

## Emission optimized control for isolated intersections

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### Abstract

Stopping and accelerating at traffic lights is one of the main contributing factors to vehicular emissions in urban environments. The work in this paper demonstrates a generic guideline for minimizing CO<sub>2</sub> emissions at traffic lights. This was done using an adaptive control, which uses a cost function for optimization, rather than network-specific control parameters. A new version of the emission model PHEMlight was used, which added of a fuel cut-off mode during coasting and other improvements compared to the previous version. Using this model, it could be determined that the emission optimal ratio between delay time and stops for the cost function of an adaptive control should be 1:4.8. Using this ratio a reduction of 7.6 % of CO<sub>2</sub> emissions was achieved compared to a vehicle actuated control.

### Introduction

Stopping and accelerating at traffic light controllers is one of the main contributing factors to vehicular emissions in urban environments. Generally, this can be derived from the fact that fuel economy is lower in urban environments than on highways despite the higher cruising speeds. This is as well visible in the driving cycle tests for new vehicles like EPA [1] and NEDC [2], where significantly lower fuel consumption is measured in highway environments. Main reasons for the high fuel consumption in urban traffic are the frequent decelerations and stops which annihilate kinetic energy in the mechanical brakes. However, traffic light controllers are generally necessary and their absence would compromise safety, throughput and pollutant emissions. Despite the large impact on the environment, traffic lights are seldom configured with the target to reduce CO<sub>2</sub> emissions and if this happens then on the level of network specific optimizations. This paper describes research that aims to find generic guidelines for an emission optimal control on isolated intersections.

Traffic controllers can generally be classified in three categories, static, actuated and adaptive. For static controllers the length of the signal phases with respect to the expected traffic volume and possible coordination and synchronization between adjacent intersections give opportunities for emission optimization. However, this is often done in a network specific manner with tools like TRANSYT [3] or with micro-simulations. Tuning done in such a manner does not directly target the emissions, since the system only accepts green durations and synchronization offsets and the resulting emissions are indirect consequences of this. Another complicating factor is the vehicle arrival pattern, which is generally not uniform. Therefore, at each cycle a different signal time setting could be optimal. Vehicle actuated control solves this problem by realizing different signal timings for every cycle. Gap time and detector locations could in theory be optimized for vehicle actuated control to be emission optimal on a very short time horizon. However, the controller could decide to extend the green phase of a signal group to prevent one vehicle from stopping, while that decision may cause a whole platoon having to stop on the next signal group in the cycle. This lack of anticipation capabilities in vehicle actuated control is solved by traffic adaptive control. This type of control has either a connection with upstream intersections to exchange information about approaching platoons, or entry detectors at a large distance upstream. Using this information it is possible to calculate an optimized strategy for a planning horizon of approximately 60

seconds. This way the effects during the entire horizon are modelled, preventing the controller to choose for short term gains with negative side-effects afterwards.

Another advantage of adaptive control is the cost function it uses to choose between possible green phase durations within the planning horizon. This function has targets that may have a good correlation to emissions. The two major cost function parameters used in both Utopia [4] and ImFlow [5] are stops and delay time. Currently, these are only used for tuning in a manner that a lower value is better. The ratio between their weight in the cost function influences if the controller will focus more on preventing stops or more on delay reduction. Stops cause extra emissions, because the vehicle has to reaccelerate again and delay time induces engine idling time which also increases emissions. This implies that an emission model should either be embedded in the control algorithm or in the simulation environment. Using the latter, the optimal ratio between stops and delay can be determined in order to let the control algorithm optimize for emissions.

The COLOMBO project develops a set of modern cooperative traffic surveillance and traffic control applications that target at different transport related objectives such as increasing mobility, resource efficiency, and environmental friendliness. It relies on simulation models that allow benchmarking the applications' performance. To acquire accurate emission measurements from the simulations, the COLOMBO project coupled the microscopic traffic model SUMO with the microscopic vehicle emission model PHEMlight [6]. This coupling opens the possibility to optimize the cost function parameters for emissions. Since those parameters are not network specific, this would result in generic guidelines for emission optimal traffic control that can be applied to any network.

Since the emission model is a key component of this research, the paper will contain an extensive dedicated section to the PHEMlight model that shows the model validation results and gives an overview on functions relevant for the development of emission optimal solutions. The next section will contain the theory on how to configure the cost function parameters for emission optimal control and is followed by a section on the simulation of effects from different traffic light control strategies on emissions to verify the previously derived theory. The last section before the conclusion discusses extensions that may be needed in the future when hybrid or electric vehicles will be more abundant or when speed advice is possible.

## **Emission modelling**

### *Overview*

Models applied for assessing emission effects resulting from changes in the traffic flow have to distinguish at least between the driving modes acceleration, cruising, deceleration, and stop time. Each deceleration using mechanical brakes annihilates energy which afterwards has to be re-supplied by the engine to accelerate again. Stop times add emissions due to engine idling without covering a distance while different speed levels result in different driving resistance losses. Also the acceleration levels are relevant for the current engine power demand, the engine's efficiency and thereby for the emission levels. Such effects cannot be simulated correctly by simple models, such as average speed models. A suitable model has to be based on physical relations to calculate the actual power needed to drive a vehicle and on characteristic curves or maps to define representative emissions as function of the engine power demand. This was found already end of the 1990ties and lead to the development of the vehicle model PHEM [7].

