Procedia Computer Science
Volume 80, 2016, Pages 2019–2029
ICCS 2016. The International Conference on Computational Science

Information Dynamics in Transportation Systems with Traffic Lights Control

Sorina Costache Litescu[1],Vaisagh Viswanathan[1],Heiko Aydt[2],Alois Knoll[3],

[1] TUM CREATE sorina.litescu@tum-create.edu.sg
[2] Singapore-ETH Centre
[3] Technical University of Munich (TUM)

Abstract

Due to recent advanced communication possibilities between traffic infrastructure, vehicles and drivers, the optimization of traffic lights control can be approached in novel ways. At the same time, this may introduce new unexpected dynamics in transportation systems. Our research aims to determine how drivers and traffic lights systems interact and influence each other when they are informed one about another's behaviour. In order to study this, we developed an agent based model to simulate transportation systems with static and dynamic traffic lights and drivers using information about the traffic lights behaviour. Experiments reveal that the system's performance improves when a bigger share of drivers receive information for both static and dynamic traffic lights systems. This performance improvement is due to drivers managing to avoid stopping at red light rather them adapting their speed to different distances to the traffic lights systems. Additionally, it is demonstrated that the duration of the fixed phases also influences the performance when drivers use speed recommendations. Moreover, the results show that dynamic traffic lights can produce positive effects for roads with high speed limits and high traffic intensity, while in the rest of the cases static control is better. Our findings can be used for building more efficient traffic lights systems.

Keywords: Information propagation; Dynamical information; Traffic dynamics; Transportation systems; Traffic lights; Traffic control; Human complex systems;

1 Introduction

Understanding and controlling complex systems is a very hard goal in natural or man made systems [17]. There are two independent factors that make the controlling difficult: the system's architecture, represented by the physical network, and the dynamical rules that capture the time-dependent interactions between the network components [17]. Complex transportation systems face a major challenge regarding the efficiency of the traffic flow. With an increasing

This work was financially supported by the Singapore National Research Foundation under its Campus for Research Excellence And Technological Enterprise (CREATE) programme.

Selection and peer-review under responsibility of the Scientific Programme Committee of ICCS 2016

doi:10.1016/j.procs.2016.05.522

urbanization, the amount of cars is growing as well, this causing numerous traffic problems. One way of steering the traffic is by creating an efficient traffic lights control systems. Nevertheless, traffic lights can cause discomfort to drivers. Surveys state that there are cases when drivers prefer to change their routes to avoid stopping to multiple traffic lights on the way [4] [20].

With the recent advancements in communication networks, computers, and sensor technologies, there is an increasing interest in developing optimized traffic lights control systems. On the one hand, new technological developments such as real time responsive traffic lights are implemented in major cities [26]. On the other hand, Dedicated Short-Range Communication (DSRC) systems, navigation devices or smart phone applications communicate and assist drivers in their trips. DSRC systems have already been installed on many roadways by the US Department of Transportation [22] and are expected become ubiquitous in the future [1]. For example EnLighten [8] is a smart phone application that connects to the traffic signal network and predicts the behaviour of traffic lights by communicating to DSRC systems on the roads. Using such technology, BMW drivers are informed when a stoplight changes [22].

The interaction of these new technologies not only offer new possibilities for improving the traffic but at the same time may introduce new unexpected complex dynamics. Receiving information about the next traffic light can have many advantages, mostly in terms of safety, but also convenience. The drivers are less surprised by sudden change to red color and they try less to accelerate so that they catch green light before it turns red. However, it is interesting to understand what is the effect on the traffic performance when a massive amount of drivers react simultaneously to information about the traffic lights. Also, how the overall traffic situation is affected by the traffic lights adapting to the traffic flow.

In this study we use an agent-based simulation of a transportation system to analyse how drivers and traffic lights systems interact and influence each other when they are informed one about another's behaviour. The drivers receive information about how to adapt the speed to avoid stopping for the red color when possible. Generally, traffic lights have two types of control: static, with a fixed phase duration and dynamic or traffic responsive, optimised the phase duration to prioritise directions for larger groups of cars [19]. We evaluate how the the overall traffic performance is impacted by the responsiveness of the dynamic traffic lights and the usage of speed recommendation simultaneously, by different shares of the traffic participants.

The current paper is organised as it follows: Sections 2 introduce the related work done on the traffic lights control strategies and how traffic recommendations have been used to steer traffic. Sections 3 and 4 describe the computational model, the experimental set-up and our results. Section 5 presents the significance and the conclusions of our study.

