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A review of traffic signal control methods and experiments based on Floating Car Data (FCD)

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Abstract

This paper intends to give a short review of the state of the art on the use of floating car data concerning the management of traffic flow at signalized intersections. New technologies such as connected and autonomous vehicles and Co-operative Intelligent Transportation Systems (C-ITS) are going to change the future of traffic control and management. Traffic signal control systems can be reorganized by using Floating Car Data (FCD), yet the concept of floating car data (FCD) has been mainly studied to gain traffic information and/or signal information. Only recent works have been focalizing on the potential application of FCD for traffic signal real-time control. This paper aims to evidence the most important concepts that can be extracted from the literature on this important topic.

Keywords: traffic management; transportation sustainability; real time traffic signal settings; traffic simulation; cooperative ITS; ITS; traffic flow.

1. Main text

New technologies such as connected and autonomous vehicles and Co-operative Intelligent Transportation Systems (C-ITS) are going to change the future of traffic control and management. Co-operative Intelligent Transportation Systems (C-ITS) are based on the sharing of information between drivers and road management.

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Connected vehicles will be able to share speeds and positions among many other various useful data. Vehicle speeds and positions can be used to better manage traffic signals in real-time. Connected vehicles can become an important part of new C-ITS systems. Some of these ideas have been explored in some European funded projects such as SAFESPOT [1], EuroFOT [2] and DRIVE C2X [3].

One of the main tasks that road managers have to deal with in traffic control is the management of signalized intersections. Control operations, unfortunately, very often are not real-time adjusted and sometimes are implemented with out-of-date fixed time traffic signal settings. Traffic congestion, which can be caused also by traffic signals, is a serious problem in cities and also a great cause of air pollution. For this reason, efforts to solve congestion problems were centered on attempts to shift demand on transit systems [4] and on better road traffic control, by adopting tools such as traffic simulation [5–10] dynamic network loading equilibrium and dynamic models [11–14] and the study and attempt to affect user route choice [15–19].

Many large scale deployments of systems based on Floating Car Data (FCD) are already showing the use of mobile phones [9,10,11,12] and wireless communications [13,14] combined with GNSS technologies. Cooperative systems based on smartphones are spontaneously spreading in ordinary use (BlaBla Car, Uber, etc.). Cooperative systems based on smart-phones have also been proposed for pedestrians and bicycles [26].

Smart-phones (and connected vehicles) can obtain localization and speed information from GNSS systems such as Galileo, GPS, and Glonass. GPS embedded in smart-phones produces an economic method to obtain vehicular travel time [27] and to evaluate traffic scenarios [16,17]. Smart-phones also allow the estimation of traffic safety parameters [30] and path choice [31]. Mobile devices have also been used to assess safety and risks by insurance companies [32] and for traffic safety [21,22] and fuel consumption estimation [35].

All these concepts have been applied also in the management of signalized intersections: GNSS data coming from private vehicles were useful in the evaluation of adaptive traffic signal systems in [36], smartphones were useful to gather information on traffic signal timings [37–39], the use of FCD in C-ITS systems is discussed in [40] where traffic signal regulation from FCD is achieved. The term Floating Car Data Adaptive Traffic Lights (FCDATL or Traffic Signals FCDATS) was introduced in [41]. The specific use of FCD data coming from smartphones to regulate in real-time adaptive traffic signals was investigated also in: [42–46]. In some cases, the adaptive traffic signal system is used in combination with driver assistance, so that both driver behavior and traffic signals are real-time adjusted.

Projects such as Colombo [42,43], have been presented in which the general potential of Vehicle communication to other vehicles or infrastructures (V2X) for traffic management are investigated. Some works have also been presented on traffic signal regulation presenting algorithms without a clear definition of the underlying communication and control systems. Among them [47–49] propose the use of game theory in traffic signal regulation implicitly assuming that information on all vehicle positions is available.

2. Systematic bibliometric analysis

In this section a systematic literature review based on a keyword search is presented.

2.1. Review Methodology

The structure of a systematic literature review about FCD adaptive traffic signal is presented in this section. The procedure which has been applied is based on the seven steps showed in Fig. 1. Similar procedures are frequently used in literature [50,51].

