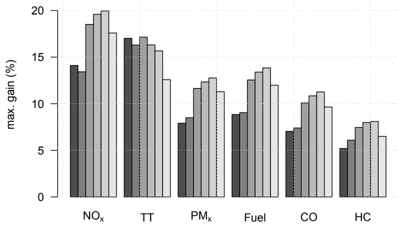

Fig. 4. Possible gains by an optimum traffic control strategy for different pollutants and travel time (TT). The six bars in each group belong to six levels of demand that have been used in the simulation.

the best and the worst possible progression, the best one is obtained when Φ is equal to the travel time between the two signals. Note, that optimizing the offset for one direction does not optimize (in almost all other cases) the other direction. Thus, the results achieved here depend on the (fixed) ratio of demand between the two directions.

The cycle time is set to 80 seconds, which is typical for German cities. However, it has not been optimized for the demand (e.g. lower demand levels would allow for smaller cycle times). Here, the concentration is on the effect of co-ordination. In addition, the main direction has a green time of 50 seconds at each intersection, while the crossing directions have 20 seconds. The intergreen time (i.e. all red time between switching phases) is set to 5 seconds.

The length of the two central links in the network depicted in Fig. 1 is 375 m. The simulation has been run with different speed limits ranging from 30 km/h (8.33 m/s), 40 km/h (11.11 m/s), 50 km/h (13.89 m/s), and 60 km/h (16.67 m/s). They result in travel times of 45, 33.75, 27 and 22.5 seconds, respectively. As observed in reality, vehicles in the simulation drive 10% faster on average with a distribution of preferred driving speeds whose coefficient of variance is 0.1. The emissions are calculated for a homogeneous fleet of vehicles with diesel EURO-4 motors.

3.2. Simulation results

Fig. 2 depicts the travel times per vehicle and the NO_x-production as function of offset Φ, showing the effect of Φ on both variables. The speed limit is 50 km/h, leading to the optimal Φ indicated by a vertical grey line in the plots. The different curves correspond to the different levels of demand that where simulated. The travel-time curve shows that the system has reached saturation with the highest demand, especially for an unfavorable choice of Φ. The NO_x-curves for the different demand levels are stacked on top of each other because they display the total emissions which depend on the demand.

These runs have been repeated with speed limits of 30, 40 and 60 km/h. Fig. 3 shows the difference in emissions in the whole network compared to the results of the base case run with the speed limit of 50 km/h. The change in the speed limit has only a small effect for most pollutants, except NO_x and HC. For the speed limit of 30 km/h, the NO_x emissions go down, while the ones for HC go up.

Another interesting metric is related to the question how much can be gained by traffic control. To answer this, the minimum and the maximum of each pollutant depending on the degree of coordination has been compared to each other, leading to a metric that is named *gain* in the following. Although it looks a bit abstract, it can be understood quite easily: the worst case (i.e. the worst possible co-ordination) is the one that leads to the maximum travel-time, NO_x-emissions, and the like. The best one corresponds to the optimal co-ordination. So, this metric gives an upper bound what can be gained by optimizing the co-ordination.

These results are displayed in Fig. 4. It can be seen that a gain of around 20% is achievable. This gain constitute the average over all links on the arterial. Of course, these results depend on the details chosen: If the crossing and opposing traffic had a lower demand, even larger gains would be possible.

Another interesting finding of Fig. 4 is that the impact of the co-ordination on NO_x-emissions and travel time has the same magnitude: the possible gains of both measures are similar in this study. This underlines again that it is important to consider emissions (and not only travel time) while optimizing traffic signals.

4. Second simulation study – a real-world network

To verify the findings from the artificial example from the previous section, the Leipziger Straße in Berlin, Germany, has been picked as a real-world example and study area. It is part of a policy experiment, where the Senate of the city of Berlin has reduced the speed limit from 50 to 30 km/h (starting 9 April 2018) in order to decrease especially the NO_x and PM_x-emissions.