Today, PHEM is used to simulate the basic emission factors for the Handbook Emission Factors (HBEFA), for the average speed model COPERT, for NEMO (Network Emission MOdel) and for several national emission models. One unique characteristic of PHEM is the huge database of emission measurements used for the parameterisation which leads to representative emission values for the vehicle fleet under real world driving conditions. Many other features useful for simulating vehicle fleet emissions on a very detailed level are implemented in PHEM. Within COLOMBO, alternative propulsion systems have been implemented in PHEM (CNG, Hybrids) to provide a suitable vehicle fleet for simulation of future traffic control systems. A description of PHEM and of these new functions is given in [8]. The manifold functionalities however made PHEM quite complex and also require the knowledge of the speed and acceleration history of a vehicle over several seconds to compute temperature levels of exhaust gas

aftertreatment systems and to correct transient effects on engine out emissions. For these reasons PHEM is only suitable for microscopic traffic models as a post-processing tool.

Since especially for optimisation loops a cascade of simulation tools is inefficient, PHEMlight was developed within COLOMBO as an integral part of the SUMO software. Since PHEMlight was not completely developed when [8] was produced, new features and results are described here. The model has been improved significantly against the last version. The validation of the actual PHEMlight version is shown in this paper by a comparison with results of the more detailed “parent model” PHEM. PHEM was validated against measurements on an extensive number of vehicle measurements, e.g. [9], [10], [11] and thus is a reliable tool for validation of PHEMlight. A validation of PHEM for new propulsion concepts (e.g. hybrid powertrains) is given in [8].

### *Choice between PHEM and PHEMlight*

In COLOMBO, two emission models developed by the technical university of Graz are applied: PHEM and PHEMlight. As described before, PHEM can be used “only” for post-processing the vehicle speed trajectories computed by SUMO, since PHEM needs information on several time steps before and after the actual computed time. PHEM needs this information to calculate the thermal status of aftertreatment systems, to consider effects of transient engine loads on the engine out emissions and to feed the driver model which selects the gears in the virtual vehicles. Since keeping long time series for each vehicle in the simulator leads to high storage demand and long computation time, PHEM cannot be integrated into a micro-scale traffic model. This certainly is a handicap when optimization loops have to be.

PHEMlight includes several simplifications compared to PHEM. Consequently also some of the PHEM functionalities are reduced or not existing in PHEMlight. The functionalities reduced in PHEMlight however, are often not relevant for the calculation of emissions from average vehicle fleets based on speed trajectories simulated by traffic models. In Table 1 the main differences between the models are explained.

**Table 1: Main differences between PHEM and PHEMlight.**

PHEM	PHEMlight	Effects
Gear choice and corresponding engine speed is calculated from transmission ratios and gear shift model.	Engine speed is implicitly approximated as function of engine power. <sup>1</sup>	Influence of different driving styles in terms of gear shift behaviour cannot be computed with PHEMlight. High road gradients – which lead to selection of lower gears in PHEM – are computed with engine speeds for normal road gradients in PHEMlight.  For simulation of fleet averages in traffic models the elimination of gear shift manoeuvres is seen as advantage, since in reality drivers shift very differently and no “sharp” gear shift effects on emissions exists for the driver+vehicle fleet mix. In PHEM small speed differences can cause higher emission differences if a different gear is selected.

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<sup>1</sup> Engine speed is not explicitly modelled in PHEMlight to simplify the driver model. In the calculation of fuel consumption and emissions the influence of engine speed is implicitly covered as function of engine power representing average gear shift behaviours of different driver/vehicle combinations. For the „fuel cut-off“ driving mode engine speed is approximated as function of vehicle speed.

Exhaust gas after treatment temperatures are simulated using heat transfer and energy balance functions. Efficiencies of catalysts are simulated as function of the temperature and exhaust gas mass flow	Exhaust gas temperatures are not simulated. Results from PHEM for representative cycles are used to produce characteristic curves for the tailpipe emissions as a function of engine power only.	The influence of the duration of low and high load driving on emissions cannot be calculated with PHEMlight (e.g. catalyst cool down at long stop&go cycles). PHEMlight always uses average temperature levels. Also cold start cannot be simulated with PHEMlight yet. Usually the history of single vehicles is not accurately known from traffic models for sufficiently long time spans to calculate thermal effects on emissions on a vehicle to vehicle basis. Thus average temperature levels are sufficient for most applications. However, especially for long stop&go or long stop phases PHEMlight will underestimate pollutant exhaust gas emissions.
Power calculated based on more detailed longitudinal dynamics.	Power calculated based on simplified longitudinal dynamics	Small deviations can occur for calculated engine power demand between PHEM and PHEM light which seem not to be relevant when fleet average emissions are calculated since also vehicle masses, loading, rotational inertias and driving resistances for the fleet average are not known exactly.
Simulates vehicle fleet by randomly mixing gasoline, diesel etc. with different EURO classes to meet the defined total fleet distribution	Can use a weighted average vehicle (different for cars, LCV, trucks, buses). Mixing different vehicles as in PHEM is also possible.	Influence of random generator is eliminated in PHEMlight when the weighted average vehicles are used. Thus reproducible results are produced already from one single simulation run.

As can be seen in the column with the effects in the table, the differences between the models average out over larger vehicle fleets. So for the purpose of a generic configuration guideline, PHEMlight is sufficient. When individual vehicle trajectories have to be optimized, then detailed parameters like gearshifts are important.

