Advanced Co-operative System Architecture for Urban Traffic Signals Control Using Dynamic Vehicular Platoons

Hamed Noori, *Student Member, IEEE,* Bilhanan Silverajan and Mikko Valkama, *Member, IEEE*

***Abstract*—In this paper, a novel architecture for traffic light control system is proposed which is able to form and manipulate vehicular platoons using clusters of traffic lights. This method, called Platoon-Based Intelligent Traffic Lights (PB-ITL) is based on coordinated traffic lights that are connected together and are also able to wirelessly communicate with vehicles. PB-ITL groups traffic lights in clusters and each cluster tries to provide proper green status for platoon of vehicles, using Platooning concept which is seeking to utilize close to full capacity of roads. The contribution of this study is threefold: Firstly, the PB-ITL architecture is proposed considering and overcoming the drawbacks of existing approaches. Secondly, preliminary optimization is done for the PB-ITL method using a mathematical model with the GAMS mathematical optimization software. Third, large scale realistic simulations are performed for a detailed investigation on the impact of the proposed architecture in a large scale realistic urban area, using SUMO traffic simulator and Python-based developed program which is able to simulate a city with dynamic intelligent traffic lights. The analyzed data and results show a significant effect in decreasing traveling time, fuel consumption and emissions. Additionally, a comprehensive study about available traffic light control systems is done and comparisons against existing approaches such as SCOOT and SCAT systems, are provided.**

***Index Terms*—Intelligent transportation systems (ITSs); Connected Vehicles; Traffic light control system; SUMO; Vehicular platooning.**

I. Introduction

TRAFFIC congestions, accidents, and carbon dioxide (CO_2) emissions lead to a poor quality of city life, as well as wastage of time and fuel. In the European Union, the annual estimated congestion cost is nearly 100 billion euros (or 1% of the EU's GDP), and it is predicted to increase by 2050 to nearly 200 billion Euros annually [1], [2].

To alleviate traffic congestion and its problems, several strategies may be applied, such as expanding the infrastructure or improving public transport. However, implementing these approaches in large cities is practically impossible, due to resource and space limitations. Thus, enhancing the use of the current capacities of cities and existing roads using emerging wireless communication technologies is seen more feasible and stimulating approach to improve the road network performance. Communication between Roadside Units (RSUs) such as traffic lights and vehicles is one of the most important, efficient, and effective applications which can help to have dynamic and automated traffic lights that can provide several benefits such as minimizing traffic congestion, reducing fuel consumption and emissions.

In general, street intersections play an important role in urban traffic and road safety. Approximately 40% of all vehicle collisions occur at intersections, while braking and acceleration of vehicles increase fuel consumption and emission of cars, consequently increasing the level of air pollution significantly [3]. Furthermore, vehicle delays at lights contributed to nearly 10% of all delays in the U.S., with delays to nearly 300 million vehicle-hours just on major roadways [4]. Also, according to a recent report, there are more than 300,000 traffic lights in the U.S. having an annual maintenance and operating cost of 1.2 billion dollars [5]. Additionally, over 75% of these traffic lights are not efficient and could be improved by updating and adjusting the timing plans or by updating equipment [6]. Hence, improving traffic light control can lead to savings of cost, fuel and time besides reducing air pollution.

Motivated by the above findings, this article deals with decreasing waiting time at traffic lights for vehicles traveling on major roads. A Platoon-based Intelligent Traffic Lights (PB-ITL) method is proposed which focuses on co-ordinating clusters of traffic lights as well as communication between vehicles and traffic lights, to form and re-form optimal sizes of vehicle platoons and provide a green wave to platoons of vehicles.

As trialing new and untested technologies for transportation onto real roads can be both expensive and dangerous, simulation plays an important role in discovering beneficial and effective technologies before implementation. This paper thus evaluates the proposed method with large scale simulations, by using an open source microscopic traffic simulation suite known as SUMO [7]. Furthermore, fundamental mathematical modeling and corresponding optimization for the proposed architecture is done using the General Algebraic Modeling System (GAMS), which is a well-known, powerful mathematical optimization software [8].

The rest of the paper is outlined as follows: Section II provides background and reviews the relevant literature on traffic light control, vehicle platooning and wireless technologies in intelligent transportation systems. The aims and objectives of the paper are elaborated in detail in Section III. The Platoon-Based Intelligent Traffic Light (PB-ITL) method is proposed in

Manuscript received

[1] Hamed Noori (hamed.noori@tut.fi) is with the Department of Electronics and Communications Engineering, Tampere University of Technology.

