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Use of system of systems and decentralized optimization concepts for integrated traffic control via dynamic signalization and embedded speed recommendation

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Abstract

In the frame of the European research project Local4Global, urban traffic control is one of the demonstrative use cases of a developed decentralized control method based on the Technical System of Systems (TSoS) concept and using machine learning capabilities. TSoS concept consists of dividing the system to semiautonomous elementary systems, called constituent systems, which shall enjoy to a major extent a local decision possibility. A remaining part of the decision shall be made after exchanging information between all participating systems to learn from each other and improve the overall performance.
In the traffic context, two basic classes of constituent systems are suggested: dynamically signalized traffic junctions and connected vehicles with speed control capabilities. Both traffic signals and vehicle speed controls receive a correction from the L4GCAO global optimizer in a bigger and common control cycle, namely each day.
This paper describes the methodology and the results of a VISSIM microscopic traffic simulation of a road section situated near Munich. For the strategy evaluation, the results in terms of the performance index, waiting time per link, coordination proportion, mean network speed and travel time are compared to a baseline. This is during off peak demand a currently running fixed green wave signalization and during rush hour demand on the evening time of day signalization, having additional both demands

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combined with a speed recommendation with corrections. First results show that during rush hour the overall performance is improved compared to the initial scenario, nevertheless in low demands opposite situation is observed.
A general advantage of such method is that it is easily scalable and transposable to other portions of the network. Since machine learning capabilities are introduced, algorithms are self-adaptive to yearly and seasonally varying demand and no important human involvement is needed. An outlook is given, how to transfer the strategy to the real road and test it in a field test.

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Keywords: system of systems; decentralized optimization; dynamic signal control; speed recommendation

1. Introduction

The concept of Technical Systems of Systems (TSoS) with machine learning capabilities is basis of the Local4Global European project. A TSoS is composed of specific semi-autonomous constituent systems that are working in local environment, optimizing themselves and together improving overall performance of the global level. The main objective of this paper is to describe simulations and their results, preceding application to real test beds. The Munich test bed implementation scheme is illustrated in figure below. Here, occupancy and traffic flow data from constituent systems of class I (signal control) are gathered and sent to the central traffic computer of the road authority. Afterwards, collected data is forwarded to L4G web service location where data from signal controllers are aggregated and refined. After calculation of new signal plans using a distributed signal control strategy and L4GCAO optimiser, plans are sent back to the central traffic computer and from there to signal controllers. The same produced signal plans together with collected position and speed data from mobile telephones are used to calculate speed recommendations for the constituent systems of class II (cooperative vehicles). The exchange of data is made through an application server, where position and speed data together with suggested speed recommendations are collected. For more accurate estimations of speed recommendations, an additional algorithm is integrated for dynamic queue length estimation.

Daily harmonization and learning functions are made by L4GCAO algorithm which is located in L4G web service location.

