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Traffic signal coordination: a measure to reduce the environmental impact of urban road traffic?

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ABSTRACT

Coordinated traffic lights that implement green waves along major arterial roads are an increasingly used traffic management strategy for reducing travel times in urban context. The potential positive effect of this measure on emissions is often called upon as an additional support for its introduction. Although a smoother traffic flow will generally lead to lower air pollutant emissions, it will not necessarily lead to lower noise emissions. Because of the challenges associated with measuring the emissions caused by a stream of vehicles, up to now, little scientific research has been spent on the effects of synchronized traffic lights on emissions. This paper presents the results of a computational study on the effects of traffic signal coordination on vehicle emissions along an arterial road. The methodology consists of coupling a microscopic traffic simulation model with state-of-the-art models for instantaneous emission of noise, carbon dioxide, nitrogen oxides and particulate matter. The influence of traffic intensity, signal timing and signal coordination parameters is investigated through the simulation of a wide range of scenarios. The introduction of a green wave was found to reduce air pollutant emissions by up to 40% in the most favorable conditions, depending on traffic flow and signal timing settings. Sound pressure levels were generally found to decrease near the traffic signals, but to increase in between intersections.

Keywords: Microscopic traffic simulation, Green wave, Noise emission

1. INTRODUCTION

In urban areas, traffic management measures are increasingly used to moderate traffic congestion. Typical examples are the introduction of variable speed limits, local-express lanes, differentiated road pricing or optimized traffic signals. These measures generally try to improve the performance in terms of traffic throughput of the existing infrastructure. For the case of traffic signal coordination, systems are usually designed to create green waves along arterial roads facing high demands [1–2], and a number of techniques exist in order to accomplish this strategy. However, there are some conflicts of interest in the selection of objectives for signal timing optimization. For example, minimizing delays may cause longer waiting times for reverse-flow traffic. Moreover, the potential positive effects of green waves on noise and air pollutant emissions are often called upon as an additional support for their introduction. The rationale behind the claim of lowering (air pollutant) emissions is that congestion causes vehicles to function at sub-optimal speeds and accelerations, leading to incomplete combustion and additional emissions of NO_X, CO etc. Although the potential of green waves to reduce travel delays are widely accepted, the side-effects on emissions are however much less clear.

Studies on the influence of traffic light control often consider the emission at a single intersection only (see e.g. [3] and [4] for an overview of literature). When the effect of traffic signal coordination is considered, usually only the emission of a single vehicle is measured (using on-board equipment), or the immission caused by all vehicles is measured at a few locations. For the case of noise, Desarnaulds *et al.* [5] found that a green wave may lower the sound level near intersections by up to 2 dBA. For the case of air pollutants, measurement studies mainly report reductions in emissions (HC, CO) due to introducing traffic signal coordination, ranging from 10% [6] to 50% [7], although some studies also

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report increases in NO_X emissions, depending on the type of vehicle and the level of congestion [7].

An important reason for the relative lack of scientific data on emissions near intersections is that well-controlled field experiments during which emissions are measured are quite complex to carry out. Computational models are increasingly used for this purpose, also because emission models that return realistic results for the stop-and-go behavior of individual vehicles have become available recently. For the case of noise, as part of the SILENCE project, simulations were carried out for a road with 3 signalized intersections with $200m$ and $500m$ in between [8]. Only a single set of traffic light parameters and a single traffic intensity ($1440\ vehicles/h$) were considered. Results indicated that a green wave could lower sound levels by up to 4 dBA near the intersections, but could increase levels by as much as 3 dBA between intersections, due to higher average speeds. For the case of air pollutants, results of simulations range from a reduction in HC, CO and NO_X in the range of 50% [9], to reductions in the range of 10% to 20% [10–11], in line with the measurement results cited earlier.

In this paper, the influence of traffic signal coordination on vehicle emissions is studied in detail. In particular, a microscopic traffic simulation model is coupled with emission models for noise and air pollutants (CO_2, NO_X, PM_{10}). A setting consisting of an urban road with several consecutive signalized intersections is considered, and through the simulation of a range of scenarios, the influence of traffic demands and signal timing parameters on emissions is investigated. The present work differs from earlier studies in two aspects: (i) noise and air pollutants are considered jointly, using state-of-the-art emission models that are representative for a complete vehicle fleet, and (ii) the ranges of traffic intensities and signal timing parameters are larger than those considered in earlier studies.

