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# Driving patterns reducing pollutant emission at traffic lights

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**Abstract**
The reduction of vehicular pollutant emissions is pursuit by different actors, from local traffic managers to vehicle manufacturers. One promising attempt are in-vehicle solutions that advice the driver to use a most environment-friendly speed and acceleration over time. One of them is GLOSA, Green Light Optimal Speed Advisory, which is based on vehicular communications. While mainly targeting on increasing comfort and traffic efficiency, GLOSA is assumed to decrease the amount of used fuel and emitted pollutants as well. This report distinguishes driving modes that differ in emission levels, shows optimal speeds and accelerations for these modes, and benchmarks existing models for approaching an intersection, including two new ones that lead to the lowest emissions.

**Keywords:**
pollutant emission, GLOSA, simulation.

## Introduction

Following the International Transport Forum ([1]), "*[the] Transport-sector CO2 emissions represent 23% (globally) and 30% (OECD) of overall CO2 emissions from Fossil fuel combustion. The sector accounts for approximately 15% of overall greenhouse gas emissions.*" Different actors are involved in reducing road traffic's environmental impact and its resource consumption, often forced to do so by law. In Europe, automobile manufacturers shall reduce their fleet emissions [2]. Cities try to keep the amounts of pollutant concentrations below the thresholds formulated in according regulations, such as [3]. Finally, pollutant generation is closely related to the consumption of fuel. As fuel price has increased in the past years, the reduction of fuel consumption, is also in the focus of end users – individuals as well as (e.g. logistics) companies. This large variety of actors and customers leads to an accordingly large amount of methods proposed for reducing emissions. They range from large-scale traffic management actions, such as the introduction of environmental zones, down to the development of more efficient engines.

The driver behaviour has a high influence on energy consumption and emissions as well. For urban scenarios, with speed limits below 80 km/h, pollutant emission is mainly dictated by the interaction with other vehicles and with traffic lights where the vehicle may need to decelerate or even halt and to accelerate afterwards. Some driver assistance systems that shall help the driver to choose the best speed for passing the controlled intersection have been developed in the past. The probably most prominent of them is the "Green Light Optimal Speed Advisory" (GLOSA) application, which is based on vehicular communication (V2X) technology.

GLOSA retrieves I2V[1]-messages from road side units (RSUs) located at traffic light controlled intersections. Two dedicated messages are sent by the traffic light: SPAT ("Signal Phase And Timings") about the current and future states of the traffic signals and TOPO ("Topology") about the controlled roads. Given this information, the vehicle may compute the speed to choose for arriving at the traffic light when it is green and to advice the driver accordingly. While GLOSA's main target is to increase traffic efficiency and comfort of driving by reducing accelerations and decelerations, it is as well reported to reduce vehicular emissions ([4]). In fact, the question whether GLOSA reduces emissions and/or to what degree is seen controversial.

The COLOMBO project ([5], [6]), co-funded by the European Commission, works on traffic management applications that use data gained from vehicular communications. The gradual increase in the number of vehicles equipped with V2X is taken into regard assuming that only a low number of vehicles is equipped with this technology. Working on according traffic surveillance and traffic light control solutions, a strong focus is put on environmental issues. Besides the implementation of a new state-of-the-art microscopic vehicular pollutant emission model PHEMlight [7], methods for optimizing traffic in means of reducing its environmental impact were investigated.

In this context, the GLOSA application has been evaluated. The basic technical functionality was well-covered in the literature. But a comparison of the different methods for computing the speed to choose seems to be missing. Thereby, such a comparison has been performed within the project and is presented in the following. Additionally, the project delivered two new models for approaching an intersection that could be used for computing the speed in GLOSA. Both use the information about the optimal velocities and accelerations that were determined using an instantaneous vehicular emissions model.

The remainder is structured as following. First, the driving process is decomposed into distinct "states", which are characterised by certain motoring and power demand conditions. For every state, the optimal behaviour in means of emission reduction is given. Afterwards, some GLOSA models from literature are given. This is followed by presenting both new models. Then, the models from the literature as well as the new ones are compared. The report ends with a summary.

## Physical and Technological Background

Emissions and fuel consumption[2] are mainly influenced by two factors: a) The amount of work the engine has to deliver to run the vehicle and its subsystems over a certain distance (e.g. road section) and b) the operation conditions of the engine and of the exhaust aftertreatment, which defines the efficiency of these components. The main parameters for operation conditions are: engine speed, engine power (or torque) and temperature of the engine and the exhaust aftertreatment systems. Second, the following driving states can be separated: a) Cruising (at constant speed), b) Acceleration, c) Deceleration, and d) Stop time.

Stop times with engine idling should be minimized, for example by turning the engine off during stand still like done automatically by Stop/Start systems of modern engines or by prolonging the deceleration time with engine in "fuel cut-off" mode. Though, choosing the speed and the acceleration has an effect on a vehicle's emission even if staying in the same driving state. To determine optimal accelerations and velocities for each of these states, simulations using the instantaneous emission model PHEM ([8], [9]) were performed. The

[1] Infrastructure-to-vehicle
[2] Fuel consumption is nearly 1:1 proportional to $CO_2$ emissions. Hence all conclusions discussed for emissions of $CO_2$ are also valid for fuel consumption. In the following, both measurements will be used as synonyms.

results are presented in the following subsections.