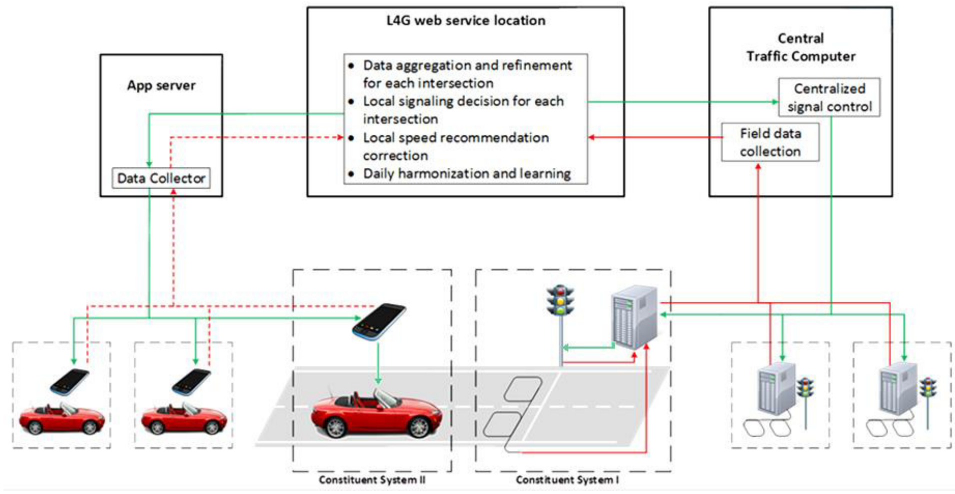

Fig. 1. L4G traffic use case implementation plan.

To evaluate algorithms and overall performance of the TSoS concept, impact assessments of mobility, safety and environment for different control situations are conducted.

2. Munich test bed

The test bed of Local4Global traffic use case is a 7 km stretch, with mostly 2 lanes per direction and 7 intersections in north of Munich (Germany). It has high traffic volumes, strong potential for improvements and comparably good level of hardware equipment. Speed limits vary from 50 km/h to 100 km/h. The microscopic simulation is based on the simulation model used during the KOLIBRI project (Kooperative Lichtsignaloptimierung – Bayerisches Pilotprojekt), thus, main parts of the simulation study already exist and Local4Global builds up on the provided model in VISSIM.

Two traffic demand scenarios have been simulated:

- Demand 1 (off-peak) – 9:30 a.m. to 2:30 p.m.;
- Demand 2 (rush-hour) – 3:00 p.m. to 8:00 p.m.

Currently signal control is made through fixed signal plans coordinated in green wave during the off-peak time. Signal control during rush-hour is rule-based actuated. In the frame of the Local4Global project, new signal plans are developed for a dynamic control through selection from a signal plan library.

3. Methodology

3.1. Signal control strategy

Among the aims of Local4Global project is the development of a signal control strategy that, acting at small scale level (local junctions), optimizes the performance of high scale level – global network. To this end, the following control logic is adopted:

At each junction, the applied local control modifies the cycle time and the green splits based exclusively on local measurements without any coordination or exchange of any kind of information among the network junctions. Cycles and splits are updated regularly, e.g. once per cycle. On the other hand, at longer intervals, e.g. once per day, the so called L4GCAO algorithm is applied to fine-tune (optimise) the parameters used by the local control in order to achieve an optimal performance at global network level.

The local signal control strategy consists of four parts: cycle control, split control, plan selection and data processing. Graphical explanation of the local control logic is provided in the figure below. Here variables on the left of the box are input parameters, those on the right are output parameters.

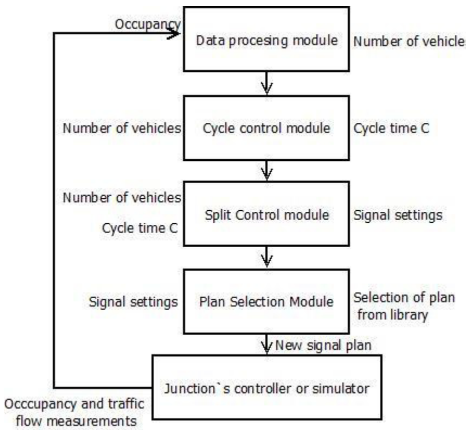

Fig. 2. Overview of the local signal control strategy (Diakaki, et al., 2015).

The cycle control approach is adapted from the TUC (Traffic-responsive Urban Control) strategy, previously developed for the coordinated control of urban networks (Diakaki, et al., 2003) (Kouvelas A. , 2011). It uses a simple feedback-based algorithm. This algorithm modifies the cycle time so that to increase the junction's capacity as much as necessary to limit the maximum observed saturation level. At the same time, it aims to avoid unnecessary cycle increases, namely when the observed high saturation levels are not caused by a corresponding demand increase, rather by other factors such as a slow moving vehicle or a downstream congestion.