[2] Bilhanan Silverajan (bilhanan.silverajan@tut.fi) is with the Department of Pervasive Computing, Tampere University of Technology.

[3] Mikko Valkama (mikko.e.valkama@tut.fi) is with the Department of Electronics and Communications Engineering, Tampere University of Technology.

where the t_{pass} is the average required time for vehicles stopped at the queue in the red light, to pass the intersection after the light turn to green.

Consequently, in order to define the final parameters, i.e., the optimal green time for the traffic lights, number of cluster and number of vehicles in each platoon, the minimum of total traveling time for vehicles in the major route (TTT) and the minimum total delay for vehicles in the minor roads (T_{delay}) should be defined. Thus,

$$TTT = \sum_{k=1}^{NV}\sum_{i=1}^{n-1}\left(ITT_{i,i+1}^{k} + t_{red(i+1)}^{k}\right) \tag{7}$$

$$T_{delay} = \sum_{i=1}^{n}(MV_i \times g_i) \tag{8}$$

$$\begin{aligned} Minimum(TTT + T_{delay}) &= Min\left(\sum_{k=1}^{NV} TT_k + \sum_{i=1}^{n} \bar{t}_{delay(i)}\right) \\ &= Min\left(\sum_{k=1}^{NV}\sum_{i=1}^{n-1}(ITT_{i,i+1}^{k} + t_{red(i+1)}^{k}) + \sum_{i=1}^{n}(MV_i \times g_i)\right) \end{aligned} \tag{9}$$

where TT_k is the traveling time for the vehicle "k". Equation (9) attempts to find the minimum traveling time for the vehicles that are traveling in the **major** route, while factoring the minimum delay for the vehicles that are in the **minor** route. In order to find the optimum number of vehicles per platoon, (6) is placed in (9). To calculate the optimum number of clusters in the route, a binary variable w_i is defined which illustrates the traffic light i status for the cluster. The existence of w_i is required to turn the problem to one-objective optimization case. Considering the previous definitions and (9), the final optimization objective can be defined as follows:

$$\begin{aligned} Minimize\Bigg(\sum_{k=1}^{NV}\sum_{i=1}^{n-1}\left(w_i^k \times \frac{l_{i,i+1}^{k}}{v_{i,i+1}^{k}}\right) + \Big(\left(1 - w_i^k\right) \\ \times t_{red(i+1)}^{k}\Big) + \sum_{i=1}^{n}\left(w_i^k \times MV_i \times NP \times t_{pass}\right)\Bigg) \end{aligned} \tag{10}$$

where the w_i^k is the status of the traffic light i for the vehicle k ("1" for green and "0" for red), $\frac{l_{i,i+1}^{k}}{v_{i,i+1}^{k}}$ is the traveling time for vehicle k among traffic lights i and $i+1$, and $t_{red(i+1)}^{k}$ is the stop time for vehicle k at traffic light $i+1$.

The presented optimization approach is thus seeking to find minimum traveling time for all vehicles in the network.

Furthermore in order to implement the model for optimization, based on the cycling time of traffic lights, the well-known $Webster$ method is considered which is able to define the optimal green and cycle time for an isolated intersection. $Webster's$ formulation can be summarized as follows [25] [45]:

$$C_i = \frac{(1.5 \times l_i) + 5}{1 - \sum_{i=1}^{\phi} q_i} \tag{11}$$

$$g_i = \frac{q_i \times (C_i - l_i)}{\sum_{i=1}^{\phi} q_i} \tag{12}$$

where the C_i is the optimum cycle time for traffic light i, l_i is the lost time (in seconds per cycle), ϕ is defined as the number of phases, $\sum_{i=1}^{\phi} q_i$ is the vehicle's flow ratio for the traffic light (in vehicles per hour), and g_i is the optimal green time for the traffic light i.