*Optimal Cruising Speed*

Driving at constant speed has been simulated with PHEM for several vehicle segments and in the range from 10 km/h to 120 km/h for determining the optimal cruising speed levels. Figure 1 exemplarily shows results for $CO_2$ emissions of a gasoline passenger car with the emission standard EURO 5.

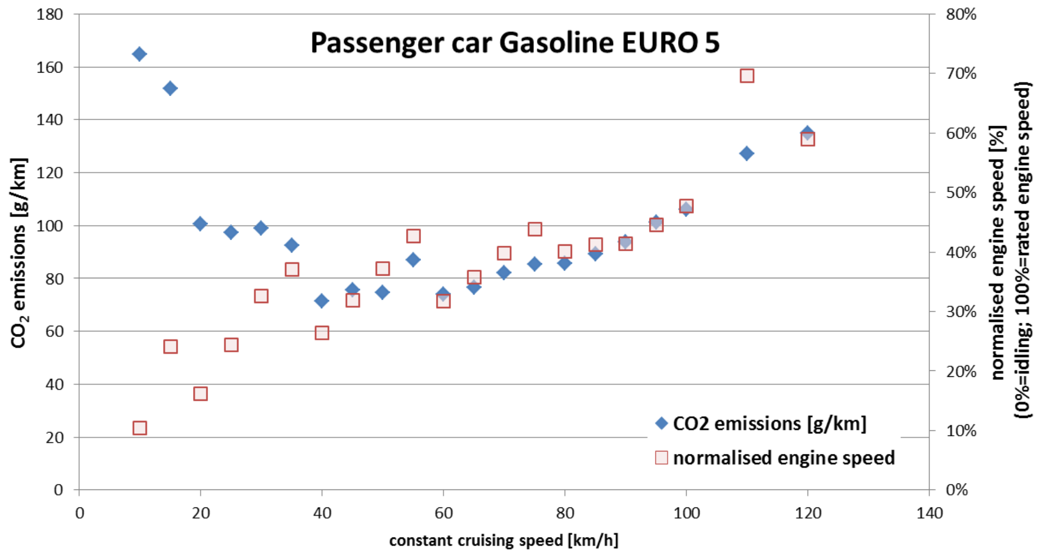



**Figure 1 - $CO_2$ emissions and engine speeds in constant speed driving (passenger car EURO5 Gasoline)**

Summarizing, one could say that for modern passenger cars the emission levels in terms of g/km for the main relevant exhaust gas components $CO_2$ and $NO_x$ are not sensitive to speed in the velocity range of about 40 km/h to 80 km/h. Driving at higher constant speeds than about 80 km/h increases the distance specific emissions mainly due to the growing influence of the aerodynamic drag, because the aerodynamic drag brakes the vehicle with a function of quadratic speed. Driving at constant speeds lower than about 40 km/h also increases emissions compared to the 40 km/h to 80 km/h range caused by low efficiencies of the engine and the powertrain system[3].

PHEM takes the gear choice into account. Independently from that, driving in a rather high gear (resulting in low engine speeds but above a minimum of approximately 1.5 times the engine idling speed) optimizes emission output and fuel consumption.

*Optimal Acceleration*

Acceleration behaviours were analysed with PHEM to find optimal acceleration values. The simulations were performed with models of average EURO 4 Gasoline and Diesel passenger cars. The test cycle consisted of an acceleration phase from stand still to 50 km/h and a cruising phase. The engine load was varied for the acceleration phases while the cruising time was adjusted towards a constant total driving distance of 500 m to ensure comparability. The

[3] In several studies the impacts of speed limits in the range of 30 km/h and 50km/h for urban roads were investigated. Extensive measurements and simulations have been performed in Baden-Württemberg ([10] and [11]). Main conclusion was that the speeds limits lower than 50 km/h do not necessarily lower emissions levels. Of course other arguments e.g. safety are also relevant for the selection of the appropriate speed limit for a certain area.

comparison shows that higher loads and therefore faster accelerations yield in higher fuel consumption. While the engine efficiency is generally higher at higher loads this effect is overcompensated by the higher energy demand needed to accelerate.

The main conclusion is that rather slow or moderate acceleration behaviour is favourable in terms of emission optimization. Early gear shifts are also advised during the acceleration phase. Beside the effects considered in the calculations here, a rather defensive acceleration behaviour in real world conditions should give additional benefits in occasions when - due to events not foreseeable at time of the acceleration phase - the intended cruising speed cannot be reached or can be held for a short time only. In these cases, a slower acceleration helps also minimizing the losses due to mechanical braking.