Split control is based on the max pressure (MP) algorithm, initially conceived to consider routing and scheduling of packet transmissions in wireless networks (Tassiulas & Ephremides, 1992). The specific MP application is a variant of the MP-setting proposed by Kouvelas et al. (Kouvelas, Lioris, Fayaz, & Varaiya, 2014), and is used to split the previously calculated cycle time to the cycle stages that serve the different traffic streams approaching the junction so that total throughput is maximised.

Therefore, the outputs of the cycle and split control parts of the local strategy are real time traffic-responsive signal control settings. However, according to application specific constraints, these output need to correspond to one of a pre-specified and authorised signal plan available within a library prepared specifically for the Munich test-bed (according to corresponding authorities and regulations). To this end, a plan selection procedure is used, to match the plans produced in real-time to the plans readily available in the library, based on minimization of the Euclidean distance (Diakaki, et al., 2003).

The aforementioned parts of the local strategy include a number of control parameters that affect its performance and efficiency. The identification of appropriate values for these parameters is not an easy and trivial task. For this reason, the cyclic run of L4GCAO algorithm gathers knowledge about the global network performance and optimise these parameters so as to improve the efficiency of the local control strategy in a way that will lead to an improved efficiency at global network level. The L4GCAO algorithm's basic ingredient is the Cognitive Adaptive Optimization (CAO) algorithm developed and tested previously (Baldi, Michailidis, Kosmatopoulos, & Ioannou, 2013) (Baldi, et al., 2015) (Baldi, Michailidis, Kosmatopoulos, & Ioannou, 2014).

3.2. Vehicles speed recommendation strategy

Cooperative vehicles are receiving speed recommendations in order to optimize overall network. The description of its working principle is provided in the following. Firstly, position, speed and direction data of each cooperative vehicle is gathered. Based on this information, the approaching signal controller is identified, and data about the green start and end instants, maximum and minimum speed values, congestion length (using TRANSQUEST algorithm) is gathered. Mentioned maximum and minimum allowed speeds are adjusted by L4GCAO optimizer using equation below:

$$s(t+1) = s(t) + a0 * m(t) + a1 * m(t-1) + a2 * m(t-2) + \ldots.. + an * m(t-n) \quad (1)$$

where:
$s(t+1) =$ maximum or minimum speed recommendation
$an =$ theta factors from L4GCAO algorithm
$m(t-n) =$ speed recommendation parameter (speed or occupancy or queue length)
$n =$ number of previous historical m(t) values

This adjustment defines more accurate boundaries of the speed recommendation. Afterwards, the duration of green time and time until green end in the approaching signal controller is calculated and according to left distance, a speed recommendations is provided to cooperative vehicles. Therefore, drivers could reduce or improve their speed in order to catch green time.

3.3. Queue length estimator

In order to provide accurate speed recommendations, there is a need to estimate the required time for the vehicle to reach the approaching intersection. This calculation could be done only when values of speed, distance to intersection and queue length are known.

The topic of queue length estimation was known for a long time and many techniques exist in literature and practice. Most of algorithms reach their best accuracy when the detectors are placed approximately 100–150 m upstream of the traffic signal. However, traffic-actuated signal control systems in Germany use mostly the time lag method described in the German traffic signalling guidelines (RiLSA, 1992), and detectors are then usually located 15–50 meters upstream of the stop-line. The back-up estimations that are taking into account only cars between stop line and detector often do not work efficiently, while there could be cases when queue length is far behind the detector. For the reasons above, a patent protected algorithm TRANSQUEST from TRANSVER was used. This algorithm, calculates congestion length while detectors are in the middle of congestion or even in cases when the length of queue is 10 times greater than distance between detector and stop-line. (Muck, 2002)

For this algorithm two quantities, which are mainly influenced by the corresponding signal, are most important:

- The fill-up time which describes time interval from start of red time of a signal till occupancy of detector reaches maximum. This value represents the speed of vehicles that are approaching the traffic signal at the end of green time;
- The time of occupancy of a detector during the green time, which could show whether there are obstacles that disturb vehicles to leave.