2 Related Work

The concept of traffic lights appeared in ancient times, during the Roman Empire when citizens noticed a conflict between pedestrian and equine travellers. Not until 1860s a practical solution was implemented in London in the form of a traffic control device with arms to command drivers at intersections. The modern traffic light was invented in America. New York had a three color system in 1918 manually operated from a tower in the middle of the street. In 1926 the first automatic signals, activated by a timer, were installed in London [2]. The control of traffic lights made a big turn with the use of computers (the first analogue computers in Denver in 1952 [18] and the first digital computers in 1959, in Toronto [26]). Nowadays, in many cities the controllers operate in real-time by applying a control action in response to the current traffic state. However, there are still numerous statical traffic lights control in operation [19].

In this paper, similar to other studies [19], we categorise the traffic light control as static and dynamic. Usually, for static traffic lights, the phases have a fixed duration based on historical traffic data. The green time can be varied between pre-timed minimum and maximum lengths depending on flows. The fixed timing of the phases is optimised by fine-tuning a set of intersections along the arterial road but there are a few attempts of optimising the timing by looking at a broader scale. For example in case of the city of Lausanne, signal times at intersections are distributed across the entire city, improving the traffic globally. For dynamic control, a traffic-actuated controller operates based on traffic demands as registered by the actuation of vehicle and/or pedestrian detectors [19].

Lately, the traffic responsive solutions have gathered more attention while the fixed-time strategies are used more for understanding the traffic conditions. There are studies where fixed-time strategies are proposed as robust control solutions or used directly or indirectly to derive the real-time strategies [19]. The real-time responsive optimization is achieved by extending the capabilities of basic traffic lights to either communicate with each other or communicate with vehicles. Traffic lights control systems can be centralised (i.e., SCOOT [25], an adaptive system based on information on traffic flow from detectors) or decentralised (i.e., [12] [10] [5]).

Modern traffic lights based on self organization seem to perform better than the traditional methods [12]. In this study, the authors use short sighted anticipation of vehicle flows and platoons. A decentralized emergent coordination based on local interactions traffic lights control is achieved that manifested in a reduction of the average travel time and the emergence of green-waves. In [10] and [5] the self-organization is achieved as well by probabilistic formation of car platoons. In turn, the platoons affect the behaviour of traffic lights, prompting them to turn green before they have reached the intersection. These methods are based on local rules and no communication between traffic lights which means that the decentralized coordination is based on local interactions of traffic lights control and the traffic flow. The cars that have been waiting longer and larger groups of cars are prioritised to cross the intersection. In this case, the traffic lights control is considered rather an adaptation problem than an optimization problem.

In [6] the authors use micro-auctions as the organizing principle for incorporating local induction loop information. When a phase change is permitted, each light conducts a decentralized, weighted, micro-auction to determine the next phase. Other studies deal with the prediction of traffic signals enabling innovative functionalities such as Green Light Optimal Speed Advisory (GLOSA) or efficient start-stop control [23].

Unlike the current research, this study proposes a systematic analysis of the interaction between drivers and traffic lights systems. Each type of traffic lights control is described in more details in Section 3. We evaluate how dynamic traffic lights systems perform in comparison to static traffic lights systems. At the same time, we investigate how the fact that drivers use information about the traffic lights behaviour and interact with responsive and static traffic lights can impact the overall performance.

Next, we present the existing work done on the effect of traffic information disseminated in transportation systems. The traffic lights system coexist with drivers accessing information about the traffic state. Surveys show that, in most cases, traffic participants trust and follow the navigation recommendations [9]. Systems for traffic planning in the presence of congestion have been researched by [3, 13, 14, 15] by controlling the information given to each participant (proposing certain routes) to achieve individual or global social optimum performance [3]. The studies done in [21] and [24] analyse the traffic performance when information about congestion, containing either local details about the neighbouring nodes or global details about the traffic networks, is disseminated according to a model of information dissemination. The authors showed that the best performance is achieved when limited local knowledge is used.

In [16], the authors show how traffic is affected by the amount of drivers receiving information about the traffic situation. Moreover, in this case the information provides details about what routes the drivers should take to avoid congestion. Providing inappropriate information to the traffic participants sometimes leads to undesirable situations such as one-sided congestion [11]. Other study have investigated methods to facilitate network coordination by disseminating knowledge about the network that may poss less risk than modifying network structure [7].