2.2. Database Selection and Keywords Selection

In this work the Scopus database was used. Keyword selection is the most important step in this procedure; the keyword choice can include or exclude different scientific works. The objective is that of creating a list of scientific works which contains the more important and influential works in the sector while at the same time avoiding the insertion of documents which are off topic. To create a thorough list of documents in this sector, the authors did perform a manual trial and error iterative procedure represented by the backward pointing arrow between the third

and second step of the procedure in Fig.1. At the end of this procedure the choice was that of including in the search all documents that contains in the title: "traffic signal" or "traffic light" and that also contain one of the following keywords in the title, keywords or abstract: "Floating car data" or "v2x" or "smartphone" or "connected vehicle" or "car communication" or "v2I" or "vehicle infrastructure" or "sensor" or "vanet". This search has brought a list "A" of 698 documents (in the list "A" 425 documents have been published between 2015 and 2020).

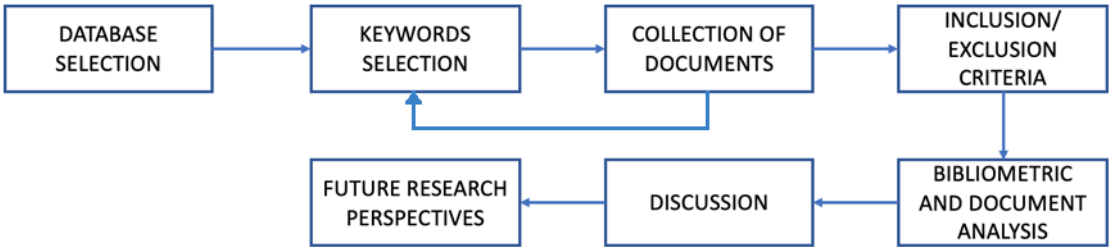

Fig. 1. Seven-steps procedure for systematic literature review.

Possibly many influential and pertaining documents at this stage may have been excluded since they might have left out from the title "traffic signal" or "traffic light".

With the above results and without manually excluding documents that are not pertinent to the field it was possible to elaborate the distribution in time for the documents of list "A" (up to 2019) that is presented in the following Fig. 2 and that shows an increasing number of published documents for year (it must be noted that also the general number of all indexed documents in Scopus has been growing year by year so a more detailed analysis would be necessary to establish if there is a growing scientific attention to this sector) :

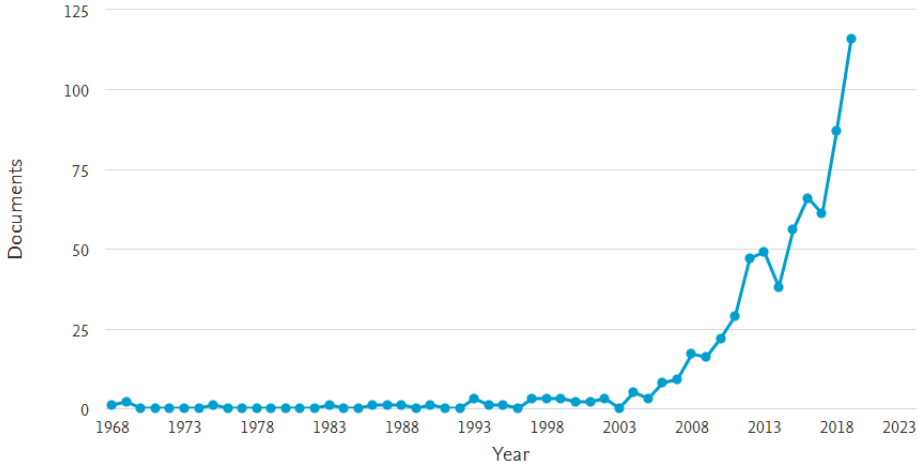

Fig. 2. Number of documents in list "A" for each year.

2.3. Collection of Documents and Filtering (Inclusion/Exclusion)

It must be noted that some previous attempted searches with different choices of keywords and logical operators either did bring a lot of documents not pertinent to the problem of floating car data and traffic signal regulations or did bring too few documents. In an attempt to establish the 20 most influential papers and to include in the list all important documents the list has been manually extended by the following procedure:

-manual selection of the first 20 documents in order of received citations creating a list "A20" of influential documents;

- to extend the list "A20" with important documents that might have left out, the procedure was repeated creating an analogous list "A20-restricted-to-2015-2020" of influential documents limited only to documents published between 2015 and 2020.