2. METHODOLOGY

The aim of the simulation experiment described in this paper is to investigate the influence of signal parameters and traffic intensity on vehicle noise and air pollutant emissions along a typical urban arterial road with coordinated traffic signals. A main hypothesis is that the traffic signal coordination works as expected, effectively creating a green wave. The latter problem is purely traffic related, has been studied already extensively (see e.g. [12–14]), and is therefore not considered in this paper.

2.1 Microscopic traffic simulation

A traffic network, consisting of an arterial road with signalized intersections, was constructed using Quadstone Paramics; a schematic view of the setting is shown in Figure 1. A one-way arterial road with a single lane is considered, having a traffic demand $D\ [vehicles/h]$ and a speed limit $v_{max} = 50\ km/h$. Five traffic signals are located at regular distances $L = 200m$ from each other (this distance was chosen to be realistic for urban situations). Additionally, given the urban rush hour context that is considered, only a single light duty vehicle type is simulated. Nevertheless, emission calculations will be representative for a complete vehicle fleet (see Section 2.3).

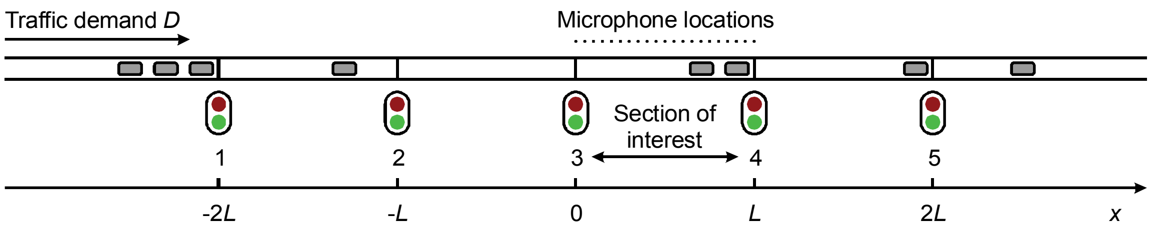

Figure 1 – Schematic view of the simulated arterial road.

In order to adhere to a generic methodology, default Paramics values and distributions were used for parameters such as driver aggression, awareness and reaction time, queue gap distance, target headways etc. The simulation time considered was 1 hour, with a simulation timestep $\Delta t = 0.2s$, but the actual simulations included additional 5-min periods for traffic build up and for trip completion. Actual simulated traffic flows $Q\ [vehicles/h]$ are calculated on the basis of the trips that started during the considered 1-hour period. Vehicles are loaded onto the network at a distance of $500m$ from the first traffic signal, randomly distributed in time according to a negative exponential distribution.

2.2 Traffic signal timing

The main parameters controlling the operation of a signalized intersection are the cycle time $\tau\ [s]$, the green split $\alpha \in [0,1]$ for the different approaches of the intersection, and the offset $\delta\ [s]$. The cycle time is defined as the sum of the durations of all distinct phases of the signalized intersection.

The green split for a given approach is defined as the ratio between the amount of green time and the cycle time. The green time is usually divided among the different approaches according to traffic intensity for each approach (there is only a single approach for the intersections in this case study). The offset of a signalized intersection is defined as the difference in time between the start of a cycle of this intersection and the start of a cycle of some reference intersection. It is used to provide signal coordination between consecutive intersections; the latter is usually accomplished through the use of a common cycle time (which may change over time), and this assumption is also held in this work. To further simplify the discussion, a common green split is assumed for all intersections, and no amber time is considered, i.e. the green time for each intersection is $\alpha\tau$, and the red time is $(1-\alpha)\tau$.

A series of scenarios was created by varying the parameters τ (30s to 90s), α (0.5 to 0.8) and D (50 to 2000 $vehicles/h$). Next to this, three signal coordination schemes were considered, labeled green, red and desynchronized. In the first scheme, the offsets δ for each intersection are set to create a green wave; vehicles will only have to stop at the first traffic light. In the second scheme, the offsets are set to create a red wave; vehicles will have to stop at every traffic light. In the third scheme, the offsets are set randomly, and in order to desynchronize the signals, a small but random number of seconds (< 2s) is added to or subtracted from the cycle times. This way, a wide range of waiting times and queue lengths at each intersection is encountered over the course of a simulation run. The results of this scheme thus represent the average over all possible schemes in which there is no signal coordination. Finally, the total number of unique traffic scenarios is equal to $7 \times 4 \times 40 \times 3 = 3360$.