For the model calculations in COLOMBO characteristics for optimal acceleration behaviour had to be generated. This optimal acceleration behaviour has been defined by a function for target acceleration over vehicle speed. At low vehicle speeds an acceleration of 1 m/s² is advised. At high vehicle speeds (above 70 km/h), for minimizing emissions accelerations should not exceed 0.3 m/s².

*Optimal Deceleration*

Mechanical braking converts kinetic energy into useless heat, therefore any mechanical braking should be avoided. An optimal deceleration phase just uses the kinetic energy of the vehicle to overcome the air and rolling resistance and the drag losses of the engine and of the drivetrain system. This is done just by removing the foot from the gas pedal without pressing the brake pedal bringing the engine into a “motoring” state. In this operation condition modern engines stop fuel injection resulting in zero emissions output for all emission components[4]. A high gear should be engaged during motoring in order to minimize the drag losses in the powertrain. When the engine speed comes close to the idling speed, the next lower gear should be selected. Otherwise the engine would start to inject fuel for not falling below idling speed.

Such optimal deceleration curves have been calculated for all vehicle categories. For passenger cars deceleration rates at motoring are in the range of 0.3 m/s² to 0.6 m/s² depending on the driving speed. Heavy duty vehicles have the lowest deceleration rates at motoring conditions due to the inertia of the high vehicle mass.

*Validation*

The model-based computations presented before have been validated using real world driving data recorded in Austria. A route consisting of approx. 25 % urban, 30 % rural, and 45 % motorway roads has been driven by several drivers in “normal”, pronounced “moderate” and “aggressive” driving styles and the speed and gradient patterns have been recorded. In the next step, the optimal acceleration and deceleration behaviour described above has been applied to the trajectories. Afterwards, the emissions of the original trajectories have been compared to the optimized ones, using EURO4 Diesel car as example.

As expected, the highest reduction potential was calculated compared to the aggressive driving trajectory (-16 % fuel consumption, -21 % $NO_x$). Even for the moderate driver a more consequent “compliance” with the strategies as discussed above would result in a further emission reduction (-7 % fuel consumption, -3 % $NO_x$). Emissions of CO, HC and PM show other trends but in general are on a very low level for this vehicle technology. Important to

[4] Only a very small amount of hydrocarbons and particle emissions originating from lube oil is found in the exhaust gas during motoring.

note is that these comparisons only show a theoretical optimum because in real driving the behaviour is influenced and limited by traffic and it would not be possible to follow the optimal acceleration and deceleration behaviour all the time.

*Summary of Strategies for Emission Optimal Driving Behaviour*

The guidelines for emission optimal driving can be summarised as follows:
1. Drive as steady as possible ("cruising") in a velocity range of 40 km/h to 80 km/h.
2. Choose the highest possible gear in order to keep the engine speed low (but above about 1.5 times the engine idling speed).
3. Drive as "anticipating" as possible in order to avoid the use of mechanical brakes as much as possible.
4. Perform decelerations in engine motoring mode (i.e. without additional mechanical braking) and using a high gear. Shift back when engine speed comes close to engine idling speed.
5. Accelerate in a moderate way using high gears.
6. Avoid stop times with running engine.

All recommendations for conventional vehicles have been elaborated quantitatively as input dataset to simulations of "optimal driver behaviour". For hybrid vehicles yet no data set for PHEMlight was prepared. This is planned in a next step since priority was given to the actually dominant technologies.

**Investigated Approach Models**

In the following, models for approaching an intersection are presented and benchmarked. They will be named "approach models". The benchmark uses a single traffic light scenario. Every vehicle was simulated individually and has an initial velocity $v_{begin}$ of 50 km/h. The position of the traffic light is at $x=0$, which makes the initial vehicle position $x_i$ negative. For every simulated vehicle, the starting position $x_i$ is decremented by $v_{begin}*dt$ to obtain different arrival times at the intersection for the complete cycle time. The so obtained vehicle trajectories will be shown in the same figure. Thereby, they may overlap. Vehicle and simulation parameters have been chosen as following:
- $dt$ (time step): 1 s
- $v_{begin}$ (initial velocity): 13.89 m/s (~50 km/h)
- $v_{max}$ (maximum velocity): 13.89 m/s (~50 km/h)
- $a_{max}$ (maximum acceleration): 1.0 m/s$^2$
- $d_{max}$ (maximum deceleration): -4.5 m/s$^2$

The simulated traffic light has a cycle duration of 60 s, with a green time that starts at second 0 and ends after 25 s. It is followed by a yellow phase of 3 s duration. Thereby, the last phase (red) has a duration of 32 s.

*Simplified Real-World Behaviour with no Speed Advice*

A very simple approximation of real-world behaviour is to assume drivers run with a constant speed towards a traffic light and decelerate only if a) they arrive on red or b) they arrive on yellow and are distant enough from the intersection to halt in front of it. In both cases, we simply use the maximum deceleration rate.