#### “Fuel cut-off” Driving Mode with Zero Emissions

If a vehicle decelerates in a way that all losses in the powertrain system including the internal combustion engine can be “covered” by the kinetic energy of the decelerating vehicle, the engine’s fuel injection system goes into the so called “fuel cut-off” mode. In this operation state – due to zero fuel injection – the emission output for all exhaust gas pollutants is zero<sup>2</sup>. The correct simulation of this effect is important in the evaluation of the effects of a traffic light on the emission output, since vehicles are likely to come to a full stop. When this is not taken into account, the emissions are overestimated in case of a stop. Which deceleration level (value in  $m/s^2$ , program internal parameter  $decel_{coast}$ ) is required to reach the fuel cut-off mode depends on the vehicle mass, the driving resistances and the losses in the engine and the drivetrain system. The latter is also significantly influenced by the selected gear.

In order to determine  $decel_{coast}$  for a given vehicle and a given vehicle operation state<sup>3</sup> PHEMlight performs the following calculations:

<sup>2</sup> Only a very small amount of hydrocarbons and particle emissions originating from lube oil can be found in the exhaust gas.

<sup>3</sup> In PHEMlight the vehicle operation state is defined by the actual values for vehicle speed, acceleration and road gradient

- Determination of the selected gear from a vehicle specific characteristic line as a function of vehicle speed. This characteristic line is parameterised by the gear shift provisions for the ERMES cycle for passenger cars and light commercial vehicles and for HDV by PHEM calculations for HDV specific cycles considering typical “average” gear shift behaviour.
- Determination of the engine speed considering the vehicle speed, the total transmission ratio in the drive train and the wheel diameter.
- Determination of the engine drag from a characteristic line as a function of engine speed.
- Converting the losses in the powertrain (consisting of the engine drag and additional losses in the transmissions assuming 90% efficiency) to a force “ $F_{loss}$ ” at the driven wheels.
- Calculation of the forces at the driven wheels originating from the driving resistance ( $F_{roll}$  rolling resistance,  $F_{air}$  air resistance,  $F_{grad}$  gradient resistance).
- The deceleration where the vehicle then would be exactly operated in “Fuel cut-off” driving mode can then be calculated by:

$$decel_{coast} = - \frac{F_{loss} + F_{roll} + F_{air} + F_{grad}}{(m_{veh} \cdot \Lambda + m_{rot} + m_{load})} m / s^2$$

where:

$m_{veh}$	mass of the empty vehicle in kg
$\Lambda$	rotating mass factor (depicting the rotational inertia of the powertrain)
$m_{rot}$	equivalent rotational mass of the wheels in kg
$m_{load}$	mass of the vehicles load in kg

If the actual acceleration of the vehicle operation state is lower than  $decel_{coast}$  the result of PHEMlight for fuel consumption and emissions are set to zero. In addition the  $decel_{coast}$  value can be used for simulating ECO-drive style decelerations, where drivers should avoid mechanical braking and thus coast down the vehicle towards lower speeds.

### Generation of “average” Vehicles

The vehicle fleet consists of various vehicle types and propulsion concepts which can differ significantly in terms of emission behavior. As a consequence in emission modelling the vehicle fleet is subdivided into vehicle groups with characteristic emission behavior, the so called “fleet segments”. A common method of fleet segmentation is to differentiate by the following criteria:

- vehicle category (e.g.: passenger cars, light duty vehicles, rigid trucks, ...),
- engine concept (e.g. gasoline, diesel),
- size class (differentiating factor: capacity or maximum allowed gross weight), and
- emission standard (legislation which was applicable at the vehicles type approval, e.g. “EURO 5”).

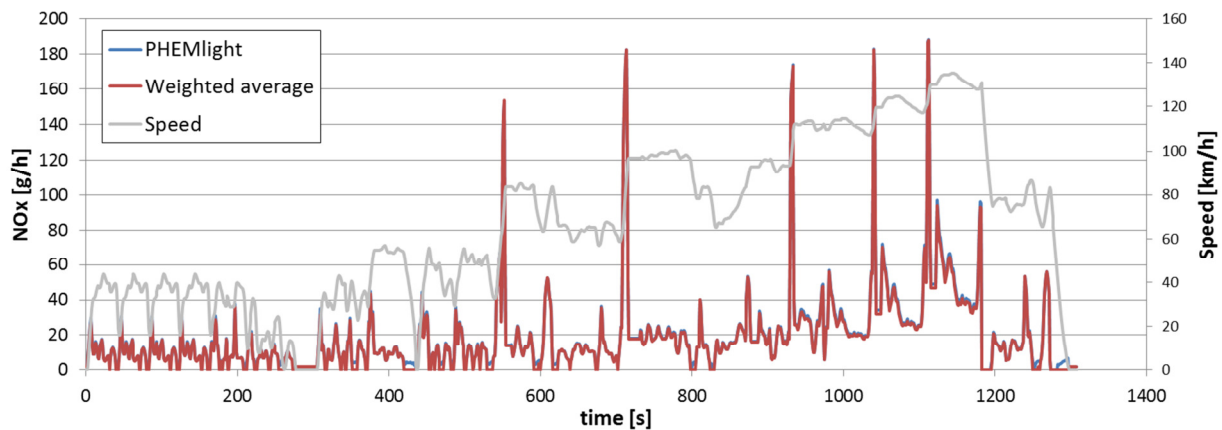
A vehicle segment is for example a “rigid truck with diesel engine, gross vehicle weight with more than 18 tons, emission standard EURO 5”.