In contrast to the previous research, we investigate how the global traffic performance is affected by the fact that both drivers and traffic lights systems adapt to the traffic situation at the same time, by using certain traffic information. In our study, the drivers receive information about what speeds they need to use to avoid stopping for the red light. Additionally, we evaluate how different shares of drivers being informed can impact the overall traffic state for both cases of static and dynamic traffic lights systems.

3 Computational model

Planning efficient traffic lights systems requires first an analysis on how the responsiveness of the traffic lights can impact the global traffic state. Moreover, it is important to understand the effect of a massive amount of drivers using speed recommendations. Microscopic agent based simulations are suitable computational tools for simulating such scenarios. The simulation (SEMSim) consists of the road network (road lanes, traffic lights) and agents (driver-vehicle units). By simulating individual agents that drive on roads and interact with the traffic lights systems, new interesting emergent traffic patterns can be observed. SEMSim is described in more details in [27], here we give a brief overview of the relevant parts.

At the beginning of the simulation, each agent is assigned an itinerary generated by a probabilistic routing technique. The origins of trips are peripheral lanes, without predecessors. A route is generated based on the turning probability for each intersection (equally distributed in our case). When the vehicle reaches a lane without successors, this link is marked as destination and the vehicle is removed from the simulation. We vary the traffic intensity by changing the inter-arrival time of generation agents (IA_{time}) and the total number of agents (N_{total}).

3.1 Road Network Model

A road Y from the road network, is characterised by a tuple with road length, number of lanes, minimum speed and maximum speed: $Road_Y =< v_Y^{min}, v_Y^{max}, N_{Lanes}, Length_Y >$. We vary the speed range v_Y^{min} and v_Y^{max} to evaluate the impact of the agents adjusting the speed.

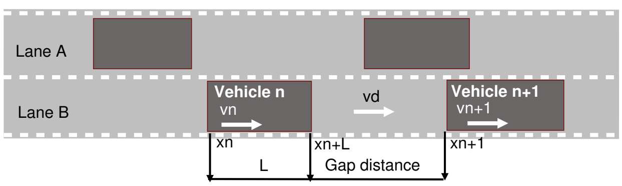


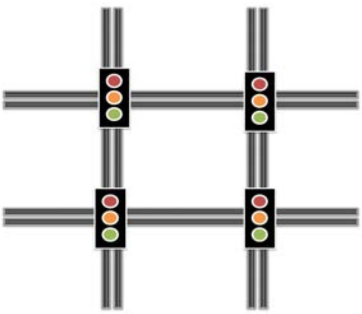
Figure 1: In an IDM scenario, a vehicle i is characterised by the current position x_i and the current speed v_i. D_{gap} is the gap distance between vehicles. The road is characterised by minimum and maximum speed, length and desired speed v_d: $Road_Y =< v_Y^{min}, v_Y^{max}, N_{Lanes}, Length_Y >$.

3.2 Driver Vehicle Unit Model

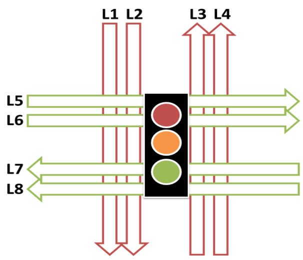
The agents (Drive-Vehicle Unit) move on roads with an acceleration and deceleration using IDM and lane-changing models. A vehicle i follows the car in front vehicle $i+1$ at a speed less than the desired speed of the road v_d, which is a value between v^{min} and v^{max}. The current speed of car i, v_i is adapted to the speed of car $i+1$, v_{i+1} to maintain a gap distance greater than D_{gap}. Where D_{gap} is a parameter of the IDM model that specifies the preferred distance between cars [16]. IDM calculates a instantaneous acceleration (or deceleration) and displacement of vehicle i for a time step δt by considering its current speed and position (v_i and x_i), the desired speed (v_d), the current speed and the position of the car in front (v_{i+1} and x_{i+1}). There are also parameters that specify vehicle length ($L_{vehicle}$), time headway (t_h) for safe acceleration and deceleration, and maximum acceleration and deceleration (a_{max}, d_{max}). There are two type of agents: informed and uninformed. The informed differ from the uninformed ones as they receive information about the speed they need to use to avoid stopping at the red light.

To capture a more realistic traffic behaviour a lane changing model is also implemented. There are a few situations when vehicles need to change the lanes: when vehicles need to turn to follow their route itinerary, or when faster vehicles need to overtake the slower vehicles by shifting to faster lanes. In our case, the agents can use two lanes available on each road as seen in Fig. 1.