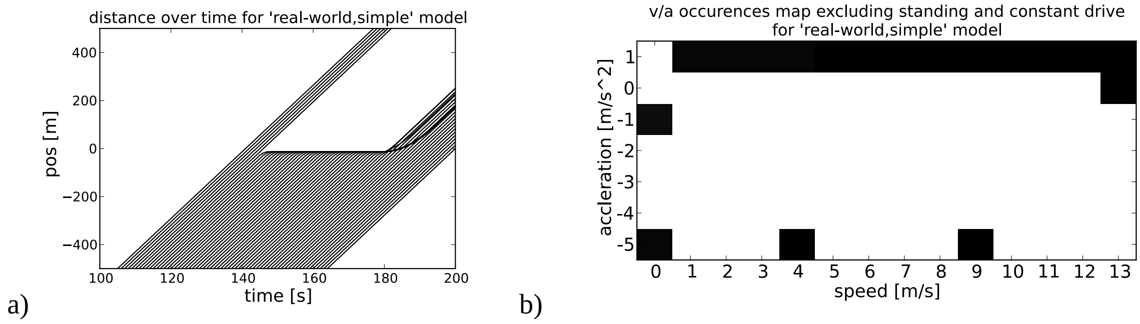



**Figure 2 - Simplified behaviour while approaching a traffic light; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs**

Figure 2 a) shows the trajectories of vehicles that approach a traffic light this way. Figure 2 b) shows the occurrences of acceleration/speed combinations for all simulated vehicles. Please note that all occurrences of $v$=0 and $v$>13.8 (near $v_{max}$) with $a$=0 are not considered; standing in front of the intersection as well as driving with $v_{max}$ are the most common speed/acceleration combinations and the other combinations would not be visible.

One may note that this model lacks any kind of pre-emption a driver may have regarding the state of the traffic light. It should be assumed that real drivers who approach a red light do not drive towards it and brake with the maximum deceleration of 4.5 m/s$^2$. Rather, they coast or brake earlier, because the state of the traffic light at arrival can be predicted. Thereby, this simplified model is rather the most still reasonable worst-case for reacting on a red traffic light. It is though supposed to be found in many microscopic traffic simulations including those used by the following references.

*GLOSA Approaches*

Only few of the available reports about GLOSA define the functions used to compute the speed to advice. [4] (“Wegener”) is one of them. It uses two methods to reduce the consumption of fuel. The first is realised by a “fuel-cut off” that takes place at a deceleration named $a_{fuelCutOff}$. This is an equivalent to the coasting behaviour described before. The second is the use of a start/stop-system that switches the engine off when halting for longer than a given time threshold ($t_{minEngineOff}$). The second method is neglected in the following, because the work presented here concentrates on the speeds to choose while approaching/starting at the intersection. Figure 3 shows the behaviour of the system described in [4].

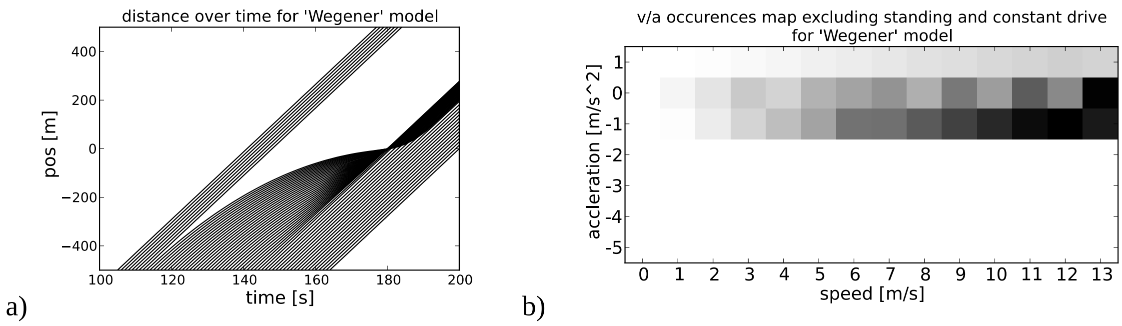



**Figure 3 - Behaviour while approaching a traffic light as described in [4]; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs**

[12] (“Katsaros”) presents a research that focusses not only on reducing the amount of emitted pollutants, but as well on reducing the halting time in front of controlled intersections. The used function to compute the speed to advice differs slightly from [4], but is nonetheless

continuously adapting the speed during the approach towards a traffic light, see Figure 4. Please note that a further clause exists in [12] named “check for accelerations”, which is used if the traffic light is yellow. This is not included in the realisation presented here.