When the emissions of a typical fleet mix e.g. on a particular road network shall be calculated, the shares of the different vehicle segments on the overall mileage have to be known. This information can be calculated by fleet models. In the link of micro-scale traffic models (like SUMO) with micro-scale emission models (like PHEM or PHEMlight) the common approach is to allocate a certain “vehicle segment” to a particular vehicle driving on the virtual road network by a random generator based on the probabilities defined by the mileage shares. This approach has the disadvantage that – unless a very high number of vehicles is simulated on the road network – the emission result contains an influence of the output of the random number generator. Additionally, micro-scale traffic models themselves use a random algorithm to generate the vehicles entering the model area. These random elements add a certain margin in the emission results for the coupled simulation run. A common way to handle this problem is to perform simulations several times – with several start values (“seeds”) for the random generator – and to analyse the overall outcome in

terms of average result and scattering of single simulation runs. This approach requires much additional computation time and additional efforts in the data analysis.

In PHEMlight, for modelling the fleet mix an alternative approach was developed, which allows to consider the same known fleet mix without the use of a random number generator. Instead of attributing a particular vehicle segment to a particular vehicle on the road network a “weighted average” vehicle is allocated. This is done in PHEMlight by weighing of all input data (e.g. vehicle mass, driving resistance parameters, characteristic emissions curves) according to the fleet mix data. In this way, it is possible to generate an average “light duty vehicle” (covering passenger cars and light commercial vehicles), an average “truck” (comprising rigid trucks as well as articulated trucks and truck- and trailer combinations) and an average “bus”.<sup>4</sup>

For a validation of this method the European Research Group on Mobile Emission Sources (ERMES) test cycle was calculated with a passenger car fleet mix configured for Austria in the year 2020 and compared with the weighted result of each single vehicle of the fleet. Figure 1 shows the results for NO<sub>x</sub>. Nearly similar emissions are obtained by the “average vehicle” when compared to the weighted average of the single simulations. The deviations are in the range of the overall model accuracy and result from averaging effects of nonlinear dependencies.



**Figure 1: Comparison of NO<sub>x</sub> emissions for the PHEMlight average passenger car with the weighted result for the single associated vehicle segments.**

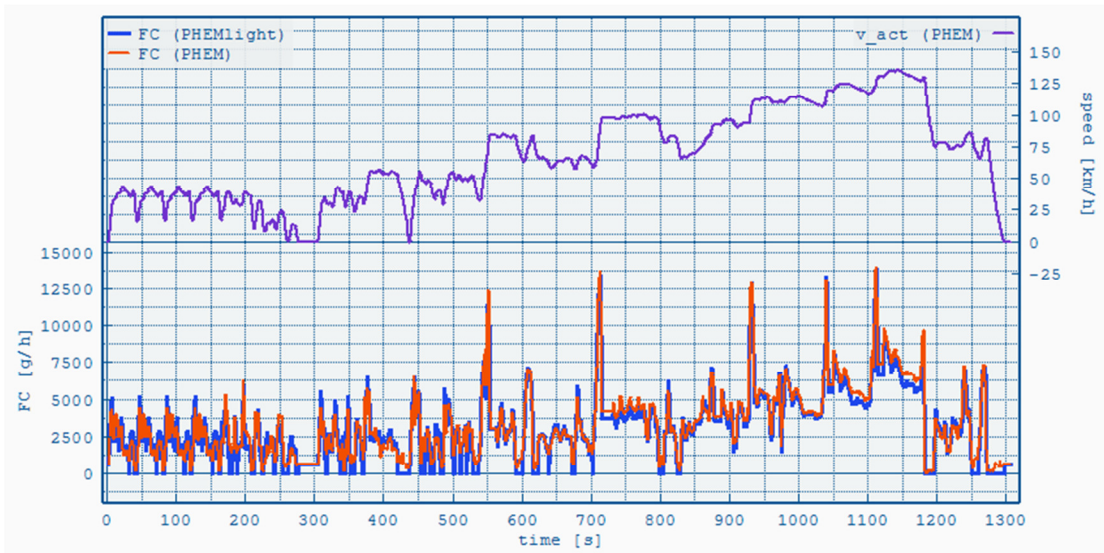
However, this method of generating a fleet average vehicle by averaging the model input data is limited to the less complex model structure of PHEMlight. For PHEM, such an approach would not result in meaningful model behavior, as the modelling of engine speeds needs a harmonized set of vehicle data (integer number of gears, gear ratios, engine full-load characteristics etc.) which cannot be expected to be the case for weighted vehicle datasets.

In this research the optimal ratio between the cost function weight of stops and delay is determined on an isolated intersection, which is a very simple simulation network. Therefore, it is possible to use very long simulation runs with over 10,000 vehicles. This will average out the random effects caused by injecting vehicles from different segments with a random generator. The use of different classes should increase the accuracy.