B. Optimization using GAMS

The previous sub-section provided the basic mathematical model that can be used in the optimization. These mathematical models are next implemented in GAMS to find the optimum variables. Based on the realistic traffic signal timing data provided in [46], the following assumptions and boundary conditions are applied in this study:

1) $g_{i,min} = 30 \ \ sec$; $g_{i,max} = 180 \ \ sec$;
2) $\bar{g}_{i,min} = 20 \ \ sec$; $\bar{g}_{i,max} = 45 \ \ sec$;
3) $t_{red(min)} = 25 \ \ sec$; $t_{red(max)} = 50 \ \ sec$;
4) $t_{pass} = 15 \ \ sec$;
5) $MV_i = Random(1-10)\% \times NV$;

Also to avoid vehicle queue length larger than streets, the following average queue approach from [46] is adopted:

$$Queue_{avg} = \frac{V}{3600/_{g_i + t_{red(i)}}} \tag{13}$$

where the V is the vehicles volume (in per hour per lane) and where $Queue_{avg}$ is the average queue (in vehicles per lane). Based on this, the following condition can be defined:

6) $Queue_{avg}^{i} \times \left(V_l + V_{Gap}\right) \le l_{i,i+1}$

where the $Queue_{avg}^{i}$ is the average queue (in vehicle per lane) for traffic light i , V_l is vehicles length and V_{Gap} is the empty space between vehicles. For the optimization the V_l and V_{Gap} are defined as 5 and 1 meters. Considering the (10), (11) and (12), the optimization problem is solved as follows to find the number of vehicles in platoon, the number of traffic lights in cluster and number of clusters:

1) Initially, in addition to the mentioned assumptions and conditions, the number of lanes controlled by traffic lights is assumed to be one, the average flow of vehicles assumed for the major route is 10 vehicles per lane per minute, the $l_i = 3sec$, yellow phase is not considered, $D = 10 \ km$, the $l_{i,i+1}$ are drawn randomly between 1 km to 5 km with conditions $\sum l_i = 10 \ km$ and $V = 50$.
2) Then, using these assumptions and conditions, optimal green time for traffic lights i is obtained and accordingly the number of vehicles in platoon and number of traffic lights in cluster is deduced.
3) Then, in order to have realistic results, the number of traffic lights in clusters is obtained based on the distance, meaning that instead of using the number of traffic lights in cluster, the lengths of clusters are considered.
4) After these steps, and solving optimization problem using GAMS, the optimal values for the two variables are, 16

TABLE II
NOTATIONS

Notation	Explanation
$Lane^{i}_{ITT}$:	Ideal Traveling Time for lane "i"
$Lane^{i}_{CTT}$:	Current Traveling Time for lane "i"
$(TL^0 - CL_j)$:	Starting Traffic Light (TL) in Cluster number "j" (ST-CL)
$DD(TL^0 - CL_j, X)$:	Driving Distance between Starting traffic light $(TL^0 - CL_j)$ and traffic light X
$Add\ (TL^k - CL_j)$ to $List^{j}_{CL}$:	This Command adds the TL at the position k in the Cluster j List
$CyST - List^{i}_{CL}[m]$:	Cycle Starting Time for TL number "m" from $List^{i}_{CL}$
$ITT_{tl}(X, Y)$:	Ideal Traveling Time between traffic light X and traffic light Y
$GrPh - List^{i}_{CL}[m]$:	Green Phase for TL "m"
T_{pass}:	The average required time for the vehicles to pass the traffic lights when it is green.

lights which control the lane and assigns new clusters (using the same cluster length, with different traffic lights that are related to and in the area of the congested lane) to provide a proper green wave for the lane and decrease the traveling time and congestion. Below, Algorithms 1-3 summarize the main control program and associated sub-entities. Furthermore, the used notations are defined in Table II.

Algorithm 1 Main Controller

$L_{CL} \leftarrow$ Cluster Length
$NV_p \leftarrow$ Desired No. of Vehicles in each Platoon
$TLS_{List} \leftarrow$ All TLs and locations (from SUMO)
function TLS CLUSTRING()
  Sort Traffic Lights in TLS_{List} ▷ based on their locations
  CLUSTERDEFINING(TLS_{List})
end function
procedure START **SUMO** SIMULATION()
  while $Simulation$ **do**
    if SimulationTime % 300 == 0 **then** ▷ every 5 minutes
      $PauseSimulation$
      $Lane_{List} \leftarrow$All Lane and locations (from SUMO)
      for i in $Lane_{List}Length$ **do**
        Calculate $Lane^{i}_{ITT}$
        Calculate $Lane^{i}_{CTT}$
        if $Lane^{i}_{CTT} \geq 1.3 \times Lane^{i}_{ITT}$ **then**
          $TLs^{list}_{Lane} \leftarrow$ Related TLs for the Lane
          CLUSTERDEFINING(TLs^{list}_{Lane})
        end if
      end for
    end if
  end while
end procedure