3.3 Traffic lights control systems



(a) Road network. Each road has 4 lanes(2 in each direction), a fixed $Length_Y = 900m$ and a maximum speed v_Y^{max} with different values(for each scenario).



(b) Traffic lights intersection of $Road_A$ and $Road_B$. $Lanes$ L_1, L_2, L_3 and L_4 are associated to $Phase_1$ and L_5 ,L_6,L_7 and L_8 are associated to $Phase_2$.

Figure 2: Traffic lights systems placement on roads

Traffic lights systems are simulated as part of the road network infrastructure being located at certain intersection of roads. They contain lanes that are called links. Links are special roads that connect two road sections in an intersection. The links can be either *active* or *inactive*. A traffic lights system consists of a set of mutually compatible phases. The green or red color of phases are simulated by controlling the accessibility of the links. A cycle of the traffic lights systems contains all the phases associated with the intersection active at least once. A phase is characterised by duration and a set of links (lanes) $Phase_x =< \delta^{phase}, Lanes >$. For example, Fig. 2b illustrates a traffic lights intersection with two roads $Road_A$ and $Road_B$. $Lanes$ L_1, L_2, L_3, L_4 are associated to $Phase_1$ (red light) and L_5 ,L_6,L_7, L_8 to $Phase_2$ (green light).

	parameter description	min value	max value	incremental step
IA_{time}	Inter-arrival time	$1[s]$	$5[s]$	$1[s]$
N_{total}	Total number of agents	$500[agents]$	$2500[agents]$	$1000[agents]$
v^{max}	Roads speed range	$15[m/s]$	$20[m/s]$	$5[m/s]$
p	Percentage of informed agents	0%	100%	10%
D^{Adj}	Adjustment distance	$0[m]$	$900[m]$	$100[m]$
δ^{Phase}	Phase duration	$11[s]$	$135[s]$	$1[s]$

Table 1: Main parameters used in the experiments.

Traffic lights systems can be static or dynamic, depending on how we determine the phase duration δ^{Phase}. Static traffic lights have the active phase duration fixed at the start of the simulation $\delta^{Phase} = k$. Dynamic traffic lights have a variable duration, determined each timestep based on the number of cars that pass trough the local intersection link. The phase weight (w^{Phase}) considers the number of cars passing the link at the current time. All the phases in the of a cycle are taken into consideration and each duration is a ratio of the weight from the sum of total weights of phases of a cycle (w^{Total}): $\delta^{Phase} = w^{Phase}/w^{Total}$.

The informed agents receive speed recommendations to avoid stopping at the red light. Only the agents situated at a distance smaller than the adjustment distance (D^{Adj}) can receive information. The recommended speed is higher then half of v_Y^{min}.

4 Experimental setup

The purpose of the experiments is two-fold: We analyse how the traffic performance is affected by traffic lights being responsive to the traffic situation. At the same time, we investigate how the fact that drivers use speed recommendations can impact the performance. For this, we identify three case studies. First, we use dynamic traffic lights that react to the traffic situation but the drivers are not informed. In the second case, all drivers receive traffic lights information but the traffic lights are static. In the third case, both the drivers and the traffic lights have information about each other and react accordingly. The main parameters used for this study are defined in Table 1.

For our experiments we use a simplified scenario of the road network and traffic lights described in Fig. 2a and 2b. Each road is characterised by the next attributes: $Road_Y =< 0.9 * v_Y^{max}, v_Y^{max}, 2[lanes], 900[m] >$. *Low* traffic intensity is generated for $IA_{time} = 5[s]$ and $N_{total} = 500[agents]$, *medium* traffic intensity is generated for $IA_{time} = 3[s]$ and $N_{total} = 1500[agents]$ and *high* traffic intensity is generated for $IA_{time} = 1[s]$ and $N_{total} = 2500[agents]$.

