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Microscopic traffic simulation models for connected and automated vehicles (CAVs) – state-of-the-art

Paweł Gora*[1], Christos Katrakazas[2], Arkadiusz Drabicki[3], Faqhrul Islam[4], Piotr Ostaszewski[3]

[1]*Faculty of Electronics, Telecommunication and Informatics, Gdańsk University of Technology*
[2]*Department of Transportation Planning and Engineering, National Technical University of Athens*
[3]*Department of Transportation Systems, Cracow University of Technology*
[4]*Edinburgh Napier University*

Abstract

Research on connected and automated vehicles (CAVs) has been gaining substantial momentum in recent years. However, the vast amount of literature sources results in a wide range of applied tools and datasets, assumed methodology to investigate the potential impacts of future CAVs traffic, and, consequently, differences in the obtained findings. This limits the scope of their comparability and applicability and calls for a proper standardization in this field of research. The objective of this paper is to contribute towards bridging this gap by providing a summary of the state-of-the-art literature review regarding microscopic simulation models for connected and automated vehicles.

Keywords: microscopic traffic models, connected and automated vehicles, metaresearch

1. Introduction

Connected and automated vehicles (CAVs) are widely expected to bring a profound revolution in transportation systems. Although the timeline and the means of introducing CAVs on a massive scale are unknown, many automotive and IT companies already work on self-driving cars (or software/hardware/services for them), with plenty of trials and pilot projects on testing self-driving cars and CAVs. Similarly, standards for communication between vehicles (V2V - vehicle-to-vehicle communication, and V2I - vehicle-to-infrastructure) are being

* Corresponding author. Tel.: +48-507-982-292.
E-mail address: pawel.gora@pg.edu.pl

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developed. Consequently, research interest in CAVs has been growing substantially in recent years, and there is an abundant amount of literature findings regarding the potential impacts of CAVs on travel safety, network performance, interactions in a mixed traffic conditions, travel behavior etc. However, the majority of such studies have various assumptions regarding their methodological framework, scenario evaluation and analysis settings. Consequently, a proper standardization of these studies is missing. Furthermore, these research studies formulated numerous modelling approaches to describe the CAVs traffic, which yet vary significantly as with regard to the traffic model, CAVs dynamics representation, input, parameters and calibration methods. Hence, the CAV-related works tend to differ substantially in their output observations and conclusions, which causes incomparable, not transferable, and sometimes also not repeatable study results. In addition, the lack of input data required to calibrate traffic models for CAVs and validate the results of simulations deepens the problem of getting reliable results. Therefore, we diagnosed that there is a need for an in-depth literature review, which will reveal the state-of-the-art research achievements regarding CAVs simulation models and their underlying methodological assumptions.

This work is a step toward satisfying the mentioned need, we aim to provide a wider analysis of papers focusing on development or application of simulation models of traffic with CAVs, including the variable input and control methods relevant in describing the traffic dynamics and mutual interactions of CAVs. The paper summarizes microscopic models including CAVs, which are analyzed and applied in various scientific papers. Section II contains a review of such models, while Section III concludes our findings and proposes guides for future research.

2. Methods and models for CAVs simulation

Since there are still no established universal standards for building self-driving cars and car companies and researchers test different approaches and various algorithms, there are also no established mathematical models for simulating traffic with such cars. In case of traffic consisting of only conventional (human-driven) cars, we can distinguish a few principal categories of simulation models, ranging from the macroscopic level (in which traffic is represented in terms of relations between aggregated values such as speed, flow, density), through mesoscopic level (in which cars travel in homogenous packets and change their behavior only in case of special events, such as turning or stopping before a red signal) to microscopic level (models which assume a detailed, disaggregated representation of traffic systems with cars/drivers represented as separate agents governed by special rules) or even nanoscopic level (in which the internal representation of the cars' state is also modeled). The manifold quantity of available models is justified because traffic models are only approximations of very complex and unpredictable real-world traffic systems, so different models may be suitable for specific purposes depending on specific needs and applications. However, in contrast to conventional cars, for which the human-driver's behavior is mostly unpredictable (and can be only approximated by analyzing large amounts of data coming from sensors), in case of CAVs the algorithms governing their behavior may be well-known *a priori*. However, it is not sure if they will be open and available, plus, it may be computationally difficult to evaluate them, especially in cases of complex interactions with the environment, so there will be still a need for models approximating real traffic with CAVs (and such models may have better compatibility with the real-world traffic than in case of models of traffic with only human drivers). Therefore, it justifies the necessity to study models of traffic including CAVs, which already found numerous applications in evaluating scenarios and exploring the future of automated and connected transport.

2.1. Microscopic models for CAVs

In microscopic traffic models, vehicles are represented as separate agents, whose motion is governed by specific rules. Those agents may be in interaction, which also has an impact on their behavior. There are many well-established microscopic models for conventional vehicles, such as Gipps model [2], Wiedemann model [3], Nagel-Schreckenberg model [4] or Intelligent Driver Model [5]. Since introduction of automation and communication between vehicles may significantly change vehicles' behavior on a microscopic level, it is clear that a need for new microscopic models including CAVs emerged and many new microscopic models have recently appeared, along with studies using such models.