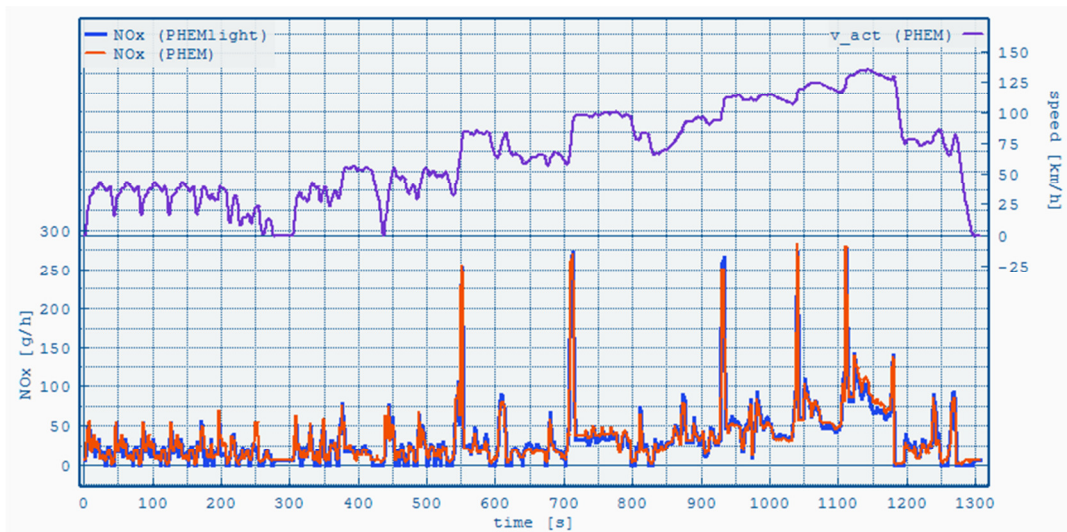
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<sup>4</sup> A further combination of these three vehicle types into a “total fleet average” vehicle would not be meaningful due to differences in the emission modelling depending on the vehicle category (e.g. different normalisation methods of characteristic emission curves).

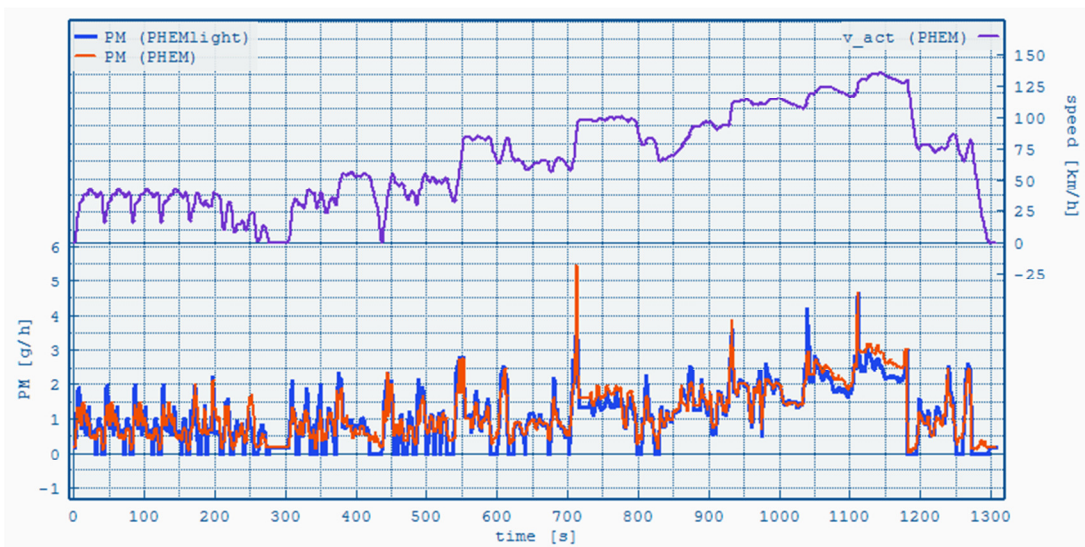




**Figure 2: Fuel consumption comparison between PHEM and PHEMlight.**



**Figure 3: NOx comparison between PHEM and PHEMlight.**



**Figure 4: PM comparison between PHEM and PHEMlight.**

### Validation of PHEMlight by Comparison with PHEM Model Results

All characteristic emission curves and vehicle data necessary as input for PHEMlight have been calculated with the model PHEM using representative driving cycles.

In order to validate the simulation results of PHEMlight, comparisons have been performed with the results of the more detailed “parent model” PHEM for all vehicle segments and several real world cycles. As an example, the comparison of results are shown for the average EURO 4 Diesel passenger car driven in the ERMES real world driving cycle in Figure 2, 3 and 4. The results present very good correlation between the two models over the whole cycle despite the fact the PHEMlight uses a significantly simpler approach with no explicit consideration of gear shifting and engine speeds.