VII. LARGE-SCALE EVALUATION RESULTS AND ANALYSIS

The traveling time, fuel consumption and CO_2 emissions have been calculated for all vehicles traveling in the simulation and results for average traveling time and fuel consumption for each set of 10 vehicles in each zone are shown in Fig.4. The proposed PB-ITL control system reduces the traveling time by 28.8%, the fuel consumption by 23.1% and the CO_2 emission by 22.5% on average for the 200 sample vehicles. Fuel consumption and CO_2 emission levels for vehicles were calculated based on the principal per-vehicle figures in different modes obtained from Hausberger et al. [48].

Algorithm 2 ClusterDefining Function

function CLUSTERDEFINING(L_{CL} , TLS_{List}, NV_p)
  $i = 1, j = 1, k = 1$
  $TL^0 - CL_j \leftarrow TLS_{List}[0]$
  for i in $TLS_{List}Length$ **do**
    Calculate $DD(TL^0 - CL_j, TLS_{List}[i])$
    if $DD(TL^0 - CL_j, TLS_{List}[i]) \leq L_{CL}$ **then**
      $TL^k - CL_j \leftarrow TLS_{List}[i]$
      $k++, i++$
      $Add\ TL^k - CL_j$ to $List^{j}_{CL}$
    else
      CYCLEDEFINING($List^{j}_{CL}$, NV_p)
      $j++, k = 0$
      $TL^k - CL_j \leftarrow TLS_{List}[i]$
      $i = i++$
    end if
  end for
end function

Algorithm 3 CycleDefining Function

function CYCLEDEFINING($List^{j}_{CL}$, NV_p)
  for $m = 0$ in $List^{j}_{CL}Length$ **do**
    $CyST - List^{j}_{CL}[m] = 0$
    $Calculate\ ITT_{tl}(List^{j}_{CL}[m], List^{j}_{CL}[m+1])$
    $CyST - List^{j}_{CL}[m+1] = CyST - List^{j}_{CL}[m] + ITT_{tl}(List^{j}_{CL}[m], List^{j}_{CL}[m+1])$
    $GrPh - List^{j}_{CL}[m] = \dfrac{NV_p}{T_{pass}}$
  end for
end function

While the results illustrate the effects of the proposed PL-ITL in some sample vehicles, a large scale analysis is next pursued to better understand the behavior of the proposed method in urban areas and take into account large changes and variations in vehicular movement in real cities.

For the analysis, more than 37000 road segments such as

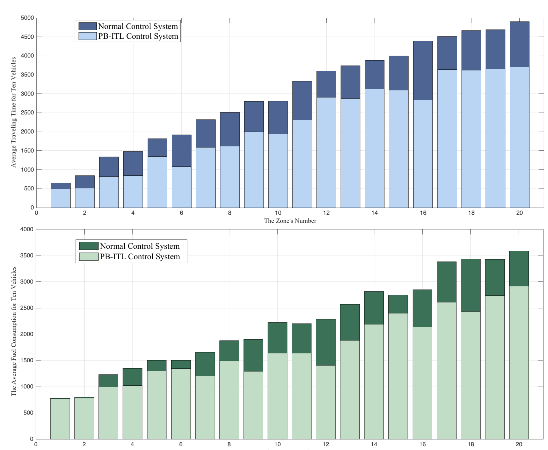
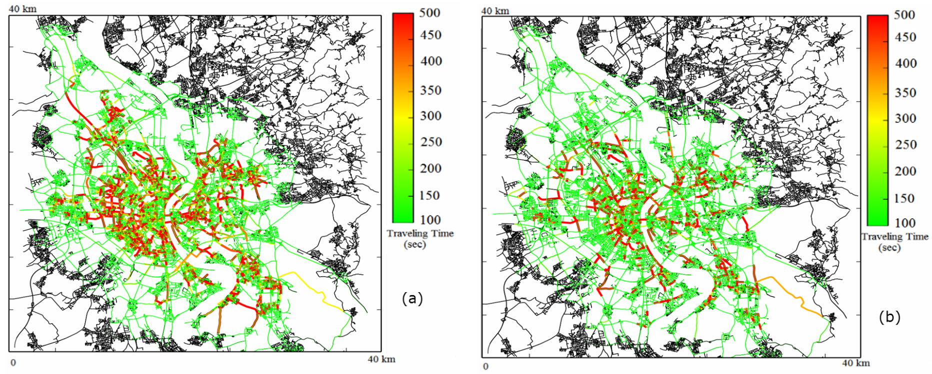
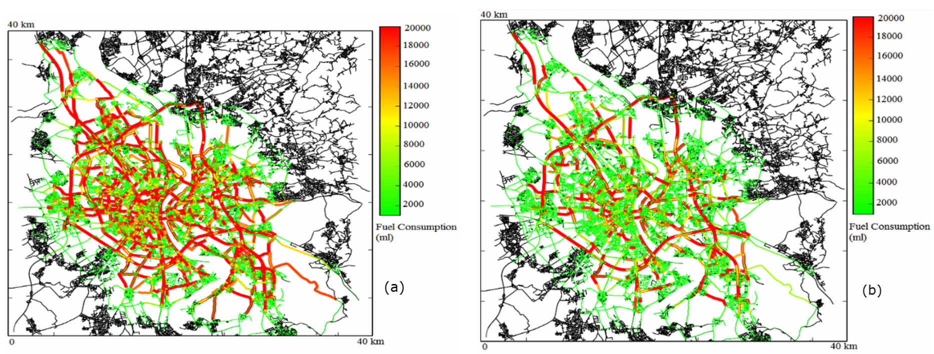