Gaspar et al. [6] proposed an energy-efficient predicted cruise control strategy which is able to adapt to the motion of the surrounding vehicles (thanks to V2V and I2V communications), attempting to minimize fuel consumption while not deteriorating traffic conditions. In this way, a balance between the designed speed and the flow of the local traffic can be guaranteed.

Chin et al. [7] present cooperative adaptive cruise control (CACC) of multiple cars in automated/unautomated mixed traffic. In order to take into account unautomated cars, the vehicle maneuver is expressed as a PrARX model that is a continuous approximation of a hybrid dynamical system. The PrARX model describes the driver's logical decision making as well as continuous maneuver in a uniform manner. The acceleration inputs of automated vehicles are computed in model predictive control framework where the state equation includes a platoon of automated and un-automated cars coupled with PrARX driver models. For computing assisting outputs in real time, a fast computation method for nonlinear model predictive control based on the continuation technique is employed. Simulation studies of the proposed CACC system indicates that explicit prediction of unautomated cars and adjusting behavior of CACC vehicles improves the overall stability of the platoon.

Xiao et al. [8] proposed a realistic and collision-free multi-regime car-following model for CACC, combining a realistic CACC system with driver intervention for vehicle longitudinal motions. The proposed model was tested in a wide range of scenarios (three regular scenarios of stop-and-go, approaching, and cut-out maneuvers, as well as two extreme safety concerned maneuvers of hard brake and cut-in) to explore model performance and collision possibilities and it turned out that the proposed model is collision free in the full-speed-range operation with leader accelerations within -1 to 1 m/s^2 and in approaching and cut-out scenarios.

Similarly, Li and Ma [9] proposed a Collision-Free car-Following Model (CFFM), a CACC controller prioritizing safety. In particular, they simulated a string of 8 vehicles for different scenarios, proving that it is collision free under all circumstances of hard braking, it has a good string stability (stability of a platoon of vehicles over space under the influence of a small perturbation that is originated from the first vehicle of the platoon) and it is efficient. The first step is to obtain an acceleration set that can ensure safety under predictable dangerous conditions, and then to decide on the exact acceleration by considering efficiency and comfort. Based on subject and the preceding (leading) vehicle data obtained from connected vehicles, the following vehicle can determine its objective acceleration through CFFM. Compared to existing semi-automated cooperative driving car-following models, the advantages and disadvantages of CFFM as they relate to safety, efficiency and string stability are evaluated. Results show that CFFM can guarantee safety under both gentle and hard braking of preceding vehicles at any time and thus can be used in complex traffic environments, namely congested urban roads. Moreover, it is demonstrated that CFFM has outstanding performance in terms of both efficiency and string stability. Comparison with Newell's trajectory replication model [10] shows that CFFM is a practical model that both accomplishes trajectory replication and also supplements it in that Newell's rule is only applicable in stable car-following scenarios while the CFFM can be applied in a variety of scenarios including catching-up.

In [11], Lu et al. presented a microscopic model incorporating a lane friction effect. The revised model has been calibrated using archived data from a complicated 13 mile long stretch of the northbound SR99 freeway near Sacramento, California. The corridor included multiple bottlenecks, multiple entry and exit ramps, and HOV lane. Calibration results showed very good agreement between field data (present fleet) and model predictions.

In [12], Rahman et al. presented an evaluation framework for the application of a driver's car-following behavior model in CACC system design to ensure user acceptance in terms of vehicle dynamics and string stability. The authors adopted two widely used driver car-following behavior models, the optimum velocity model (OVM) [13] and the intelligent driver model (IDM) [5] to prove the efficacy of the evaluation framework developed in that research for CACC system design. A platoon of six vehicles was simulated for three traffic flow states (uniform speed, speed with constant acceleration, and speed with constant deceleration), with different acceleration and deceleration rates. The maximum acceleration or deceleration and the sum of the squares of the errors of the follower vehicle speed were measured to evaluate user acceptance in terms of vehicle dynamics and string stability.

Analysis of the simulation results revealed that the OVM performed better at modeling a CACC system than did the IDM in terms of acceptable vehicle dynamics and string stability. The result becomes especially important considering that the IDM's adoption is a popular way to model traffic on a microscopic level, also including CAVs.