- all documents cited by the 20 documents in the list " A20-restricted-to-2015-2020" were added to a list "C" consisting of 736 documents. The list C was then ordered by citations and all documents were manually examined reading the title, abstract, and in some cases, the full paper, pertaining papers with a number of citations higher than 71 were added to the list "A20". The number 71 was used as a reference since it was the number of citations of the less cited document in the list "A20".

With this procedure, a list "A31" was created containing 31 documents that can be considered among the most influential in the sector. It must be noted that some general scope papers have been left in the list since they have been considered relevant and also papers on the following topics have been left inside the list:

-the use of floating car data as a means to establish traffic signal timings

-the use of Green Light Optimized Speed Advisory (GLOSA).

The list "A31" comprehends the following papers: [46,52–81] that have been published between 2008 and 2016.

3. Conclusion

The objective of this short review was that of extracting the most influential papers in the sector. The database of documents directly known to the authors (all the documents referenced in the introduction) has been extended by a systematic bibliometric analysis reaching a total of more than 700 documents. A detailed analysis of the contents of the extracted database has been performed and presented in the Workshop. Given editorial limitations in this document only the list of 31 most influential papers [46,52–81] in terms of received citation has been presented in the hope that this can be useful to readers. A lot of information, unfortunately, had to be left out. In most all the examined documents the evaluation of control systems has been performed in a simulation environment without a real implementation in the field. Exceptions are all methods were information is extracted and eventually fed to vehicles. In the domain of FCDATS, we are aware of only one experiment in the field [82] (using real vehicles in a controlled environment).

References

[1] Schubert,R., Schlingelhof,M., Cramer,H. and Wanielik,G. (2007) Accurate positioning for vehicular safety applications - The SAFESPOT approach. *IEEE Vehicular Technology Conference*,. https://doi.org/10.1109/VETECS.2007.516

[2] Benmimoun,M., Zlocki,A. and Eckstein,L. (2012) Advanced Driver Assistance Systems: Benefit Evaluation Method and User Acceptance for Adaptive Cruise Control and Collision Warning System. *Transportation Research Board 91st …*,.

[3] Stahlmann,R., Festag, a, Tomatis, a, Radusch,I. and Fischer,F. (2011) Starting European Field Tests for Car-2-X Communication : the Drive C2X Framework. *ITS World*,.

[4] Marzano,V., Tocchi,D., Papola,A., Aponte,D., Simonelli,F. and Cascetta,E. (2018) Incentives to freight railway undertakings compensating for infrastructural gaps: Methodology and practical application to Italy. *Transportation Research Part A: Policy and Practice*,. https://doi.org/10.1016/j.tra.2018.01.040

[5] Astarita,V., Florian,M. and Musolino,G. (2001) A microscopic traffic simulation model for the evaluation of toll station systems. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*,.

[6] Astarita,V., Giofré,V., Guido,G. and Vitale,A. (2011) Investigating road safety issues through a microsimulation model. *Procedia - Social and Behavioral Sciences*, **20**, 226–35. https://doi.org/10.1016/j.sbspro.2011.08.028

[7] Young,W., Sobhani,A., Lenné,M.G. and Sarvi,M. (2014) Simulation of safety: A review of the state of the art in road safety simulation modelling. *Accident Analysis and Prevention*,. https://doi.org/10.1016/j.aap.2014.01.008

[8] Astarita,V. and Giofré,V.P. (2019) From traffic conflict simulation to traffic crash simulation: Introducing traffic safety indicators based on the explicit simulation of potential driver errors. *Simulation Modelling Practice and Theory*, Elsevier. **94**, 215–36. https://doi.org/10.1016/j.simpat.2019.03.003

[9] Osorio,C. and Punzo,V. (2019) Efficient calibration of microscopic car-following models for large-scale stochastic network simulators. *Transportation Research Part B: Methodological*,. https://doi.org/10.1016/j.trb.2018.09.005

[10] Martinez,F.J., Toh,C.K., Cano,J.C., Calafate,C.T. and Manzoni,P. (2011) A survey and comparative study of simulators for vehicular ad hoc networks (VANETs). *Wireless Communications and Mobile Computing*,. https://doi.org/10.1002/wcm.859

[11] Gentilea,G. (2018) New formulations of the stochastic user equilibrium with logit route choice as an extension of the deterministic model. *Transportation Science*,. https://doi.org/10.1287/trsc.2018.0839

[12] Gentile,G. (2016) Solving a Dynamic User Equilibrium model based on splitting rates with Gradient Projection algorithms. *Transportation Research Part B: Methodological*,. https://doi.org/10.1016/j.trb.2016.02.005

[13] Cantarella,G.E., Di Febbraro,A., Di Gangi,M. and Giannattasio,O. (2019) Stochastic Multi-Vehicle Assignment to Urban Transportation Networks. *MT-ITS 2019 - 6th International Conference on Models and Technologies for Intelligent Transportation Systems*,.