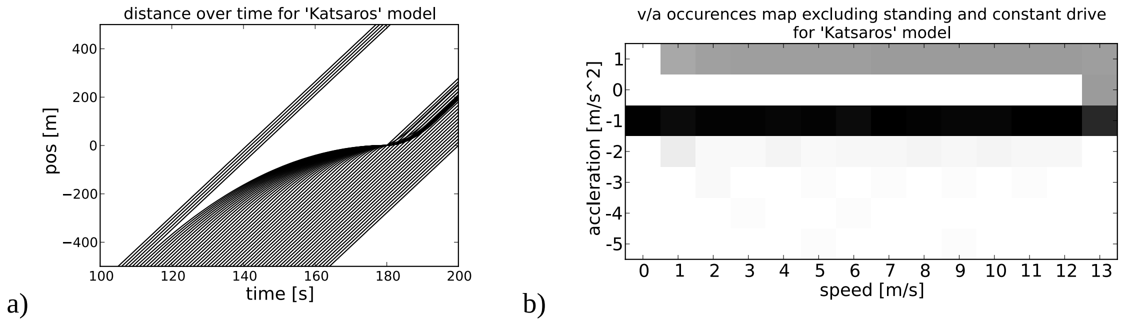



**Figure 4 - Behaviour while approaching a traffic light as described in [12]; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs**

A different attempt was used in [13] (“Krajzewicz”). Here, a constant speed to pass the next traffic light is computed. The behaviour is shown in Figure 5.

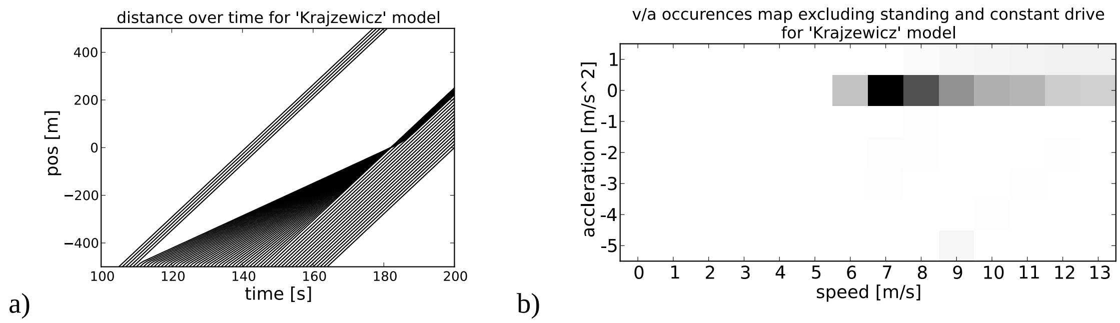



**Figure 5 - Behaviour while approaching a traffic light as described in [13]; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs**

## New Approach Models

Two further approach models have been developed. Instead of focussing on driver comfort and/or traffic efficiency, they were designed to reduce the amount of emitted pollutants. Both models are presented and benchmarked as shown before for already existing models.

### *Kinematic COLOMBO Model*

In the following a simple kinematic method to describe the trajectory of the vehicle is presented, first. Kinematic means that only constant accelerations are considered so that the whole vehicle movement can be decomposed into time intervals that are characterized by certain accelerations or decelerations, respectively. Let us shortly introduce some further variables. Let $x_f$ and $v_f$ be the final position and speed. Red starts at time $\Phi$ (offset) and ends at time $t_R=\Phi+R$, where $R$ is the red time. As mentioned, one often has $v_i=v_f=v_{max}$. If the vehicle is too close to the traffic light so that it must stop, the needed deceleration is:

$$a_{\text{stop}} = -\left|\frac{v_i^2}{2x_i}\right| \tag{1}$$

Otherwise, if the distance is “right” then the vehicle hits $t_R$ exactly at $x = 0$ with a certain velocity $v_R \geq 0$. Thereby, two decelerations are needed:

- $a_R$: Using this deceleration the vehicle comes to a halt exactly at the time $t_R$ where the traffic light switches from red to green. Note that the position where it halts is not specified. The deceleration to apply is:

$$a_R = -\frac{v_i}{t_R} \tag{2}$$

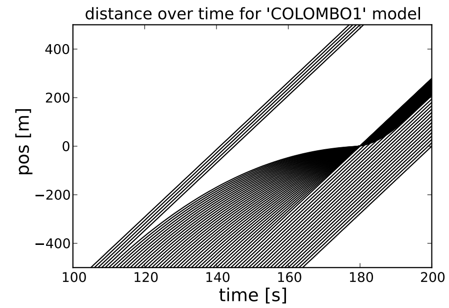
- $a^*$ is the deceleration needed to arrive at $x=0$ at time $t_R$. So this (or even stronger) deceleration is necessary in order not to violate the stop line when the traffic light shows red. It is computed as following:

$$a^* = -2\frac{x_i + v_i\, t_R}{t_R^2} \tag{3}$$

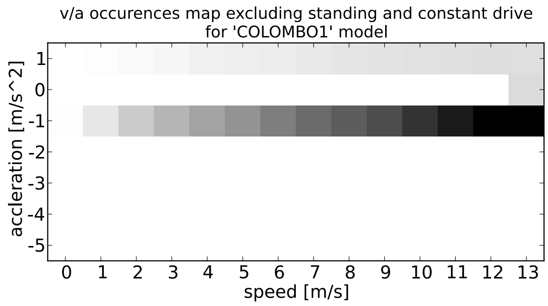
This originates from $x_i + v_i\, t_R + \frac{1}{2} a^*\, t_R^2 = 0$. There is but a small window of opportunity to reach $t = t_R,\ x = 0$ with any speed $v_R \geq 0$.