The algorithm is based on the following relation considering the fill-up time:

When congestion is not resolved after the end of green time, a number of vehicles cannot exceed the stop line as if they have been in free flow. In such case, the fill-up time falls very often below a certain reference period, which depends on the distance between the detector and the stop-line.

Empirical study showed that frequency of fill-up time falling under the reference period correlated up to a certain degree with the length of the congestion. The event of falling below the reference period is described using a congestion characteristic δ as follows:

$$\delta = \begin{cases} 1 & d_t \leq d_{t0} \\ 0 & d_t > d_{t0} \end{cases} \quad (2)$$

where:
$d_t =$ the measured filling time at the end of the signal opening
$d_{t0} =$ reference value

3.4. Simulation Model

Before real implementation in roads, there is a need to test traffic use case using microscopic traffic simulation. The simulation work is made of four components (Figure 3):

- VISSIM simulation environment with two constituent system classes (cooperative vehicles and signal control systems);
- VISSIM COM interfaces controlling constituent systems and queue length estimator;
- Shared folder with directories for speed correction parameters, selection of signal plans and traffic flow information;
- Local4Global Optimization system, the control component responsible for global optimization through the selection of suitable signal plans and correction parameters for better speed recommendations.

Firstly, flow and occupancy data from signalized junctions are gathered using VISSIM COM interface and then sent to LOCAL4Global optimization system where signal plans are selected by the local signal control strategy taking into account an (theta factors) values from L4GCAO algorithm in order to improve next selection. Afterwards, using the same VISSIM COM interface, new signal control decisions in real-time are activated in VISSIM signal controllers.

Additionally, another VISSIM COM interface collects speed and position data from other constituent systems – cooperative vehicles and calculates speed recommendation according to collected data, speed correction parameters and selected signal plans from Local4Global optimization system.

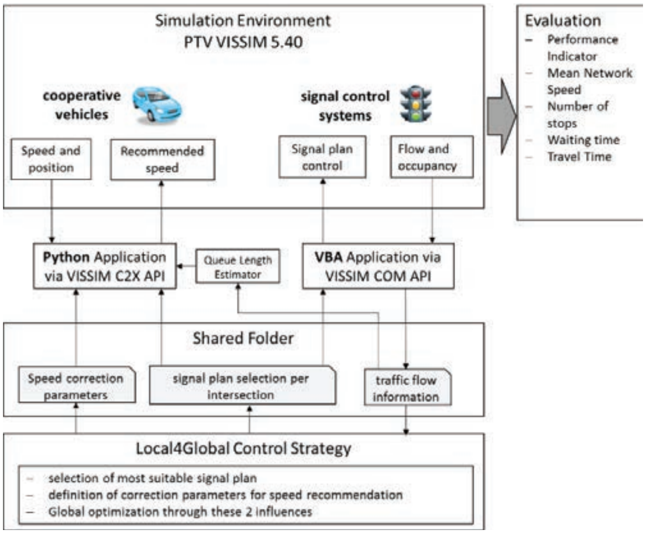

Fig. 3. Simulation components.

3.5. Mobility impact assessment

Evaluation for mobility impact assessment is made using multiple criteria: level of service, mean network speed and travel time. The indicator we adopt to consider most of traffic variables is the performance index (PI), which describes traffic quality in the network considering waiting time and number of stops. Formula below is according to Brilon et al. (Brilon & Wietholt, 2013) and on the calculations of the traffic control tool TRANSYT (Robertson, 1969). Harmonization of input parameters uses the assumption that a stop is equal to 60 seconds. It is important to mention that a higher value of PI means a lower performance of network.