[14] Cantarella,G.E. and Watling,D.P. (2016) A general stochastic process for day-to-day dynamic traffic assignment: Formulation, asymptotic behaviour, and stability analysis. *Transportation Research Part B: Methodological*,. https://doi.org/10.1016/j.trb.2016.05.005

[15] Trozzi,V., Gentile,G., Kaparias,I. and Bell,M.G.H. (2015) Effects of Countdown Displays in Public Transport Route Choice Under Severe Overcrowding. *Networks and Spatial Economics*,. https://doi.org/10.1007/s11067-013-9207-5

[16] Kucharski,R. and Gentile,G. (2018) Simulation of rerouting phenomena in Dynamic Traffic Assignment with the Information Comply Model. *Transportation Research Part B: Methodological*,. https://doi.org/10.1016/j.trb.2018.12.001

[17] Marzano,V., Papola,A., Simonelli,F. and Papageorgiou,M. (2018) A Kalman Filter for Quasi-Dynamic o-d Flow Estimation/Updating. *IEEE Transactions on Intelligent Transportation Systems*,. https://doi.org/10.1109/TITS.2018.2865610

[18] Papola,A., Tinessa,F. and Marzano,V. (2018) Application of the Combination of Random Utility Models (CoRUM) to route choice. *Transportation Research Part B: Methodological*,. https://doi.org/10.1016/j.trb.2018.03.014

[19] Papola,A. (2016) A new random utility model with flexible correlation pattern and closed-form covariance expression: The CoRUM. *Transportation Research Part B: Methodological*,. https://doi.org/10.1016/j.trb.2016.09.008

[20] Astarita,V. and Florian,M. (2001) The use of mobile phones in traffic management and control. *ITSC 2001 2001 IEEE Intelligent Transportation Systems Proceedings (Cat No01TH8585)*,. https://doi.org/10.1109/ITSC.2001.948621

[21] Astarita,V., Bertini,R.L., d'Elia,S. and Guido,G. (2006) Motorway traffic parameter estimation from mobile phone counts. *European Journal of Operational Research*, **175**. https://doi.org/10.1016/j.ejor.2005.02.020

[22] Barceló,J., Montero,L., Marqués,L. and Carmona,C. (2010) Travel Time Forecasting and Dynamic Origin-Destination Estimation for Freeways Based on Bluetooth Traffic Monitoring. *Transportation Research Record: Journal of the Transportation Research Board*,. https://doi.org/10.3141/2175-03

[23] Barceló,J., Montero,L., Bullejos,M., Serch,O. and Carmona,C. (2013) A kalman filter approach for exploiting bluetooth traffic data when estimating time-dependent od matrices. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*,. https://doi.org/10.1080/15472450.2013.764793

[24] Guido,G., Vitale,A., Saccomanno,F.F., Festa,D.C., Astarita,V., Rogano,D. et al. (2013) Using Smartphones as a Tool to Capture Road Traffic Attributes. *Applied Mechanics and Materials*,. https://doi.org/10.4028/www.scientific.net/AMM.432.513

[25] Guido,G., Gallelli,V., Saccomanno,F., Vitale,A., Rogano,D. and Festa,D. (2014) Treating uncertainty in the estimation of speed from smartphone traffic probes. *Transportation Research Part C: Emerging Technologies*,. https://doi.org/10.1016/j.trc.2014.07.003

[26](2012) Gap Analysis in Cooperative Systems within Intelligent Transportation Systems [Internet]. Royal Institute of Technology.