2.3 Noise and air pollutant emission modelling

The output of a microscopic traffic simulation run consists of the instantaneous position, speed and acceleration of each vehicle at each timestep. Subsequently, the instantaneous emission of each vehicle is calculated. For noise emissions, the Harmonoise/Imagine emission model is used [15]. This model was calibrated to generate the noise emission of the "average" European vehicle: while there may be differences between different types of vehicles in terms of noise emission, the model will predict measurement results aggregated over a sufficiently large number of vehicles sampled from the European fleet (regional corrections can be applied). The light duty vehicle considered in this work corresponds to the Imagine category 1. When a vehicle trip through the network is considered, we may define the contribution L_W^{tot} of the particular vehicle, over the course of its trip, to the total sound power level (all vehicles travel the same distance). Trip results averaged over all simulated vehicles are noted $\langle L_W^{tot} \rangle$. This quantity relates directly to the sound power level used for noise mapping purposes. In particular, the hourly averaged A-weighted sound power level emitted by the simulated road segment equals $\langle L_W^{tot} \rangle + 10\log_{10} Q$, where Q is the traffic flow. Next to this, the L_{Aeq} at a number of locations along the simulated road segment is considered in this work. Levels are calculated at a height of 1.5m and at a distance of 7.5m from the road. The hourly L_{Aeq} is derived from the time series of instantaneous sound pressure levels, and is calculated assuming free field propagation conditions and only considering geometric divergence.

For the case of air pollutants, the instantaneous CO_2, NO_X and PM_{10} emission of each vehicle is calculated using the VERSIT+ vehicle exhaust emission model [16]. The VERSIT+ model is based on measurements on vehicles of a wide range of makes and models, fuel types, fuel injection technology, types of transmission etc. The model uses multivariate regression techniques to determine emission factor values for different vehicle classes. With the coupling with microscopic traffic simulation models in mind, a derived model was recently developed, in which emission parameters of different vehicles are aggregated into a prototypical vehicle representing the average emission of the Dutch vehicle fleet [17]. Note that this procedure is similar to the one used in the Harmonoise/Imagine noise emission model. In this work, the VERSIT+ light duty vehicle class representing the fleet in Dutch urban environments during the year 2009 was used. Similar to the case of noise emission, we will note the total emission of (part of) a vehicle trip through the network as CO_2^{tot}, NO_X^{tot} and PM_{10}^{tot}, and the trip results averaged over all simulated vehicles as $\langle \mathrm{CO}_2^{tot} \rangle$, $\langle \mathrm{NO}_X^{tot} \rangle$ and $\langle \mathrm{PM}_{10}^{tot} \rangle$.

3. SIMULATION RESULTS

Results for vehicles crossing the whole network will be partly determined by the behavior of vehicles in front of the first traffic signal, for which the signal coordination scheme does not make a difference. In order to assess the influence of the different coordination schemes, we will therefore focus, for the remainder of this work, on a particular section of interest, from stopline to stopline between the third and fourth traffic signal (see Figure 1). This section has a length of $200m$, and contains an acceleration, a cruising and a queueing zone. Results for this section of interest will reflect the influence of the traffic signal coordination normalized to a single traffic light.

3.1 Noise emission

Figure 2(a) shows the total emitted sound power level, averaged over all simulated vehicles, and only considering the section of interest, as a function of traffic flow and signalization scheme. It can be seen that introducing signal coordination will increase the total noise emission in all cases except for very low traffic flows, and this increase will be larger for high traffic flows, up to a value of 0.6 dBA. The implementation of a green wave will reduce the number of vehicles decelerating/accelerating near the traffic signals, but will also increase the average vehicle speed. From Figure 2(a) one can conclude that the decrease in noise emission caused by the former effect is more than compensated by the increase in noise emission caused by the latter effect. Finally, the difference between the two extreme cases of a green wave and a red wave can be up to 1.2 dBA for high traffic flows.