- If $a^* < a_R$ then by braking at $a_R$ the vehicle would violate the stop line. Thus is it too close and needs deceleration $a_{\text{stop}}$
- If $a^* > a_R$ then by braking with $a^*$ the vehicle will reach $x = 0$ exactly at $t_R$ with a remaining speed $v_R = -v_i - 2x_i/t_R$
- If $a^* = a_R$, then the deceleration needed to come to a halt at $t_R$ and the deceleration needed to come to a halt at $x = 0$ are the same and $v_R = 0$

One can state that first, it is best to avoid standing. Then, by considering strategies with stronger and stronger decelerations, at one point, it is better to decelerate strongly and stand for a certain time. Then finally deceleration at intermediate strength without standing is preferable. The developed model (“COLOMBO#1”) behaves as shown in Figure 6.



a)



b)

**Figure 6 - Behaviour while approaching a traffic light as described in this section; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs**

*Emission-optimal deceleration*

The second approach model (“COLOMBO#2”) builds upon the COLOMBO#1 model in the following way. Consider the case $\mathrm{a}^* > \mathrm{a}_\mathrm{R}$. $\mathrm{a}^*$ is the deceleration that is necessary to arrive with the maximum possible velocity $\mathrm{v}_\mathrm{R}$ at the traffic light exactly when it switches to green at $\mathrm{t}_\mathrm{R}$ so that $\mathrm{a}^* = (\mathrm{v}_\mathrm{i} - \mathrm{v}_\mathrm{R})/\mathrm{t}_\mathrm{R}$. There is a certain $\mathrm{a}_0(\mathrm{v})$ below which the fuel injection is shut down (coasting). For the velocities considered here this deceleration is around $\mathrm{a}_0 = -0.3\ \mathrm{m/s}^2$. Below 10 km/h coasting is disabled. COLOMBO#2 has the following changes:

- If the deceleration $a^*$ is stronger than $a_0$ take $a^*$ as before.
- If, however, $a^*$ is weaker than $a_0$ then decelerating at $a^*$ would lead at time $t_R$ to the velocity $v^* = v_i + a^* t_R$. Instead of doing so, it is suggested to coast with $a_0$ for a

certain time until the vehicle obtains the velocity $v^*$. Then it continues at constant velocity.

The resulting behaviour is shown in Figure 7.

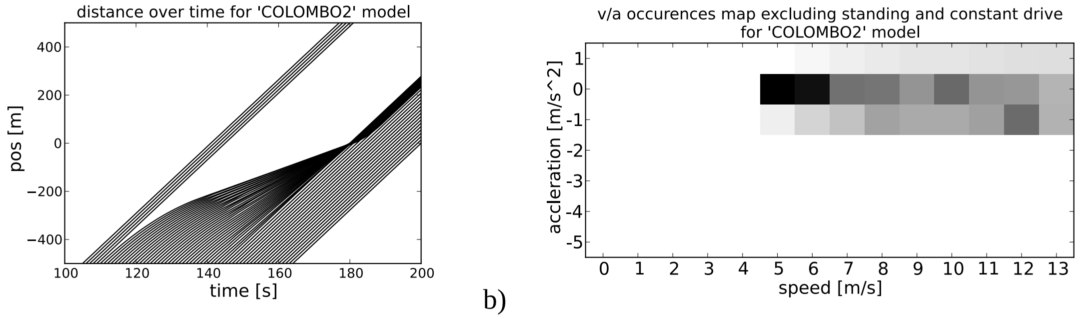



**Figure 7 - Behaviour while approaching a traffic light as described in this section; left: positions of vehicles over time, right: occurrences of speed/acceleration pairs**

## Comparisons

The prior sections describe a simplified “real-world” behaviour model, three models from the literature as well as two models generated in COLOMBO. In the following, the implemented models are compared, focussing on their emission behaviour. For a deeper inspection, a decomposition of the trajectories into modes of driving is performed, first. The driving modes “HALTING”, “BRAKING”, “COASTING”, “CONSTANT”, and “ACCELERATING” are distinguished as following:

$$mode(v,a) = \begin{cases} -0.01 < a \leq 0: \begin{cases} v < 0.1: & HALTING \\ otherwise: & CONSTANT \end{cases} \\ a \leq -0.01: \begin{cases} a < -.3 \ AND \ v > 2.78: & COASTING \\ otherwise: & BRAKING \end{cases} \\ a > 0: \quad ACCELERATING \end{cases} \tag{4}$$

The same simulation settings as before are used. Even though the figures that show these runs look “dynamic”, most of the driving is done with $v=v_{max}$; for avoiding this bias, only data for vehicle positions between -500 m (500 m in front of the traffic light) and 100 m (100 m after the traffic light) are used in the following. For this subset of time lines, Figure 8 shows the distributions of driving modes for each of the models.