Fig. 4. Average traveling time and fuel consumption (ml) for 200 vehicles divided in 20 zones, using platoon based intelligent traffic light control system, and with normal traffic light control system. (average reduction: 28.8% in traveling time and 23.1% in fuel consumption).



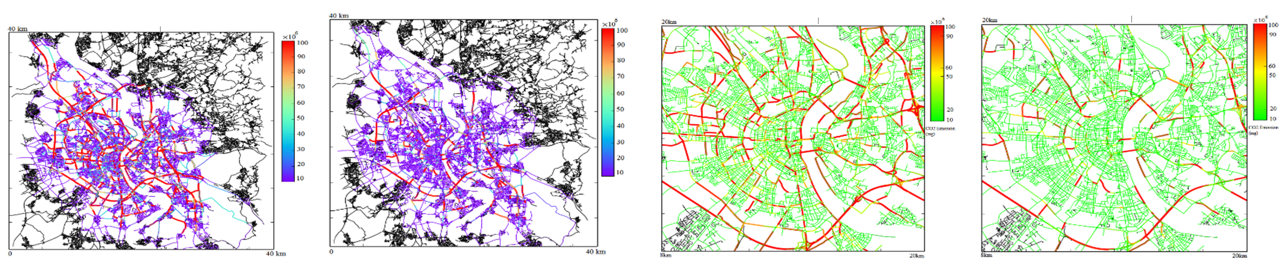
(a) (b)

Fig. 8. Traveling time for all road segments (streets, highways, etc.). a) Normal traffic light control. b) Platoon-based intelligent traffic light control.



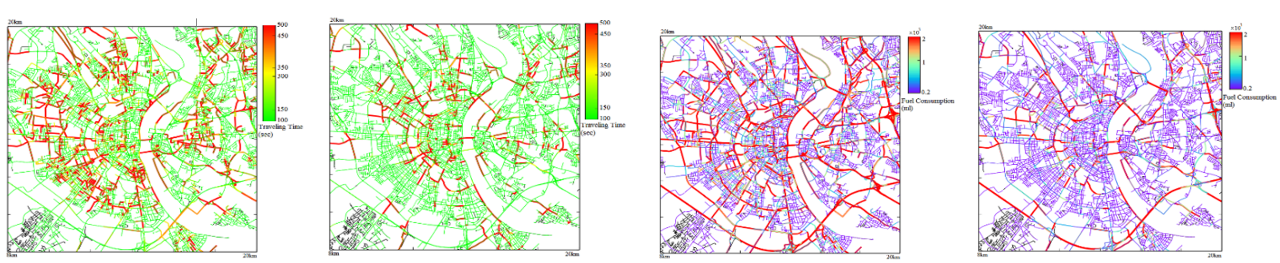
(a) (b)

Fig. 9. Average fuel consumption for all road segments. a) Normal traffic light control. b) Platoon-based intelligent traffic light control.