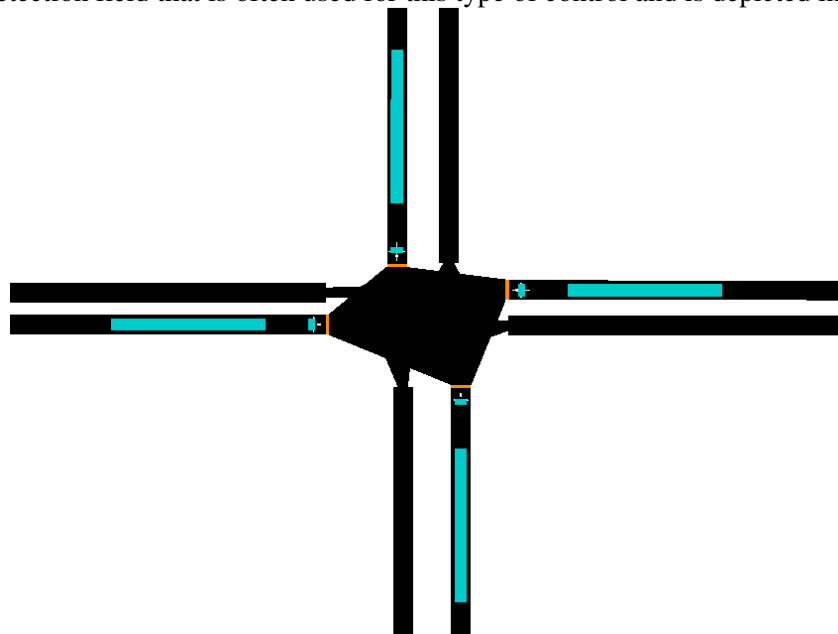
Table 2 shows the cycle average emission results for fuel consumption and emissions. PHEMlight slightly underestimates the cycle average PHEM result. This underestimation is to a high extent caused by the PHEMlight “fuel cut-off” model element, which has been implemented in order to better depict relative influences of changes in driving style on the emission output. In the parent model PHEM the motoring emissions are based on measurements on the chassis dynamometer where, due to technical limitations of the emission measurement systems, the measured emission level is not zero at the same moment as the engine stops injecting fuel. It is planned to update PHEM in this regard for more realistic behaviour by developing sophisticated correction methods for input data from the chassis dynamometer. Therefore, in this aspect PHEMlight is more suitable for the current research.

**Table 2: Average emissions in ERMES cycle for PHEM and PHEMlight (EURO 4 Diesel Car).**

	Fuel	NOx	PM	CO	HC
PHEM	3352.8	33.83	1.18	1.76	0.59
PHEMlight	3183.6	33.13	1.12	1.62	0.54
Deviation	-5.0%	-2.1%	-4.9%	-7.6%	-8.1%

### Emission optimal control on isolated intersections

To create green waves for coordination on an isolated intersection is not possible. The most common strategy for such an intersection is vehicle actuated control. With this method, a signal group is simply kept green until the flow is interrupted or the maximum green time was expired. This can best be understood considering the detection field that is often used for this type of control and is depicted in Figure 5.

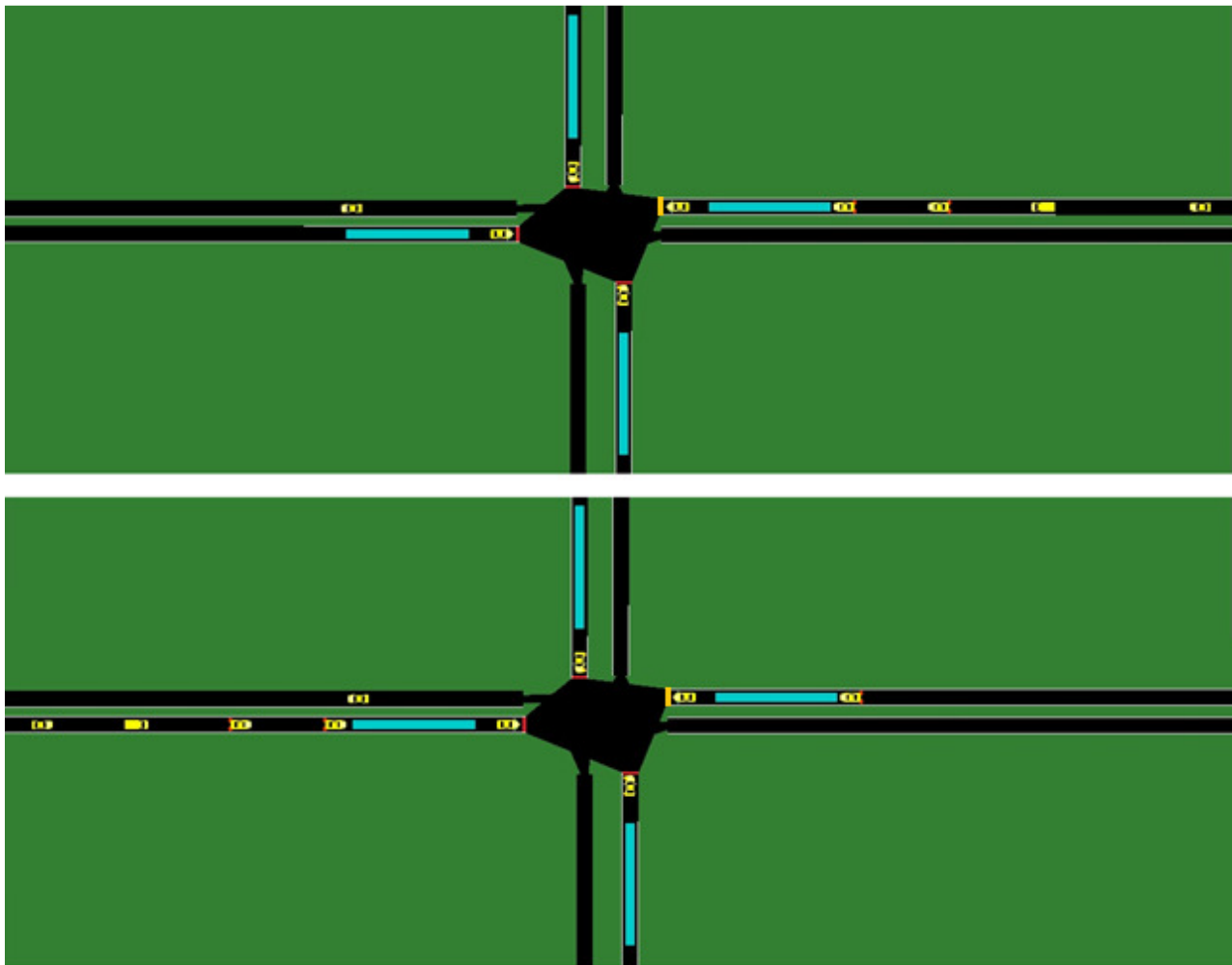


**Figure 5: Simple vehicle actuated intersection layout, including the inductive loops used for adaptation (light blue)**