$$PI = \frac{G_W * \sum W_{k,z} * Q_{k,z} * g_z + G_H * \sum H_{k,z} * Q_{k,z} * g_z}{\sum Q_{k,z} * g_z} \quad (3)$$

where:
PI = performance index
G_w = weight of waiting times (here: 1)
G_H = weight of number of stops (here: 60)
$W_{k,z}$ = sum of waiting times per hour for all vehicles on intersection k, branch z
$H_{k,z}$ = sum o fnumber of stops per hour for all vehicles on intersection k, branch z
$Q_{k,z}$ = traffic volumes of all vehicles on intersection k, branch z

3.6. Traffic safety impact assessment

The growing amount of traffic users makes traffic safety an important issue, inciting researchers to find more efficient safety measures. The definition of safety metric of a traffic facility is simply the number of crashes expected to occur in a certain time period. However, prediction of exact numbers is rarely accurate and that led researchers to develop surrogate models that estimate at least probability of crash rates by using traffic conflicts technique. Identification of conflicts could be done either by human observers at intersections, which is costly and subjective, or by using microscopic traffic simulations. Latter method defines that conflict event must meet two requirements (Siemens Energy & Automation, 2008) (1) one of the vehicles must change its movement to avoid conflict, and (2) the result must be less than specified threshold.

The measurements made on each single potential conflict event are specified as minimum time to collision (TTC), minimum post-encroachment time (PET), initial deceleration rate of the reacting vehicle (DR), maximum speed of the two vehicles (MaxS), maximum difference between the two vehicle speeds (DeltaS), maximum deceleration of the second vehicle (MaxD), maximum DeltaV value of either vehicle in the conflict (MaxDeltaV). In the paper, the Surrogate Safety Assessment Model (SSAM) software was used in order to calculate these measurements.

3.7. Environment impact assessment

The model adopted for environmental impact assessment and used in this paper is VT-Microscopic Vehicle Fuel Consumption and Emission Model. It is based on instantaneous speed, acceleration data, fuel consumption and emission measurements that were collected by the Oak Ridge National Laboratory (ORNL) for eight light-duty vehicles and light-duty trucks. Fuel consumptions and emissions rates for hot-stabilized and steady state operations were obtained through field and dynamometer testing. To get accurate results, vehicles were tested on real conditions and then the same conditions were replicated on a chassis dynamometer measuring fuel consumptions and emissions. In the model, it is assumed that speed and acceleration have major impact on fuel consumptions and emissions, thus, only them are taken into account (Yue, 2008).

4. Overview of the simulation results

4.1. Traffic performance

Figures below illustrate performance index in different scenarios. The abbreviations are explained in the following:

- Basis* – initial scenario with fixed signal plan and 10% of cooperative vehicles (Obermaier, 2015);
- L4G C2X00 – scenario using L4G with optimization turned on for signal control. No cooperative vehicles are introduced;
- L4G C2X10* – scenario using L4G with optimization turned on for signal control. Penetration rate of cooperative vehicles is set to 10% (Obermaier, 2015);
- L4G C2X10 FT QLE n=6 – scenario using L4G with optimization turned on for signal control and speed recommendation (using 6 previous values of queue length). Penetration rate of cooperative vehicles is set to 10%;
- L4G C2X20 FT QLE n=6 – same scenario as previous one, but penetration rate of cooperative vehicles is set to 20%.

It could be observed that fixed signal plan is showing best performance in demand 1 (Figure 4), since performance index is lower by 13% compared to the second lowest PI (L4G C2X00). Introduction of cooperative vehicles decreased performance by 5% in case with penetration rate of 10% and by 11% in case with penetration rate of 20%. Nevertheless, turning off optimization of speed recommendation has shown 13% higher PI compared with the scenario without cooperative vehicles. Reasons that L4G concept is not improving the situation here as expected could be that cooperative vehicles make the traffic too smoothed, since they have information about signal control timings. Another reason could be that speed recommendation algorithm needs more tuning together with adjustments of L4GCAO parameters.