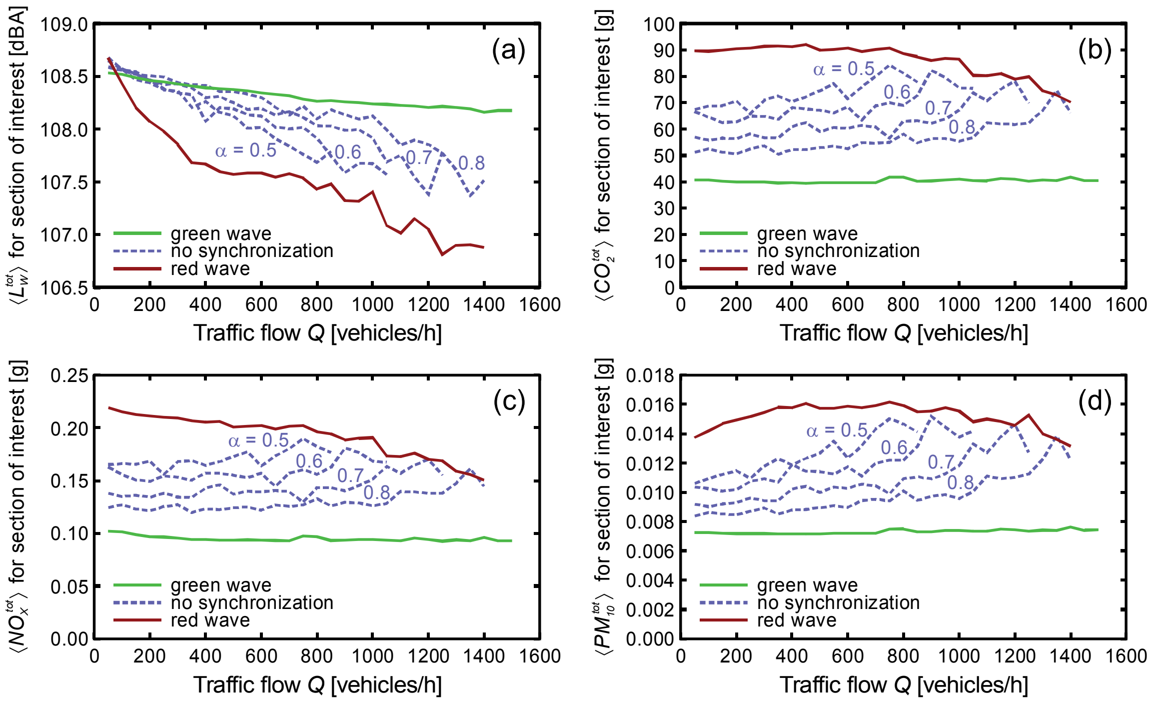

Figure 2 – Average vehicle emission for the section of interest, as a function of traffic flow, for various signal coordination schemes and green split. Results are averaged over cycle time and green split (for the green/red wave).

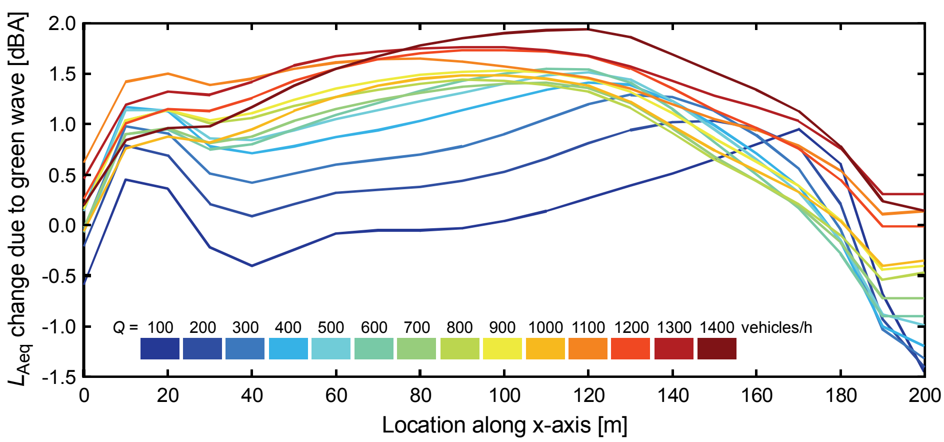

Figure 3 – Maximum change in L_{Aeq} along the section of interest (7.5m from road, height of 1.5m), due to the installation of a green wave, as compared to the red wave coordination scheme, as a function of traffic flow.

The effect of a green wave on the sound level may vary depending on the measurement location [8]. Figure 3 shows the difference in L_{Aeq} along the section of interest, between the green and red wave coordination schemes. It is found that the implementation of a green wave will result in a decrease in sound pressure level by up to 1.5 dBA near the signalized intersections ($x = 200m$), due to the reduction in number of accelerating vehicles, but will result in an increase by up to 2 dBA between intersections, due to higher average vehicle speeds. When compared with the desynchronized schemes, somewhat smaller effects are found: differences vary between a 1 dBA decrease and a 1.5 dBA increase (for green split $\alpha = 0.5$). When one takes into account the fact that the absolute value of the effect will be larger when the microphone is placed closer to the road, these extremes are roughly in accordance with those found in literature [5, 8]. From Figure 3 it also follows that a green wave will have the least detoriating effect on noise levels when traffic intensities are low. For higher intensities, the decrease in level near the signalized intersections will be somewhat less, while in between intersections, the increase in level will clearly be higher. The point of maximum increase also shifts with traffic intensity, because of the shift in queue length for the red wave scheme.