The small loop at the stop line serves to detect if there are vehicles waiting for that signal group. The longer loop detects whether the flow is interrupted or not. This gap detection loop is dimensioned in such a way that the traffic light can achieve optimal throughput at minimal waiting time. The length and position take two factors into account: 1) a vehicle that leaves the gap detection loop at green will not stop anymore if the light is switched to amber right after it leaves the loop and 2) a normal car following distance is smaller than the length of the loop. This also implies that the higher the speed of the traffic the longer the distance between this loop and the stop line and the length of the loop itself. Therefore, at higher speeds the single long loop is often replaced by several small loops, since extremely long loops are not practical. A common value for the loop position is 10 m before the stop line and a loop length of 25 m for a speed limit of 50 km/h.

Vehicle actuated control generally results in an acceptable control strategy and simply follows the maximum green phase durations in case the network is oversaturated. One of the main shortcomings, however, occurs when there is a gap that is just a bit larger than the size of the loop. This calls for a decision based on how large this gap is and how many vehicles are behind the gap. When there are many vehicles waiting at the other signal groups, it is probably not worth waiting for a single vehicle if there is a large gap. However, in case there is a platoon of 10 cars after this gap, then the situation is different. Two different situations that appear the same to a vehicle actuated controller, but require a different decision are depicted in Figure 6. The situation at the top would require further extension of the green phase, while the situation at the bottom should have switched green to the west-east direction already. Lastly, when the intersection is saturated, any gap is loss of capacity and the signal group should be terminated, especially near the end of the maximum green time.



**Figure 6: Two situations that appear the same to a vehicle actuated controller, but require a different emission optimal decision**

When knowing the pattern of arriving vehicles and the queue lengths, better informed decisions can be made. This is the main advantage of traffic adaptive control; an entry detector upstream at the approaches enables the controller to model the positions of approaching vehicles. ImFlow has a cost function that uses both delay time and the number of stops, which are the main parameters that correlate with emissions. Other parameters, for instance for route coordination or spillback prevention, are also possible, but not necessary since they do not correlate with emissions directly and therefore will not be used.

To determine the impact of both delay time and stops, the PHEMlight model connected to a very simple set of simulations was used. The purpose of those was to isolate the effects of both idling and stopping with reacceleration. To achieve this, four simulations were defined: a baseline where all vehicles drive with a constant speed of 50 km/h and three simulation runs where all vehicles stop once and wait for 5, 10 and 15 seconds respectively. This stop occurs at an artificial traffic light that is configured to make the vehicles stop for an exact amount of time. Achieving exactly 0 seconds of stopping, while still always reaching a full stop, is very difficult in a simulation environment where small random variations are possible. Therefore, no simulation with 0 seconds of stopping was performed and the extra emissions of stopping were extrapolated from the 5, 10 and 15 second stopping scenarios. For the simulation a short stretch of road was used, just long enough to brake and reaccelerate normally. A vehicle segment distribution according to Austria's traffic in 2014 was used, which should be representative to most of Western Europe. The ratios between the vehicle classes "passenger cars", "HDVs", and "busses" can vary per region and the overall average fleet mileage in urban areas for Austria was used, which is 96.1%, 2.9%, and 1.0% respectively.

The simulation resulted in baseline CO<sub>2</sub> emissions of 72 g/km and data points of 162, 207 and 253 g/km for 5, 10 and 15 seconds of waiting time respectively. This means a stop with reacceleration causes an additional 44 g/km, while each second of waiting with the engine idling requires an additional 9.1 g/km. Note that these are averages over the entire trip of all vehicles. The stretch of road of 200m for this experiment was relatively short, so on longer roads idling and stopping have a smaller impact on the emissions per kilometre. All numbers can be converted to grams by dividing by the trip length to get absolute numbers that hold for every scenario. In this case, using a short stretch of road, it helps isolating the effects of stops and waiting time and increases measurement accuracy. Another factor that should be taken into account is the difference between waiting time and delay time. Delay time also includes the time lost due to acceleration and deceleration, while waiting time is generally defined as the time the vehicle travels slower than 5 km/h. ImFlow compensates for this internally by taking acceleration and deceleration losses into account. So a vehicle that stops at an intersection effectively gets a cost composed of the following elements: the stop itself, approximately 4 seconds of delay time for acceleration and deceleration losses and its waiting time also counts as delay time. Therefore, using the derivative of the waiting time between 5 and 15 seconds isolates only the waiting time, while the difference between acceleration and deceleration loss and actual waiting time is embedded in the stop costs. Since stopping and reaccelerating always occur together, this is a valid simplification. The stopping cost was determined by interpolation of the previously acquired data points. Using the resulting numbers, it could be derived that 4.8 seconds of waiting time with the engine running stationary causes the same amount of extra emissions as stopping and accelerating back to 50 km/h as compared to travelling at a constant speed. Using this ratio between cost of delay time and stops for configuring the optimization of a traffic adaptive controller, should therefore result in the least emissions possible.