With higher traffic volumes in demand 2 initial scenarios with fixed signal plans (basis) is showing worst performance in terms of total PI. The scenario having the lowest PI (L4G C2X00) is 40% lower than the basis scenario. Furthermore, the introduction of cooperative vehicles also decreases the performance by 3%. Nevertheless, scenario with fine tuning of speed recommendation (L4G C2X10 FT QLE, n=6) decreased PI by 18% compared with scenario without optimization of speed recommendation.

Finally, the scenario with higher penetration rate cooperative vehicles (L4G C2X20 FT QLE, n=6) has shown 21% higher PI than the same scenario with 10% of cooperative vehicles.

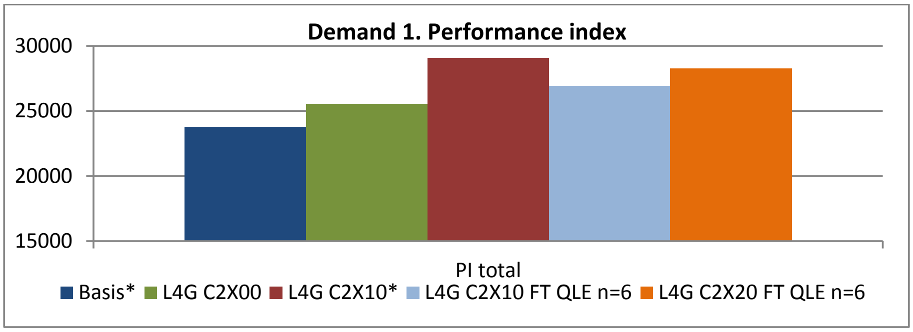

Fig. 4. Demand 1. Overview of performance index (Aliubavicius, 2015).

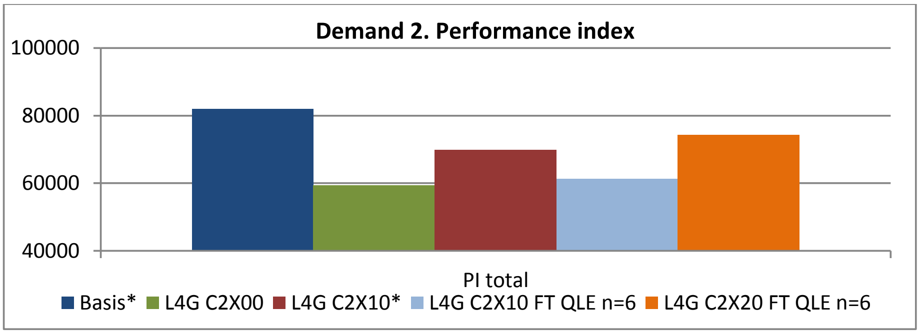

Fig. 5. Demand 2. Overview of performance index (Aliubavicius, 2015).

4.2. Impact on safety

Impact assessment on safety was conducted using SSAM software. Mean values of the safety measures per demand are listed in the tables below.

Table 1. Summary of safety impact assessment (Aliubavicius, 2015).

Demand 1	**L4G C2X00**	**L4G C2X10 FT**	**L4G C2X20 FT**
TTC	0.95	0.95	0.99
PET	1.66	1.68	1.66
MaxS	6.88	6.92	7.04
DeltaS	3.48	3.42	3.39
DR	-2.07	-2.06	-2.17
MaxD	-2.86	-2.98	-3.15
MaxDeltaV	2.02	1.95	1.91

Demand 2	**L4G C2X00**	**L4G C2X10 FT**	**L4G C2X20 FT**
TTC	0.78	0.79	0.76
PET	1.65	1.66	1.62
MaxS	4.52	4.63	4.32
DeltaS	2.75	2.78	2.67
DR	-2.59	-2.55	-2.62
MaxD	-3.2	-3.19	-3.18
MaxDeltaV	1.53	1.55	1.49

The maximum value of minimum time to collision (TTC) is set to 1.5 s. TTC in demand 1 is always 0.95 s, except in L4G C2X20 FT simulations where an increase of 4% is observed. In demand 2, the value is lower (about 0.78 s) and does not fluctuate much over different simulation scenarios.