(a) (b) (c) (d)

Fig. 10. Average CO_2 emission for all road segments (streets, highways, etc.). a) Normal traffic light control system. b) Platoon-based intelligent traffic light control system. c) Normal traffic light control system (zoom). d) Platoon-based intelligent traffic light control system (zoom).



(a) (b) (c) (d)

Fig. 11. a) Average traveling time for all road segments (streets, highways, etc.) with normal traffic light control system. b) Average traveling time for all road segments using PB-ITL c) Fuel consumption for all road segments using normal traffic light control system. d) Fuel consumption for all road segments with PB-ITL.

Intelligent Transportation Systems - (ITSC), 2013 16th International IEEE Conference on, Oct 2013, pp. 2439–2444.
[27] D. Robertson and R. Bretherton, "Optimizing networks of traffic signals in real time-the SCOOT method," *Vehicular Technology, IEEE Transactions on*, vol. 40, no. 1, pp. 11–15, Feb 1991. [Online]. Available: http://www.scoot-utc.com
[28] A. Sims and K. Dobinson, "The Sydney coordinated adaptive traffic (SCAT) system philosophy and benefits," *Vehicular Technology, IEEE Transactions on*, vol. 29, no. 2, pp. 130–137, May 1980. [Online]. Available: http://www.scats.com.au/
[29] S. A. Fayazi and A. Vahidi, "Crowdsourcing phase and timing of pre-timed traffic signals in the presence of queues: Algorithms and back-end system architecture," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 3, pp. 870–881, March 2016.
[30] S. Kwatirayo, J. Almhana, and Z. Liu, "Adaptive traffic light control using vanet: A case study," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2013 9th International*, July 2013, pp. 752–757.
[31] D. Jia, K. Lu, and J. Wang, "A Disturbance-Adaptive Design for VANET-Enabled Vehicle Platoon," *Vehicular Technology, IEEE Transactions on*, vol. 63, no. 2, pp. 527–539, Feb 2014.
[32] J. E. Anderson, "An intelligent transportation network system: Rationale, attributes, status, economics, benefits, and courses of study for engineers and planners," *PRT International*, 2009.
[33] P. Fernandes and U. Nunes, "Algorithms for management of a multi-platooning system of IVC-enabled autonomous vehicles, with high traffic capacity," in *Intelligent Transportation Systems (ITSC), 2011 14th International IEEE Conference on*, Oct 2011, pp. 1935–1941.
[34] S. Shladover, "PATH at 20 - History and Major Milestones," in *Intelligent Transportation Systems Conference, 2006. ITSC '06. IEEE*, Sept 2006, pp. 1_22–1_29.
[35] S. E. Shladover, "PATH at 20-History and major milestones," *IEEE Transactions on intelligent transportation systems*, vol. 8, no. 4, pp. 584–592, 2007.
[36] S. Hallé, B. Chaib-draa, and J. Laumonier, "Car platoons simulated as a multiagent system," in *In: Proc. 4th Workshop on Agent-Based Simulation*, 2003, pp. 57–63.
[37] P. Daviet and M. Parent, "Longitudinal and lateral servoing of vehicles in a platoon," in *Intelligent Vehicles Symposium, 1996., Proceedings of the 1996 IEEE*, Sep 1996, pp. 41–46.
[38] M. Abualhoul, M. Marouf, O. Shagdar, and F. Nashashibi, "Platooning control using visible light communications: A feasibility study," in *Intelligent Transportation Systems - (ITSC), 2013 16th International IEEE Conference on*, Oct 2013, pp. 1535–1540.
[39] R. Rajamani and S. Shladover, "An experimental comparative study of autonomous and co-operative vehicle-follower control systems," *Transportation Research Part C: Emerging Technologies*, vol. 9, no. 1, pp. 15 – 31, 2001.
[40] B. Van Arem, C. J. Van Driel, and R. Visser, "The impact of cooperative adaptive cruise control on traffic-flow characteristics," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 7, no. 4, pp. 429–436, 2006.
[41] H. Noori and B. Olyaei, "A novel study on beaconing for vanet-based vehicle to vehicle communication: Probability of beacon delivery in realistic large-scale urban area using 802.11p," in *Smart Communications in Network Technologies (SaCoNeT), 2013 International Conference on*, vol. 01, June 2013, pp. 1–6.
[42] H. Noori, L. Fu, and S. Shiravi, "Connected vehicle based traffic signal control strategy for emergency vehicle preemption," in *Transportation Research Board 95th Annual Meeting*, no. 16-6763, 2016.
[43] H. Noori, "Modeling the impact of vanet-enabled traffic lights control on the response time of emergency vehicles in realistic large-scale urban area," in *Communications Workshops (ICC), 2013 IEEE International Conference on*, June 2013, pp. 526–531.
[44] H. Noori and M. Valkama, "Impact of vanet-based v2x communication using ieee 802.11p on reducing vehicles traveling time in realistic large scale urban area," in *Connected Vehicles and Expo (ICCVE), 2013 International Conference on*, Dec 2013, pp. 654–661.
[45] F. V. Webster and B. M. Cobbe, "Traffic Signals," Road Res. Lab. , H.M.S.O, Berkshire, U.K., Tech. Rep., 1966.
[46] *Traffic Signal Timing Manual*, U.S. Department of Transportation, The Federal Highway Administration (FHWA), 2008. [Online]. Available: http://ops.fhwa.dot.gov/publications/fhwahop08024/fhwa_hop_08_024.pdf
[47] S. Uppoor and M. Fiore, "Large-scale urban vehicular mobility for networking research," in *Vehicular Networking Conference (VNC), 2011 IEEE*, Nov 2011, pp. 62–69.
[48] *Handbook Emission Factors for Road Transport*, UBA Berlin and BUWAL Bern, produced by INFRAS Bern, 2014. [Online]. Available: http://www.hbefa.net/
[49] U. Dutta and D. S. McAvoy, "Comparative performance evaluation of scats and pre-timed control systems," in *Transportation Research Forum*, 2010.
[50] J. Peters, C. M. Monsere, H. Li, M. Mahmud, and S. Boice, "Field-based evaluation of corridor performance after deployment of an adaptive signal control system in gresham, oregon," in *87th Transportation Research Board Annual Meeting, Washington, DC*, 2008.
[51] K. Fehon and J. Peters, "Adaptive traffic signals, comparison and case studies," in *Institute of Transportation Engineers Western ITE Meeting. San Francisco*, 2010.
[52] S. Richter, D. Aberdeen, and J. Yu, "Natural actor-critic for road traffic optimisation," in *Advances in neural information processing systems*, 2006, pp. 1169–1176.
[53] S. El-Tantawy, B. Abdulhai, and H. Abdelgawad, "Multiagent reinforcement learning for integrated network of adaptive traffic signal controllers (marlin-atsc): Methodology and large-scale application on downtown toronto," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 14, no. 3, pp. 1140–1150, Sept 2013.
[54] D. H. Stolfi and E. Alba, "Red swarm: Reducing travel times in smart cities by using bio-inspired algorithms," *Applied Soft Computing*, vol. 24, no. 0, pp. 181 – 195, 2014.