[27] Herrera,J.C., Work,D.B., Herring,R., Ban,X. (Jeff), Jacobson,Q. and Bayen,A.M. (2010) Evaluation of traffic data obtained via GPS-enabled mobile phones: The Mobile Century field experiment. *Transportation Research Part C: Emerging Technologies*,. https://doi.org/10.1016/j.trc.2009.10.006

[28] Chen,W.J., Chen,C.H., Lin,B.Y. and Lo,C.C. (2012) A traffic information prediction system based on Global Position System-equipped probe car reporting. *Advanced Science Letters*,. https://doi.org/10.1166/asl.2012.2192

[29] Zhou,X., Wang,W., Yu,L., Zhou,X., Yu,Á.L., Wang,W. et al. (2012) Traffic Flow Analysis and Prediction Based on GPS Data of Floating Cars. *Lecture Notes in Electrical Engineering*,. https://doi.org/10.1007/978-3-642-34528-9_51

[30] Guido,G., Vitale,A., Astarita,V., Saccomanno,F., Giofré,V.P. and Gallelli,V. (2012) Estimation of Safety Performance Measures from Smartphone Sensors. *Procedia - Social and Behavioral Sciences*,. https://doi.org/10.1016/j.sbspro.2012.09.824

[31] Bierlaire,M., Chen,J. and Newman,J.P. (2010) Modeling Route Choice Behavior From Smartphone GPS data. *Transport*,.

[32] Händel,P., Ohlsson,J., Ohlsson,M., Skog,I. and Nygren,E. (2014) Smartphone-based measurement systems for road vehicle traffic monitoring and usage-based insurance. *IEEE Systems Journal*,. https://doi.org/10.1109/JSYST.2013.2292721

[33] Astarita,V., Caruso,M.V., Danieli,G., Festa,D.C., Giofrè,V.P., Iuele,T. et al. (2012) A Mobile Application for Road Surface Quality Control: UNIquALroad. *Procedia - Social and Behavioral Sciences*,. https://doi.org/10.1016/j.sbspro.2012.09.828

[34] Vaiana,R., Iuele,T., Astarita,V., Caruso,M.V., Tassitani,A., Zaffino,C. et al. (2014) Driving behavior and traffic safety: An acceleration-based safety evaluation procedure for smartphones. *Modern Applied Science*, **8**. https://doi.org/10.5539/mas.v8n1p88

[35] Astarita,V., Guido,G., Mongelli,D. and Giofrè,V.P. (2015) A co-operative methodology to estimate car fuel consumption by using smartphone sensors. *Transport*, **30**. https://doi.org/10.3846/16484142.2015.1081280

[36] Hu,J., Fontaine,M.D., Park,B.B. and Ma,J. (2015) Field evaluations of an adaptive traffic signal — using private-sector probe data. *Journal of Transportation Engineering*,. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000806.

[37] Axer,S. and Pascucci,F. (2015) Estimation of traffic signal timing data and total delay for urban intersections based on low frequency floating car data. *Proceedings of the 6th Mobility TUM (2015)*,.

[38] Axer,S. and Friedrich,B. (2016) Estimating signal phase and timing for traffic actuated intersections based on low frequency floating car data. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*,. https://doi.org/10.1109/ITSC.2016.7795889

[39] Axer,S. and Friedrich,B. (2014) Level of service estimation based on low-frequency floating car data. *Transportation Research Procedia*,. https://doi.org/10.1016/j.trpro.2014.10.085

[40] Saust,F., Bley,O., Kutzner,R., Wille,J.M., Friedrich,B. and Maurer,M. (2010) Exploitability of vehicle related sensor data in cooperative systems. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*,. https://doi.org/10.1109/ITSC.2010.5625165

[41] Astarita,V., Giofrè,V.P., Guido,G. and Vitale,A. (2017) The use of adaptive traffic signal systems based on floating car data. *Wireless Communications and Mobile Computing*, **2017**. https://doi.org/10.1155/2017/4617451

[42] Bellavista,P., Foschini,L. and Zamagni,E. (2014) V2X Protocols for low-penetration-rate and cooperative traffic estimations. *IEEE Vehicular Technology Conference*,. https://doi.org/10.1109/VTCFall.2014.6966225

[43] Krajzewicz,D., Heinrich,M. and Milano,M. (2013) COLOMBO: Investigating the Potential of V2X for Traffic Management Purposes assuming low penetration Rates. *ElibDlrDe*,.

[44] Astarita,V., Vincenzo Pasquale,G., GUIDO,G. and Vitale,A. (2019) A Single Intersection Cooperative-Competitive Paradigm in Real Time Traffic Signal Settings Based on Floating Car Data. *Energies*, **12**.