3.2 Air pollutant emission

Figure 2(b-d) shows the average amount of CO_2, NO_X and PM_{10} that vehicles emit while travelling over the section of interest, as a function of traffic flow, for various signal coordination schemes and green split. It was chosen to present the results in g rather than in g/km, such that the figures represent the absolute effect per intersection. In order to get the average emissions in g/km, one has to multiply the values in Figure 2 by a factor 5. One can see that, in contrast to the case of noise emissions, all types of air pollutant emissions decrease when a green wave is installed, which is in accordance with most results reported in Section 1. Because acceleration has a large influence on air pollutant emission, a potential increase of emissions caused by the increase in average vehicle speed is overcompensated by the smoother traffic flow resulting from the coordinated traffic signals. Irrespective of the type of air pollutant, the difference in emission between the desynchronized scheme and the red wave scheme reduces to zero for traffic flows close to capacity. This is caused by the influence of idling vehicles in the queue in front of a traffic light: while idling vehicles still emit a considerable amount of noise, the fraction of total air pollutant emission caused by idling vehicles is relatively small.

From Figure 2, one can estimate the reduction in percentages caused by the implementation of a green wave, although these estimates are strictly speaking only valid for a distance of $200m$ between traffic signals. Reductions vary between 10% for low traffic flows and high green split, and 40% for traffic flows near capacity and low green split, in accordance with the ranges reported in literature.

4. CONCLUSIONS

This paper reported on a study in which the influence of traffic signal coordination on vehicle noise and air pollutant emissions (CO_2, NO_X and PM_{10}) was investigated. A microscopic traffic simulation model was used, coupled with the recently developed Imagine and VERSIT+ emission models, which return results representative for the Dutch vehicle fleet. A simplified setting was considered, and through the simulation of a range of scenarios, the influence of traffic intensity, the signal coordination scheme and signal parameters on emissions was investigated. It was found that, for the considered setting, the introduction of a green wave could potentially lower the emissions of the considered air pollutants by 10% to at most 40% (if a perfect green wave is achieved, see below), a range which is in accordance with those reported in literature. The largest potential reduction occurs when traffic intensities are close to capacity and the green split is low. The introduction of a green wave resulted in all cases in an increase of the total emitted noise level, by up to 0.6 dBA. Sound pressure levels were found to decrease by up to 1 dBA near the traffic signals, but to increase by up to 1.5 dBA between intersections, when compared with the situation without signal coordination. Although applied to the specific case study of traffic signal coordination, the methodology presented in this paper could be used to study the effects of a wide range of intelligent transportation systems.

The simulation results presented in this work consider the extreme case of the perfect green wave, in which all vehicles are able to traverse the simulated road segment without having to stop. As such, this study focused on the limits of what can be expected by introducing signal coordination. However, in practice, introducing signal coordination will almost never result in a perfect green wave, and a wide range of literature exists that investigates the conditions for which coordinated signals are effective in creating a green wave (see the references in Section 1). Examples of important factors to consider, and which could lead to the green wave (partly) breaking down, are congestion, traffic entering from sidestreets, the distance between signalized intersections, the presence of slow or heavy vehicles (i.e. a distribution of target speeds), the presence of pedestrian crossings or the effect of prioritization of public transport. Some (theoretical) studies even suggest that signal coordination has little effect when traffic is saturated, and as a consequence, a green wave can not be created for saturated traffic [13].

Finally, it has to be noted that traffic signal coordination decreases travel times and increases road capacity; the effect of facilitating traffic flow may in the long term induce additional traffic [18]. This side effect potentially offsets the environmental benefits of signal coordination, or could even make the situation worse [19]. Predicting the amount of induced traffic is not a trivial task, because it depends on a wide number of intricately interrelated factors such as land use, accessibility or household's decisions concerning residence and job location [18]. On the other hand, introducing a green wave may be a way to make drivers stick to the speed limit more closely. In that case, noise emissions may not increase as much as predicted by the model.

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