4.1. Empirical study

After one year, and with the help of active speed control measures, a small reduction of NO_x has been observed. The range was 4. . . 6% with slightly higher gains during the Winter season [3]. In addition, no rat-run traffic had been reported, as was suspected beforehand based on model calculations. Note, that the gains can not directly be compared with the numbers from the simulation, since the simulation calculates emissions, while the measurement reports immissions. However, the sign of the change should be identical, and in fact, it is.

4.2. Simulation scenario

The simulation was run to learn more about this real-world experiment, and to generalize the results achieved. It consists of a very detailed description of the 7-node arterial, including the traffic signal plans, and a reconstructed traffic demand based on (manual) traffic counts at the intersections in the study area.

The network has been constructed from OpenStreetMap (OSM) [8] with the help of SUMO's `osmWebWizard`, and with some manual amendments to correct for inaccuracies of the import. Pedestrian as well as bike traffic have been ignored, since no data had been available for the study area. Also, the bus-traffic has not been modelled, because it consists of one bus-line with a frequency of 10 minutes and so its effect is limited.

The manual counts have been adjusted so that they fit together and yield the aggregated traffic load displayed in Fig. 5. From these traffic counts, detailed hourly OD-matrices have been derived which serve as basis for the simulated demand. The traffic counts cover the time from 7am to 7pm and, therefore, the period with the strongest demand. The simulated time has been extended by two hours before and after these core times to account for warm-up and cool-down times of the simulation, however, simulation results were analyzed from 7am to 7pm only.

Traffic signals at the simulated intersections are controlled by a fixed-time schedule that switches between four different plans, named *Night* (active from 2am to 5am, not simulated here), *Early* (active from 6am to 10am), *Day* (active from 10am to 2pm), and *Late* (active from 2pm to 8pm).

Altogether 14 different scenarios have been investigated. The most interesting six of them are specified in Tab. 6. The cases with a speed-limit of 30 km/h are named 3.x, the ones with 50 km/h 1.x. Each scenario has been run five times with different random seeds but only slight fluctuations between runs for the same scenario have been observed.

4.3. Simulation results

A detailed discussion on all simulation results can be found in [10]. Here, the focus is on the effect of the speed limit, and on the difference between the co-ordinated signal plans at work in the study area, and a simple actuated control that tries to adapt the traffic signal plans to the current demand pattern.

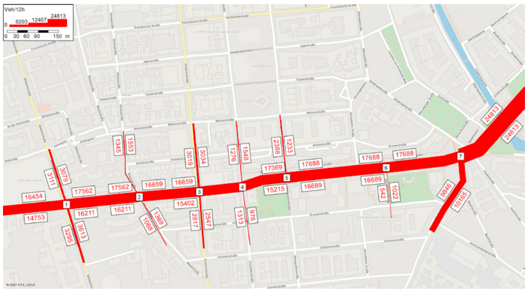

Fig. 5. Traffic load constructed from counts in the study area along Leipziger Straße, Berlin, Germany.

Fig. 6. Overview of some of the simulated scenarios. The speed factor indicates how much faster vehicles drive than the speed limit allows.

Case	Speed limit	Speed factor	Early	Late	Day	Actuated
1.1	50	1.0	x	x	x	No
1.2	50	1.3	x	x	x	No
1.3	50	1.3	x	x	x	Yes
3.1	30	1.0	x	x	x	No
3.2	30	1.3	x	x	x	No
3.3	30	1.3	x	x	x	Yes