[45] Astarita,V., Festa,D.C. and Vincenzo,G. (2018) Cooperative-competitive paradigm in traffic signal synchronization based on floating car data. *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, IEEE.

[46] Gradinescu,V., Gorgorin,C., Diaconescu,R., Cristea,V. and Iftode,L. (2007) Adaptive traffic lights using car-to-car communication. *IEEE Vehicular Technology Conference*,. https://doi.org/10.1109/VETECS.2007.17

[47] Alvarez,I., Poznyak,A. and Malo,A. (2008) Urban traffic control problem a game theory approach. *Proceedings of the IEEE Conference on Decision and Control*,. https://doi.org/10.1109/CDC.2008.4739461

[48] Tan,L., Zhao,X., Hu,D., Shang,Y. and Wang,R. (2010) A study of single intersection traffic signal control based on two-player cooperation game model. *Proceedings - 2010 WASE International Conference on Information Engineering, ICIE 2010*,. https://doi.org/10.1109/ICIE.2010.172

[49] Abdelghaffar,H.M., Yang,H. and Rakha,H.A. (2016) Isolated traffic signal control using a game theoretic framework. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*,. https://doi.org/10.1109/ITSC.2016.7795755

[50] Kamble,S.S., Gunasekaran,A. and Gawankar,S.A. (2018) Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process Safety and Environmental Protection*,. https://doi.org/10.1016/j.psep.2018.05.009

[51] Mishra,D., Gunasekaran,A., Papadopoulos,T. and Childe,S.J. (2018) Big Data and supply chain management: a review and bibliometric analysis. Ann. Oper. Res. https://doi.org/10.1007/s10479-016-2236-y

[52] Rakha,H., Van Aerde,M., Ahn,K. and Trani,A.A. (2000) Requirements for evaluating traffic signal control impacts on energy and emissions based on instantaneous speed and acceleration measurements [Internet]. Transp. Res. Rec. National Research Council, Virginia Tech Transp. Institute, 3500 Transportation Research Plaza, Blacksburg, VA 24061, United States. p. 56–67. https://doi.org/10.3141/1738-07

[53] Lindner,F., Kressel,U. and Kaelberer,S. (2004) Robust recognition of traffic signals. *2004 IEEE Intelligent Vehicles Symposium*, Daimler-Clirysler AG, Research and Technology, RIC/AP, 89075 Ulm, Germany. p. 49–53.

[54] Chen,W., Chen,L., Chen,Z. and Tu,S. (2005) A realtime dynamic traffic control system based on wireless sensor network. *International Conference on Parallel Processing Workshops 2005, ICPP 2005*, Department of Computer Science and Engineering, Fudan University, 220 Handan Rd., Shanghai, 200433, China. p. 258–64. https://doi.org/10.1109/ICPPW.2005.16

[55] Rose,G. (2006) Mobile phones as traffic probes: Practices, prospects and issues. Transp. Rev. https://doi.org/10.1080/01441640500361108

[56] Tubaishat,M., Shang,Y. and Shi,H. (2007) Adaptive traffic light control with wireless sensor networks. *2007 4th Annual IEEE Consumer Communications and Networking Conference, CCNC 2007*, Department of Computer Science, University of Missouri - Columbia, Columbia, MO 65211-2060, United States. p. 187–91. https://doi.org/10.1109/CCNC.2007.44

[57] Wen,W. (2008) A dynamic and automatic traffic light control expert system for solving the road congestion problem. *Expert Systems with Applications*, Department of Information Management, LungHwa University of Science and Technology, Taiwan. **34**, 2370–81. https://doi.org/10.1016/j.eswa.2007.03.007

[58] Hartenstein,H. and Laberteaux,K.P. (2008) A tutorial survey on vehicular ad hoc networks. IEEE Commun. Mag. https://doi.org/10.1109/MCOM.2008.4539481

[59] Mandava,S., Boriboonsomsin,K. and Barth,M. (2009) Arterial velocity planning based on traffic signal information under light traffic conditions. *2009 12th International IEEE Conference on Intelligent Transportation Systems, ITSC '09*, Department of Electrical Engineering, University of California Riverside, Riverside, CA 92507, United States. p. 160–5. https://doi.org/10.1109/ITSC.2009.5309519