Next we define the global performance indicator, where t_i is the trip duration and d_i is the trip distance of an agent i. N_c is the total number of agents to complete their trip.

$$I_P = \frac{1}{N_c}\sum_{i=0}^{N_c}\frac{d_i}{t_i}, \tag{1}$$

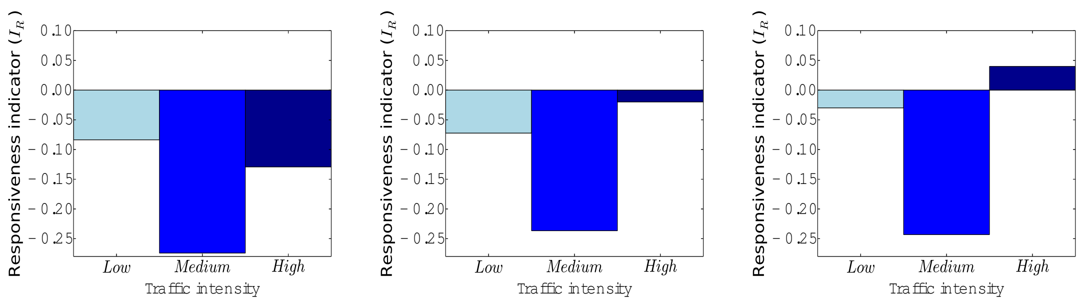
4.1 Dynamic traffic lights are responsive to the traffic situation

In the first study we aim to determine how the real-time traffic responsiveness of the traffic lights can impact the overall traffic performance (I_P defined in Eq. 1). The agents are not informed ($p = 0\%$), $D^{Adj} = 900[m]$, $v^{max} = 20[m/s]$, $\delta^{Phase} = 45[s]$. For this we define the responsiveness indicator I_R that shows the impact on I_P of the *dynamic* traffic lights control in comparison to the *static* one for each level of traffic intensity *low, medium and high*:

$$I_R = (I_P^{Dynamic} - I_P^{Static})/I_P^{Static} \tag{2}$$

where I_P^{Static} is the reference performance indicator.

Fig. 3 shows that dynamic traffic lights control produces a worse effect on the traffic than the static one for lower levels of traffic intensity. However, there are cases when the dynamic traffic lights control outperforms the static one for high traffic and high speed roads ($v^{max} = 20[m/s]$).



(a) $v^{max} = 10m/s$ (b) $v^{max} = 15m/s$ (c) $v^{max} = 20m/s$

Figure 3: Illustration of the he effect of dynamic traffic lights in the traffic using responsiveness indicator I_R(defined in Eq. 2). None of the agents have information ($p = 0\%$), only the traffic lights are responsive to the traffic situation for roads with different v^{max}.

4.2 Drivers adapt their speeds based on navigation recommendations

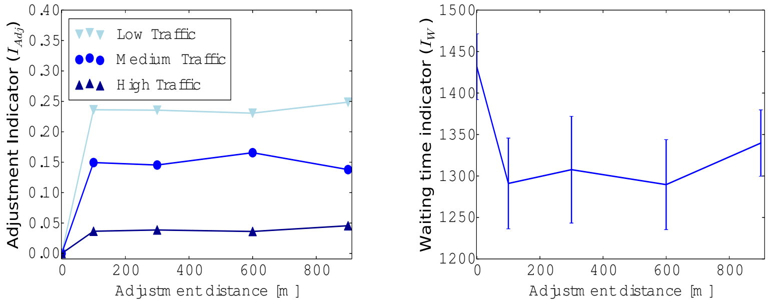
In the second study we analyse what is the effect on the overall traffic when a massive amount of drivers are using speeds recommendations. In this case the traffic lights are *static* and all the agents are informed ($p = 100\%$, $\delta^{Phase} = 45[s]$, $v^{max} = 20[m/s]$). It is important to note that our scenario implies that traffic is generated symmetrically in both directions (north-south/ south-north and east-west/ west-east). The waiting time in one direction is compensated by the fact that more cars are going on the green wave in the other direction.

First we investigate how the adjustment distance D^{Adj} influences the traffic. We define:

$$I_{Adj} = (I_P^{D^{Adj}} - I_P^0)/(I_P^0), \tag{3}$$

where $I_P^{D^{Adj}}$ is the performance indicator defined in Eq. 1 and I_P^0 is the performance indicator for the reference case of $D_{Adj} = 0[m]$