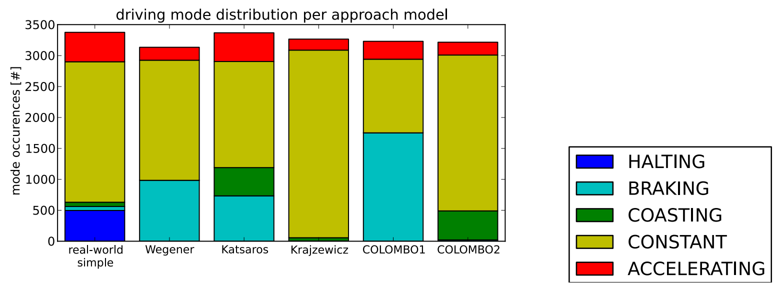



**Figure 8 - Occurrences of driving modes by approach model**

The resulting emissions produced by the simulated vehicles in the boundaries given above are shown in Figure 9. Here, the “PKW_D_EU4” emission class from the PHEMlight was used, which models a Euro norm 4 Diesel passenger vehicle. The colours distinguish the driving modes again and have thereby the same meaning as in Figure 8. The emissions have been computed by driving the obtained speed time lines virtually within PHEMlight. Please note that the realisation of fuel-cut off at motoring was done by setting respective pollutants to zero when the vehicle was in this driving mode.

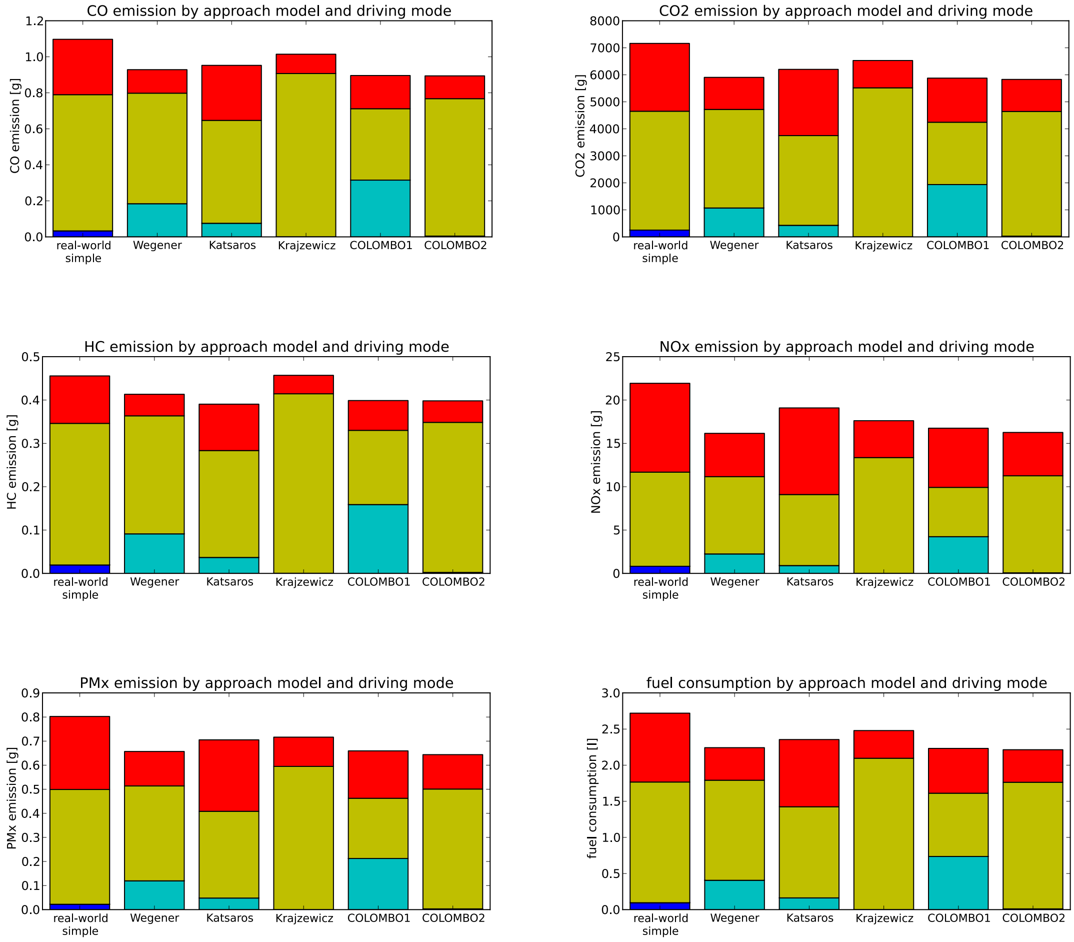



**Figure 9 - Emission and consumption by model (divided by driving mode)**

Of course, the resulting emission behaviour differs across different emission classes. Figure 10 shows the emissions produced / the consumed fuel for modern passenger vehicles. From left to right, the bars represent the emission types “PKW_G_EU4”, “PKW_G_EU5”, “PKW_G_EU6”, “PKW_D_EU4”, “PKW_D_EU5”, and “PKW_D_EU6” (Gasoline and Diesel passenger cars with Euro norms 4 to 6).