Hamed Noori received the B.Sc. degree in electrical engineering from Zanjan National University, Zanjan, Iran in 2010, and the M.Sc. degrees in Machine Automation - Mechatronics and Micromachines and Wireless Communication from the Tampere University of Technology, Tampere, Finland, in 2014. He is currently doing research at Tampere University of Technology and Radio Science Lab (RSL) at University of British Columbia, Canada. His current research interests include Intelligent Transportation System, Vehicular Ad-Hoc Network, Connected Vehicles Technologies, Large Scale Traffic and Network Simulations.

Bilhanan Silverajan received his M.Sc in Engineering from Lappeenranta University of Technology, Finland in 1998 and his B.Sc in Computer Engineering from Nanyang Technological University, Singapore in 1993. He is currently pursuing his PhD in Tampere University of Technology. His research interests include pervasive networking, smart cities and traffic, communications and protocols for the Internet of Things.

Mikko Valkama received the M.Sc. and Ph.D. degrees (both with honors) in electrical engineering (EE) from Tampere University of Technology (TUT), Finland, in 2000 and 2001, respectively. Currently, he is a Full Professor and Department Vice-Head at the Department of Electronics and Communications Engineering at TUT. His general research interests include communications signal processing, full-duplex radio systems, radio localization, and 5 G mobile cellular radio.