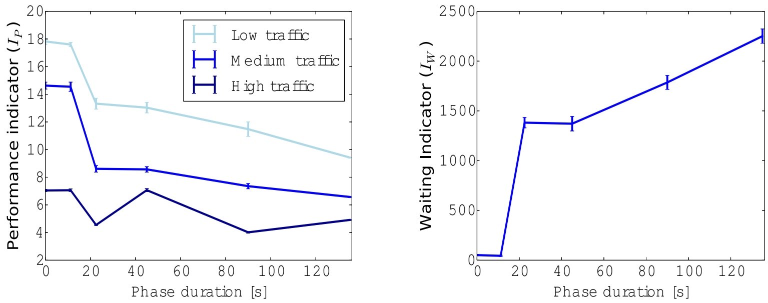
Fig. 4a illustrates the effect of drivers using speed recommendations for different values of D^{Adj}. The adjustment distance indicator I_{Adj}, defined in Eq. 3, is affected even by small values of the $D_{Adj} = 100[m]$. Nevertheless, for higher D_{Adj}, I_{Adj} does not have a significant variation. This effect is explained by observing how much time the drivers stop at the traffic lights. Even for small D_{Adj}, some drivers manage to avoid stopping at the red light when using the speed recommendation. Fig. 4b shows how much the cars stop at the red light by using the waiting indicator I_W, which shows the total number of timesteps when agents are stopped. We notice that I_W is improved even for small values of D_{Adj} ($D_{Adj} = 100[m]$). It is important to note that, the fact that agents adapt their speed does not cause a significant difference on the traffic performance I_P but rather the fact that they avoid stopping at the red light.



(a) I_{Adj} (Eq. 3) for low, medium and high traffic intensity

(b) Waiting Indicator I_W (number of timesteps) for medium traffic intensity

Figure 4: Illustration of the effect of drivers adapting their speed for different values of the adjustment distance D^{Adj} for *static* traffic lights.



(a) I_P expressed in m/s (Eq. 1) for low, medium and high traffic intensity

(b) Waiting Indicator I_W (number of timesteps) for medium traffic intensity

Figure 5: Illustration of the he effect of drivers using speed recommendations for different phase durations δ^{Phases} of *static* traffic lights.

Further, we analyse how the phase duration influences the traffic situation. Fig. 5a illustrates the effect of drivers using speed recommendations for different phase duration δ^{Phase}. In this case $D^{Adj} = 900[m]$ and $v^{max} = 20[m]$. I_P, defined in Eq. 1, has better values for smaller δ^{Phase} ($< 11s$). For high values, δ^{Phase} does not have a significant impact on the traffic performance. This effect is explained in Fig. 5b using the waiting indicator I_W that shows the total number of timesteps when the agents are stopped. It can be observed that, for higher δ^{Phase}, I_W increases.

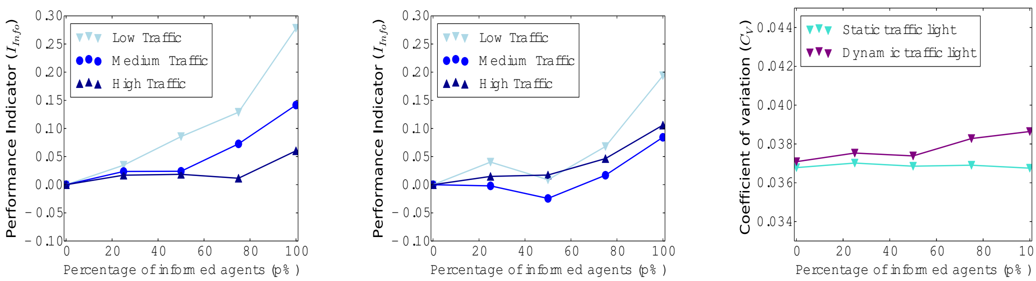
4.3 Both drivers and the traffic lights adapt to traffic

In the third study, different shares of agents receive navigation recommendations about how to adapt their speed in order to avoid stopping for the red light ($p \in [0, 100]\%$, $D^{Adj} = 900m$, $\delta^{Phase} = 45[s]$, $v^{max} = 20[m]$). For this we define the information indicator as it follows:

$$I_{Info} = (I_P^p - I_P^0)/(I_P^0), \tag{4}$$

where I_P^p is the performance indicator defined in Eq. 1 and I_P^0 is the performance indicator for the reference case of $p = 0\%$.

In Fig. 6a and 6b we notice that the traffic is improved when more agents are using information both in the case of static and dynamic traffic lights. For static traffic lights the reference I_P^0 for low, medium and high traffic intensity have the following values : 10.1m/s, 7.4m/s and 4.2m/s. For dynamic traffic lights I_P^0 are 9.8m/s, 6.1m/s and 4.4m/s. Therefore, the reference cases for static and dynamic traffic lights have similar values. The increase rate is smaller for dynamic traffic lights because, in this case, the instability of the system is growing when more agents receive speed recommendations. This effect is shown in Fig. 6c by the coefficient of variation of the average speeds on roads: $C_V = \frac{\sigma}{\mu}$ is defined as the ratio of the standard deviation and the mean of the total speed on roads. In conclusion, informing more agents is beneficial for both static and dynamic traffic lights systems. Nevertheless, in the case of dynamic control, the transportation system is affected by a higher level on instability.