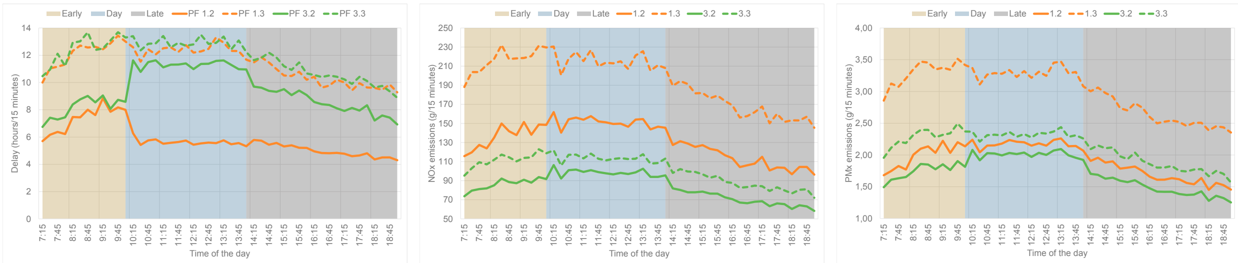

Fig. 7. Delay (left), NO_x (middle) and PM_x emissions (right) over the time of the day. The active signal program is given by the background color.

Fig. 7 illustrates the results for four of the scenarios; two each with a speed limit of 30 (green lines) and 50 km/h (orange lines). The solid lines are for the fixed-time signal plans, while the broken lines have been obtained with the actuated control implemented in SUMO.

The left part of Fig. 7 shows that reducing the speed limit from 50 to 30 km/h increases the delay. In addition, one can see that the actuated control works worse than the co-ordinated fixed-cycle plans. This means that the co-ordination is already quite good in this study area and, at least, can not be improved by the simple traffic actuated control implemented in SUMO. The middle and right part of Fig. 7 show the NO_x and PM_x emissions for the same scenarios. One can see that the speed limit of 30 km/h lowers the emissions, but again the actuated control does not constitute an improvement over the co-ordinated signal plans.

In addition, the simulation results from Rhode [10] indicate that if vehicles adhere to the speed-limits, the emissions would go down as well. This is especially true for the scenarios with a speed limit of 50 km/h. It certainly stems from a mismatch between the green wave co-ordination which assumes a certain speed, and the speed actually realized by the vehicles. While such an adherence to a given speed limit is difficult to achieve with a fleet of human controlled vehicles, this might point to additional gains from the introduction of autonomous vehicles.

5. Conclusion

This work shows a certain pattern in the dependency of traffic control and emissions that at least is robust between the artificial and the real-world example considered here. Most importantly, reducing the speed limit from 50 km/h to 30 km/h improves the situation especially with the two pollutants of interest, NO_x and PM_x; in the real-world experiment by up to 40 % and 10 %, respectively. In the synthetic scenario, the reduction in NO_x was smaller and around 10 %, while the PM_x emission even increased slightly. The difference can be attributed to the different vehicle fleets used: the synthetic scenario used one type of passenger cars only, while the real-world example used a more realistic fleet composed of passenger cars and trucks. Compared to reality, the emission gains seemed to be over-estimated, but they run in the same direction. And clearly, only immissions have been measured, while the simulation produces emissions. So one might expect that there is some dilution process at work that reduces the emission reductions found in the simulation.

The impact of the traffic signal control on the emissions observed in this study is less distinct: A carefully designed co-ordination reduced emissions in the illustrative scenario, while an improvement in traffic flow and therefore increased pollutant production could not been found in the real-world study. Note, however, that the signal control used in the field is already co-ordinated, and it is therefore hard to improve upon them, especially for an arterial network as it is considered here. In addition, the approach in the illustrative scenario gives some bound on what can be achieved by traffic signal control: in comparing the best to the worst case, it does not matter where the real value is, which is notoriously difficult to estimate; it nevertheless gives some number of improvement, which depends only weakly on demand itself (see Fig. 4).

Future work should investigate whether the dependencies of traffic control and emission, that have been found in this study, are also valid in more complicated, non-arterial real-world networks. Furthermore, improvements in delay might attract additional traffic in the long run, which again increases delay and also increases emissions, see e.g. [12]. It would be interesting to also analyze the long-term effects on delay and emissions of the traffic control methods considered in this study.

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