[60] Priemer,C. and Friedrich,B. (2009) A decentralized adaptive traffic signal control using V2I communication data. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*,. https://doi.org/10.1109/ITSC.2009.5309870

[61] Wu,X., Liu,H.X. and Gettman,D. (2010) Identification of oversaturated intersections using high-resolution traffic signal data. *Transportation Research Part C: Emerging Technologies*, Elsevier Ltd, Department of Civil Engineering, 500 Pillsbury Drive S.E., Minneapolis, MN 55455, United States. **18**, 626–38. https://doi.org/10.1016/j.trc.2010.01.003

[62] Yousef,K.M., Al-Karaki,J.N. and Shatnawi,A.M. (2010) Intelligent traffic light flow control system using wireless sensors networks. *Journal of Information Science and Engineering*, Department of Computer Engineering, Jordan University of Science and Technology, Irbid 22110, Jordan. **26**, 753–68.

[63] Tielert,T., Killat,M., Hartenstein,H., Luz,R., Hausberger,S. and Benz,T. (2010) The impact of traffic-light-to-vehicle communication on fuel consumption and emissions. *2nd International Internet of Things Conference, IoT 2010*, Institute of Telematics, Karlsruhe Institute of Technology, Germany. https://doi.org/10.1109/IOT.2010.5678454

[64] Zhou,B., Cao,J., Zeng,X. and Wu,H. (2010) Adaptive traffic light control in wireless sensor network-based intelligent transportation system.

2010 IEEE 72nd Vehicular Technology Conference Fall, VTC2010-Fall, Department of Computing, Hong Kong Polytechnic University, Hong Kong, Hong Kong. https://doi.org/10.1109/VETECF.2010.5594435

[65] Jeff Ban,X., Hao,P. and Sun,Z. (2011) Real time queue length estimation for signalized intersections using travel times from mobile sensors. *Transportation Research Part C: Emerging Technologies*, Elsevier Ltd, Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute (RPI), 110 Eighth St., Troy, NY 12180-3590, United States. **19**, 1133–56. https://doi.org/10.1016/j.trc.2011.01.002

[66] Koukoumidis,E., Peh,L.-S. and Martonosi,M.R. (2011) SignalGuru: Leveraging mobile phones for collaborative traffic signal schedule advisory. *9th International Conference on Mobile Systems, Applications, and Services, MobiSys'11 and Co-Located Workshops*, University of Karlsruhe, Karlsruhe, Germany. p. 127–40. https://doi.org/10.1145/1999995.2000008

[67] Katsaros,K., Kernchen,R., Dianati,M. and Rieck,D. (2011) Performance study of a Green Light Optimized Speed Advisory (GLOSA) application using an integrated cooperative ITS simulation platform. *7th International Wireless Communications and Mobile Computing Conference, IWCMC 2011*, Centre for Communications Systems Research (CCSR), Department of Electronic Engineering, University of Surrey, Guildford, GU2 7XH, United Kingdom. p. 918–23. https://doi.org/10.1109/IWCMC.2011.5982524

[68] Levinson,J., Askeland,J., Dolson,J. and Thrun,S. (2011) Traffic light mapping, localization, and state detection for autonomous vehicles. *2011 IEEE International Conference on Robotics and Automation, ICRA 2011*, Stanford Artificial Intelligence Laboratory, Stanford University, CA 94305, United States. p. 5784–91. https://doi.org/10.1109/ICRA.2011.5979714

[69] Fairfield,N. and Urmson,C. (2011) Traffic light mapping and detection. *2011 IEEE International Conference on Robotics and Automation, ICRA 2011*, Google Inc., United States. p. 5421–6. https://doi.org/10.1109/ICRA.2011.5980164

[70] Fajardo,D., Au,T.-C., Waller,S., Stone,P. and Yang,D. (2011) Automated intersection control: Performance of future innovation versus current traffic signal control [Internet]. Transp. Res. Rec. Department of Civil Engineering, University of Texas, 6.202 ECJ Hall, Austin, TX 78712, United States. p. 223–32. https://doi.org/10.3141/2259-21

[71] Chang,J.-J., Li,Y.-H., Liao,W. and Chang,I.-C. (2012) Intersection-based routing for urban vehicular communications with traffic-light considerations. *IEEE Wireless Communications*, National Taiwan University, Taiwan. **19**, 82–8. https://doi.org/10.1109/MWC.2012.6155880