(a) I_{Info} (defined in Eq. 4) for static traffic lights.

(b) I_{Info} (defined in Eq. 4) for dynamic traffic lights.

(c) Coefficient of variation of the average speeds on roads C_V for medium traffic

Figure 6: The effect of different shares of drives using speed recommendations

5 Conclusions

We presented our experimental results involving traffic lights control and information dissemination in transportation systems. In this study we considered two types of traffic lights: static and dynamic. The static traffic lights have a pre-defined fix phase duration. The dynamic traffic lights have smarter adaptive mechanisms for reacting to the traffic situation. Our model of disseminating information consists of selecting different shares of drivers to receive speed recommendations. The drivers use the recommendations only if they are closer than a specified adjustment distance to the traffic light. It was assumed that all agents are rational and follow the recommendations. Future work will aim to extend the existing models of the real time traffic responsive traffic lights by considering more details when determining the phase duration. In addition, we plan to use more realistic city networks and human behaviour models to determine how agents decide to use the real time speed recommendations.

The experimental results show that the system's performance is affected by the level of responsiveness of the traffic lights. Dynamic traffic lights perform worse than the static ones for roads with smaller speeds limits. However, for rapid roads with high traffic intensity, the responsive traffic lights control can produce positive effects. When all drivers receive information, the distance to the traffic lights system within they adapt their speeds does not influence significantly the performance. Generally, the fact that cars do not wait for the red light decreases the travel time even for low values of adjustment distance. For fixed phase duration smaller than 11s, drivers adapting speeds produces a bigger effect on traffic than for higher phase duration. Moreover, different shares of drivers that receive information about the traffic lights behaviour produce different effects on the traffic performance for both static and dynamic traffic lights control. More drivers receiving information is beneficial for the overall traffic performance.

Our findings are relevant in the context of information based solutions for ITS [28], involving traffic lights control, information processing, advanced communication and sensing. It is useful to anticipate what impact can have the fact that a massive amount of drivers use real time information about the traffic lights behaviour. At the same time, it is important to explore the effect of the real time traffic responsiveness of the traffic lights under different circumstances. The main challenge in optimising the traffic lights control consists in minimising the time spent in the network by agents [19]. This means determining the most efficient proportion of green allocated to each phase. A practical solution to improve traffic should take into consideration not only the travel time but also the comfort and safety of the drivers while approaching a traffic lights. For planning efficient traffic lights systems in the context of future ITS, it is necessary to consider the negative and the positive effects that real time traffic responsiveness of the traffic lights control combined with a massive number of drivers using speed recommendations.

References

[1] Transportation Research Board Of The National Academies. Review of the status of the dedicated short-range communications technology and applications [draft] report to congress. [online], 2015. Available at http://onlinepubs.trb.org/onlinepubs/reports/DSRC_April_28_2015.pdf; Accessed 01-April-2016.

[2] Azrulnor Ahmad. *Development of traffic light control system using programmable logic controller*. PhD thesis, Universiti Malaysia Pahang, 2007.

[3] Javed Aslam, Sejoon Lim, and Daniela Rus. Congestion-aware traffic routing system using sensor data. In *Intelligent Transportation Systems (ITSC), 2012 15th International IEEE Conference on*, pages 1006–1013. IEEE, 2012.

[4] Shlomo Bekhor, Moshe E Ben-Akiva, and M Scott Ramming. Evaluation of choice set generation algorithms for route choice models. *Annals of Operations Research*, 144(1):235–247, 2006.

[5] Seung-Bae Cools, Carlos Gershenson, and Bart DHooghe. Self-organizing traffic lights: A realistic simulation. In *Advances in applied self-organizing systems*, pages 41–50. Springer, 2008.

[6] Michele Covell, Shumeet Baluja, and Rahul Sukthankar. Micro-auction-based traffic-light control: Responsive, local decision making. In *IEEE Intelligent Transportation Systems Conference (ITSC-2015)*, 2015.