Post-encroachment time (PET) is limited with an upper boundary of 5 s. The values in demand 1 and demand 2 are respectively in range of 1.62 s and 1.68 s, thus fluctuations are significantly small.

Maximum speed of the two vehicles (MaxS) is evaluated only when TTC value is less than specified threshold. In demand 1 MaxS is about 6.9 m/s what is about 30 m/s higher than in demand 2. DeltaS value in demand 1 is ~3.4 m/s and in demand 2–2.7 m/s.

Values of DR, MaxD and MaxDeltaV (meters/seconds) are very similar over different runs and always slightly smaller in demand 2 case.

It can be concluded that values of safety criterions are very similar in all scenarios and no significant negative effect was observed.

4.3. Impact on environment

Impact assessment on environment was analysed using VT-Micro software. In the table below, environment parameters – emissions of carbon dioxide (CO2) and fuel consumptions – were compared. Here D1 and D2 refer to the two demand cases.

Table 2. Summary of environment impact assessment (Aliubavicius, 2015).

		CO_2 (kg/unit)	FUEL (kg/unit)
L4G C2X00	D1	0.00494874	0.00240058
	D2	0.00366763	0.0017471
L4G C2X10 FT	D1	0.00494356	0.00239473
	D2	0.00370727	0.00176521
L4G C2X20 FT	D1	0.00488254	0.00235976
	D2	0.00323783	0.00152631

In demand 1, values of emissions show a slight decrease, nevertheless the deviations are not significant. In demand 2, emissions were lower by approximately 25% which was a consequence of lower fuel consumptions per vehicle – in demand 1 every vehicle consumed ~0.0024 kg of fuel, while in demand 2– ~0.0017 kg.

Finally, it could be concluded that fuel consumption and CO_2 emissions are varying very slightly, and it is difficult to draw a conclusion that one or another scenario show better results in terms of environment.

5. Conclusions and outlook

Even though results of learning to control/control for learning algorithm in low demands are still not satisfying, this approach shows successful trends in demand with higher volumes. Furthermore, it does not ask for frequent revision of the signal plans, since machine-learning capabilities are introduced together with dynamically reacting algorithm for signal plan creation. This paper shows that a performance increase has no negative effect on safety and environment, which may mean that this strategy has a significant potential for increasing overall performance of the intersections.

The simulation results show that an increased penetration rate of informed drivers contribute indirectly in reducing fuel consumption. This is in line with findings from former researches, where a highly optimized (coordinated) signalization reduced the fuel consumption. An extra benefit for informed drivers regarding fuel consumption could not be found in real traffic (Krause, Yilmaz, & Bengler, 2014). Nevertheless, the driver information system was formerly rated with high acceptance (Krause, Knott, & Bengler, 2015) and formerly showed a reduction in speeding behaviour (Krause, Yilmaz, & Bengler, 2014).

The next step in the project is to implement the L4G strategy on the real road and it is planned that the broad public can participate in the project with an Android application (app) on the road section in the North of Munich. This interface for driver information shall be used while driving. Therefore, special care must be taken concerning driver distraction. In a former project, the user interface was already tested with subjects, reading the cognitive workload (Krause, Knott, & Bengler, 2015) and glance durations (Krause, Weichelt, & Bengler, 2015).

The field test could be used as a proof-of-concept to observe the driving behaviour, long-term usage and acceptance of the app; as well as the implementation and adaption of the L4G concept to a real world example.

In the project Local4Global, this concept will be also applied to a second use case in which the energy consumption for energy management of an office building is optimized.

Acknowledgement

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