[72] Barba,C.T., Mateos,M.Á., Soto,P.R., Mezher,A.M. and Igartua,M.A. (2012) Smart city for VANETs using warning messages, traffic statistics and intelligent traffic lights. *2012 IEEE Intelligent Vehicles Symposium, IV 2012*, Departament d'Enginyeria Telemàtica, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain. p. 902–7. https://doi.org/10.1109/IVS.2012.6232229

[73] Pandit,K., Ghosal,D., Zhang,H.M. and Chuah,C.-N. (2013) Adaptive traffic signal control with vehicular Ad Hoc networks. *IEEE Transactions on Vehicular Technology*, Institute of Electrical and Electronics Engineers Inc., Department of Computer Science, University of California at Davis, Davis, CA 95616, United States. **62**, 1459–71. https://doi.org/10.1109/TVT.2013.2241460

[74] Goodall,N., Smith,B. and Park,B. (2013) Traffic signal control with connected vehicles [Internet]. Transp. Res. Rec. Virginia Center for Transportation Innovation and Research, 530 Edgemont Road, Charlottesville, VA 22903, United States. p. 65–72. https://doi.org/10.3141/2381-08

[75] He,Q., Head,K.L. and Ding,J. (2014) Multi-modal traffic signal control with priority, signal actuation and coordination. *Transportation Research Part C: Emerging Technologies*, Elsevier Ltd, Department of Civil, Structural and Environmental Engineering and Department of Industrial and Systems Engineering, University at Buffalo, Buffalo, NY 14260, United States. **46**, 65–82. https://doi.org/10.1016/j.trc.2014.05.001

[76] Li,L., Wen,D. and Yao,D. (2014) A survey of traffic control with vehicular communications. *IEEE Transactions on Intelligent Transportation Systems*, Department of Automation, Tsinghua University, Beijing 100084, China. **15**, 425–32. https://doi.org/10.1109/TITS.2013.2277737

[77] Feng,Y., Head,K.L., Khoshmagham,S. and Zamanipour,M. (2015) A real-time adaptive signal control in a connected vehicle environment. *Transportation Research Part C: Emerging Technologies*, Elsevier Ltd, Department of Systems and Industrial Engineering, The University of Arizona, 1127 E. James E. Rogers Way, P.O. Box 210020, Tucson, AZ 85721-0012, United States. **55**, 460–73. https://doi.org/10.1016/j.trc.2015.01.007

[78] Collotta,M., Lo Bello,L. and Pau,G. (2015) A novel approach for dynamic traffic lights management based on Wireless Sensor Networks and multiple fuzzy logic controllers. *Expert Systems with Applications*, Elsevier Ltd, Faculty of Engineering and Architecture, Kore University of Enna, Italy. **42**, 5403–15. https://doi.org/10.1016/j.eswa.2015.02.011

[79] He,X., Liu,H.X. and Liu,X. (2015) Optimal vehicle speed trajectory on a signalized arterial with consideration of queue. *Transportation Research Part C: Emerging Technologies*, Elsevier Ltd, NEXTRANS Center, Purdue University, 3000 Kent Avenue, West Lafayette, IN 47906, United States. **61**, 106–20. https://doi.org/10.1016/j.trc.2015.11.001

[80] Mahmassani,H.S. (2016) 50th Anniversary invited article autonomous vehicles and connected vehicle systems: Flow and operations considerations. *Transportation Science*, INFORMS Inst.for Operations Res.and the Management Sciences, Transportation Center, Northwestern University, Evanston, IL 60208, United States. **50**, 1140–62. https://doi.org/10.1287/trsc.2016.0712

[81] Yang,K., Guler,S.I. and Menendez,M. (2016) Isolated intersection control for various levels of vehicle technology: Conventional, connected, and automated vehicles. *Transportation Research Part C: Emerging Technologies*, Elsevier Ltd, Traffic Engineering Group, Institute for Transport Planning and Systems, ETH Zurich, Switzerland. **72**, 109–29. https://doi.org/10.1016/j.trc.2016.08.009

[82] Astarita,V., Giofré,V.P., Festa,D.C., Guido,G. and Vitale,A. (2020) Floating car data adaptive traffic signals: A description of the first real-time experiment with "connected" vehicles. *Electronics (Switzerland)*,. https://doi.org/10.3390/electronics9010114