[7] Daniel Enemark, Mathew D McCubbins, and Nicholas Weller. Knowledge and networks: An experimental test of how network knowledge affects coordination. *Social Networks*, 36:122–133, 2014.

[8] EnLighten. Connected signals. [online], 2015. Available at https://connectedsignals.com/enlighten.php; Accessed 01-April-2016.

[9] Verena Franken and Transportation Research Board. Use of navigation systems and consequences for travel behaviour . In *ECTRI-FEHRL-FERSI Young Researcher Seminar, Brno, Czech Republic*, 2007.

[10] Carlos Gershenson. *Design and control of self-organizing systems.* CopIt Arxives, 2007.

[11] Takeaki Imai and Katsuhiro Nishinari. Optimal information provision for maximizing flow in a forked lattice. *Physical Review E*, 91(6):062818, 2015.

[12] Stefan Lämmer and Dirk Helbing. Self-control of traffic lights and vehicle flows in urban road networks. *Journal of Statistical Mechanics: Theory and Experiment*, 2008(04):P04019, 2008.

[13] Sejoon Lim, Hari Balakrishnan, David Gifford, Samuel Madden, and Daniela Rus. Stochastic motion planning and applications to traffic. In *Algorithmic Foundation of Robotics VIII*, pages 483–500. Springer, 2009.

[14] Sejoon Lim and Daniela Rus. Stochastic motion planning with path constraints and application to optimal agent, resource, and route planning. In *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, pages 4814–4821. IEEE, 2012.

[15] Sejoon Lim and Daniela Rus. Congestion-aware multi-agent path planning: distributed algorithm and applications. *The Computer Journal*, page bxt067, 2013.

[16] Sorina Litescu, Vaisagh Viswanathan, Michael Lees, Alois Knoll, and Heiko Aydt. Information impact on transportation systems. *Journal of Computational Science*, 9:88–93, 2015.

[17] Yang-Yu Liu, Jean-Jacques Slotine, and Albert-László Barabási. Controllability of complex networks. *Nature*, 473(7346):167–173, 2011.

[18] Neng-Chao Lv, Xin-Ping Yan, and Chao-Zhong Wu. A novel urban traffic control approach considering travelers' intentions. In *CICTP 2012@ sMultimodal Transportation SystemsConvenient, Safe, Cost-Effective, Efficient*, pages 1318–1326. ASCE, 2012.

[19] Carolina Osorio and Michel Bierlaire. A multiple model approach for traffic signal optimization in the city of lausanne. In *Swiss Transport Research Conference*, number TRANSP-OR-CONF-2006-078, 2008.

[20] Dominik Papinski, Darren M Scott, and Sean T Doherty. Exploring the route choice decision-making process: A comparison of planned and observed routes obtained using person-based gps. *Transportation research part F: traffic psychology and behaviour*, 12(4):347–358, 2009.

[21] Giovanni Petri, H Jeldtoft Jensen, and John W Polak. Global and local information in traffic congestion. *EPL (Europhysics Letters)*, 88(2):20010, 2009.

[22] Plant. Bmws nifty new enlighten app predicts traffic light changes. [online], 2015. Available at http://www.plant.ca/general/bmws-nifty-new-enlighten-app-predicts-traffic-light-changes-video-150476/; Accessed 01-April-2016.

[23] Valentin Protschky, Kevin Wiesner, and Stefan Feit. Adaptive traffic light prediction via kalman filtering. In *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*, pages 151–157. IEEE, 2014.

[24] Salvatore Scellato, Luigi Fortuna, Mattia Frasca, Jesús Gómez-Gardeñes, and Vito Latora. Traffic optimization in transport networks based on local routing. *The European Physical Journal B-Condensed Matter and Complex Systems*, 73(2):303–308, 2010.

[25] Scoot. Spilt cycle offset optimisation technique. [online], 2016. Available at www.scoot-utc.com; Accessed 04-April-2016.

[26] Ronald Theodoor Van Katwijk. *Multi-agent look-ahead traffic-adaptive control.* TU Delft, Delft University of Technology, 2008.

[27] Vaisagh Viswanathan, Daniel Zehe, Jordan Ivanchev, Dominik Pelzer, Alois Knoll, and Heiko Aydt. Simulation-assisted exploration of charging infrastructure requirements for electric vehicles in urban environments. *Journal of Computational Science*, 12:1–10, 2016.

[28] Thomas A. Dingus Woodrow Barfield. *Human factors in intelligent transportation systems.* Psychology Press, 2014.