## Summary

Crossing intersections controlled by a traffic light is one of the major reasons for changing the speed and thereby losing kinetic energy, forcing additional fuel consumption and pollutant emission. Optimizing a vehicle’s approach towards an intersection controlled by a traffic light requires the knowledge about the influence of a chosen speed or acceleration on the emission behaviour. For this purpose, a set of simulative investigations was performed using the PHEM emission model. Besides describing the dependencies between speeds, accelerations, and emissions, they as well delivered the emission-optimal accelerations and speeds. Based on this ground information, three models to adapt a vehicle’s speed when approaching a traffic light for passing it at green from the literature as well as a very simplified model of a real car driver were benchmarked. This was again done in simulations, using a simple traffic light scenario. The trajectories obtained from these simulations were then used to compute the amounts of the respectively emitted pollutants.

Additionally, two new models were presented. The results show that these new models perform better in means of yielding in the lowest fuel consumption and pollutant emission than the one known so far. The work continues into different directions. One to name is the optimization for crossing more than a single traffic light. As well, for honest comparisons of the benefits in means of reduction of fuel consumption and pollutant emission, the real-world behaviour should be revisited by including the drivers' anticipation of the state of the traffic light at arrival.

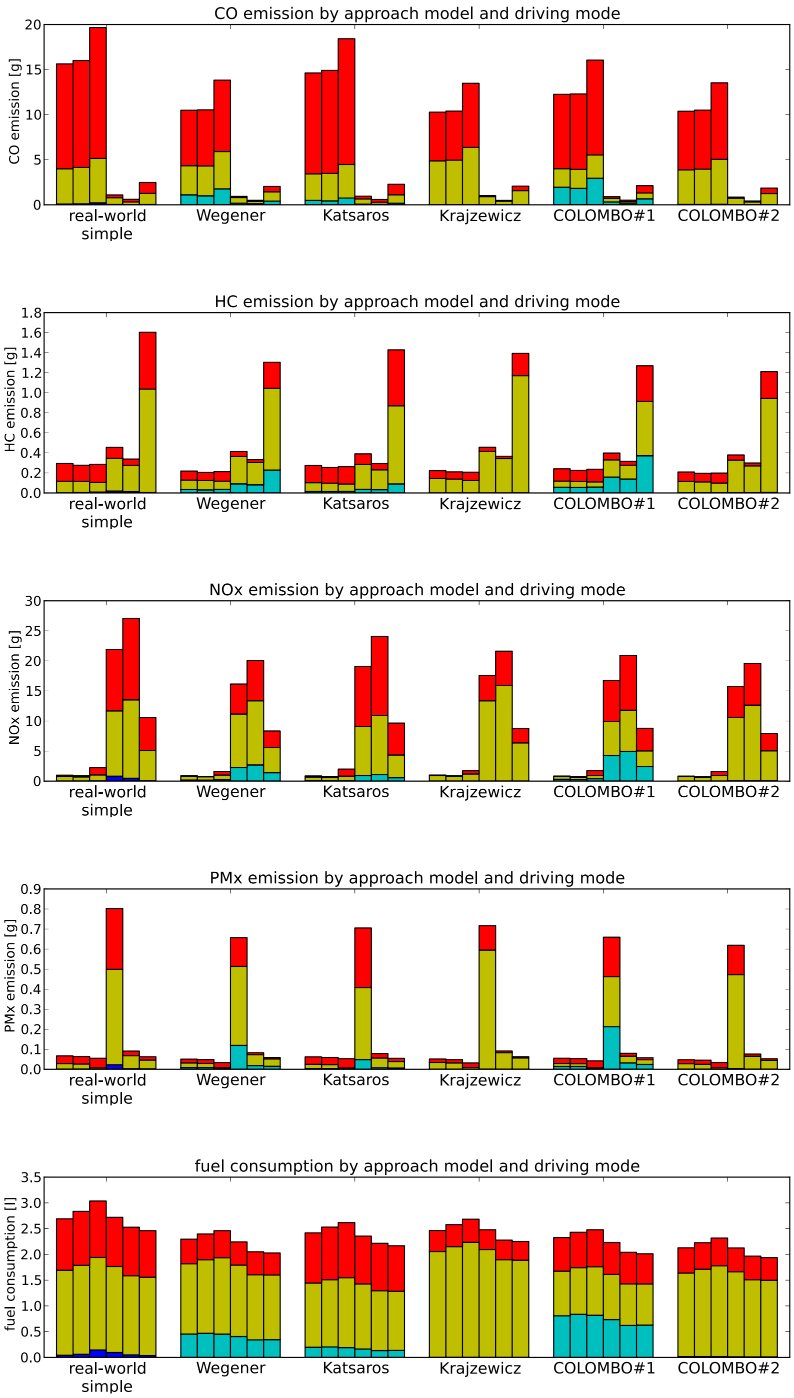



**Figure 10 - Emission and consumption of vehicle classes named in the text by model.**

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