Using this ratio, the expected CO<sub>2</sub> savings should be approximated by the following formula:

$$p_{CO_2} = 100 \left( 1 - \frac{delay_{new}}{delay_{old}} - \frac{delay_{old} + 4.8 stops_{new}}{delay_{old} + 4.8 stops_{old}} \right) \%$$

In which  $p$  represents the percentage difference between two simulations, delay is in seconds per vehicle and stops is per vehicle. Note that the improvement in stops is independent and gets on top of the improvement of delay, but since the stops are converted into delay by the 4.8 factor, they need to be compared to the old delay value.

## Results

To test this theory, a simulation on the networks shown in Figure 6 was carried out with both a vehicle actuated controller and the traffic adaptive controller ImFlow. The results are shown in the charts of Figure 7. None of the scales start at 0, which is to show the differences better. Note that this network has much longer areas where the vehicles travel at free flow, with 1000m of road before the stop line and 200m after it. This causes the CO<sub>2</sub> per kilometre to scale differently with stops and delay than in the synthetic scenario of the previous chapter. The ratio between delay time and stops should still be the same. This means that the CO<sub>2</sub> reduction of the emissions due to the control is 7.5% for traffic adaptive control with respect to vehicle actuated. This can mostly be explained by the delay reduction of 6.7%. The last 0.8% reduction can be explained by the 5.1% fewer stops, which get on top of this. The reduction of stops was measured at 0.043 per vehicle, when this is multiplied by 4.8, it would result in an additional equivalent delay reduction of 0.21 seconds. Filling this in the formula – using non-rounded values – of the theory section, results in the same 7.5% emission reduction.

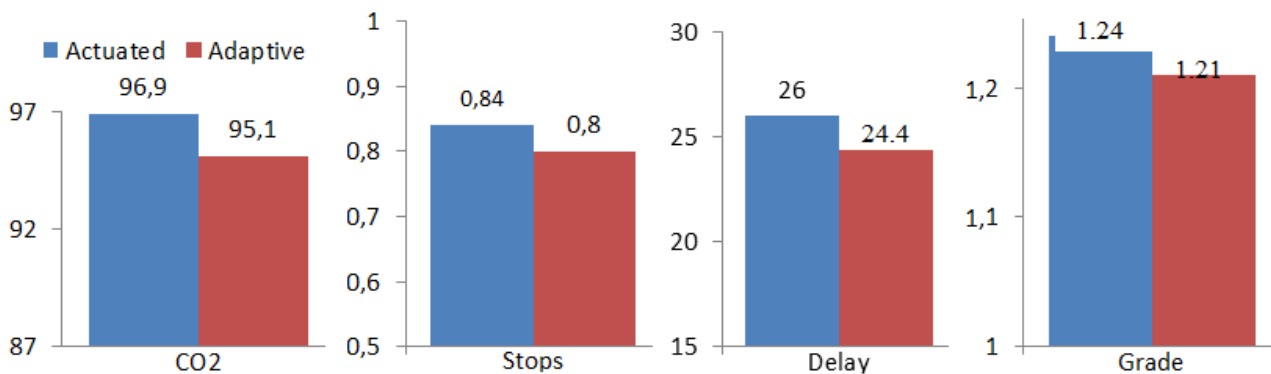


Figure 7: Comparison between vehicle actuated and traffic adaptive (ImFlow) control

## Conclusion

The work in this paper demonstrated the possibilities of having a generic guideline for minimizing CO<sub>2</sub> emissions by changing the traffic control. This is due to the fact that adaptive control uses a cost function for optimization, rather than network-specific control parameters. Adaptive control was also shown to have theoretical conceptual advantages over both fixed time control and actuated control, due to predictive modelling and control flexibility. This also showed in simulations comparing an actuated controller with an adaptive controller, which resulted in a 7.6% reduction of CO<sub>2</sub> emissions.

For the research a new version of the PHEMlight model was used, which is suitable for real-time simulations while approaching the accuracy of the more detailed PHEM model. Using this model it could be derived that the optimal ratio between delay time and stops for the cost function of adaptive control should be 1:4.8. Simulations also verified this, since the expected CO<sub>2</sub> reduction using the ratio on both the delay and stops difference between the actuated and adaptive controller matched the total CO<sub>2</sub> reduction.

For further research it should be considered that the ratio of 1:4.8 in this research was calculated for a fleet that should on average match the fleet in Western Europe. The procedure for calculation is straightforward and reproducible for other fleet compositions. However, when a larger share of vehicles has electric or hybrid powertrains, delay time will be less important. Even start-stop systems, which are becoming more abundant, have a significant impact on this ratio. All these developments allow vehicles to stop their engine while waiting and would cause the ideal weight of stops to get very high. The latter may result in an unacceptable control plan for certain drivers, since the controller has no interest of letting the vehicle pass if a stop can be prevented at another signal group. The effect is slightly offset by the regeneration of brake energy done by hybrid and electric vehicles, and even while waiting with the engine off there can be some energy consumption for heating or air-conditioning.

Another development for the near future is speed advice through cooperative V2I technology. This opens up the possibility to slow down a vehicle a bit in at a longer distance from the intersection to prevent it from stopping. Then the optimization is not just about stopping or not stopping but also contains various degrees of slowing down.

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