The aforementioned IDM is a car-following model which describes the dynamics of the positions and velocities of single vehicles using ordinary differential equations. Although IDM was developed to model accurately human-driver behaviour [5], its extensions have also found applications in research on CAVs. For instance, in [14], Khan et al. used an acceleration component of IDM and integrated it with a lane-changing model MOBIL [15] in order to find the optimal lane-changing strategy. A modified IDM is also introduced as a baseline model for comparison purposes in [16], where Bae et al. aim to find optimal speed trajectories minimizing the fuel consumption. However, the algorithm developed by the authors outperforms modified IDM. It turns out that thanks to V2I communication, traffic signal timing awareness can help the vehicle avoid unnecessary deceleration or idles (and reduce wasted energy), without sacrificing the arrival time at the destination. In [17], Liu et al. also modified IDM to capture the drivers' perception of traffic conditions thanks to V2V communication. The study considered only human-driven vehicles (a human driver of a connected vehicle not only takes into account the behavior of the immediate leader, but also receives the movement information of several connected vehicles ahead), but it showed that connectivity may improve the traffic. It turned out that the new model is more stable than the original IDM model. However, experiments were conducted only for a single level of a penetration rate (35%). Similar results are shown in [18], where stability of CAV-IDM (being extension of IDM for the case of connected vehicles) was investigated and it turned out that the local stability (any sufficiently small initial perturbation always remains small) and string stability are significantly enhanced thanks to the introduction of connectivity.

Another popularly used microscopic model for CAVs is a model introduced by Talebpour and Mahmassani [19]. The authors review several other microscopic models and introduce a new model consisting of a few variants:

- no automation and no communication capability (only acceleration model adopted from [20])
- active V2V communication (adoption of IDM)
- inactive V2V communication
- active V2I communication
- inactive V2I communication
- autonomous vehicles (based on studies of van Arem at al. [21] and Reece et al. [22])

The work of Talebpour and Mahmassani analyzes also stability and effectiveness in preventing shockwave formation and propagation on one-lane highway (no lane-changing) with a various number of vehicles in platoons. Their model found applications also in other works, e.g., Talebpour et al. [23] used it also to model driver behavior in a connected driving environment with connected vehicles. They also included a lane-changing model in a connected environment, which was earlier introduced in [24]. The acceleration model from [19] was also applied in Makridis et al. [25]. They studied a realistic road network, ring road of Antwerp, and considered 3 types of vehicles:

- Manual Vehicles, for which they used a modified Gipps car following model from Aimsun [2]
- Autonomous Vehicles (AVs), for which they used a model introduced by Shladover [26]
- CAVs, for which they used the aforementioned model introduced by Talebpour and Mahmassani [19].

21 different combinations of mixed vehicle types were implemented, for penetration rates ranging from 0% to 100% with 20% step. In addition, three different traffic demand scenarios were tested, one with travel demand corresponding to an estimated peak demand based on real counts, another, with an estimated peak demand increased by 20% and another decreased by 20%, making a total of 63 scenarios tested. The results are that AVs introduction over the network has a negative impact even at very low penetration rates. This can be linked with increased headways in comparison with human-driven vehicles, which are imposed mainly for safety-related reasons. Human drivers take risks while driving, trying to predict the movement of other neighbouring vehicles. On the other hand, AVs should not take any risk under any conditions, which eventually leads to more conservative headway thresholds on the road. Moreover, the maximum acceleration in AVs is lower than the one on manual vehicles and this is something that can be already observed in ACC systems of commercially available vehicles. As a consequence, the

flow downstream of a bottleneck is reduced, deteriorating the situation upstream. The ACC model used in the simulations has also been tested for one section networks and the capacity was not much smaller than the default case. In contrast to AVs, the impact of CAVs in the network is positive and it is improved as the penetration of CAVs increases. CAVs that follow AVs or manually driven vehicles react as AVs, since they do not have any information from other vehicles to make use of their connectivity and cooperation functionalities. Moreover, on low penetration rates, the probability of a CAV following another CAV to form a connected platoon is much smaller than the probability of a CAV following a manually driven vehicle or an AV. Hence most CAVs act as AVs, demanding larger headways to cruising or lane changing. The probability of two CAVs to be able to connect increases with the introduction of more CAVs over the network. With higher penetration of CAVs gaps are smaller, lane changes are easier and the traffic streams are more stable, able to absorb oscillations without traffic breakdown occurring. Consequently, the harmonic average speed remains high, even for the large demand scenarios.

There are also some other interesting approaches to microscopic traffic modelling, e.g., in [27], Hu et al. studied lane assignment strategies for CAVs in a highway scenario and their impact on the overall traffic efficiency and safety. They formulated a model of CAVs, which includes three features: traffic data available online, ultra-short reaction time, and cooperative driving. Based on this model, the authors propose a novel lane change maneuver, Politely Change Lane (PCL), which achieves the tradeoff between traffic safety and efficiency. Its effectiveness is validated and evaluated by extensive simulations. The performance shows that PCL improves both safety and efficiency of the overall traffic, especially with heavy traffic. Antoniotti et al. [28] applied their original algorithm for a 10km highway section with 3 merge junctions and 3 exit ramps. Many other publications are also focused on implementing different scenarios for CAVs in highway sections [29, 30].

Another approach is presented in Gora et al. [31], where the authors introduced a microscopic model based on BDI (Beliefs-Desires-Intentions) originating from the field of multiagent systems [32]. The main objective of an agent is to satisfy its desires by completing some well-defined goals. In order to plan and execute actions that lead to meeting established goals, an agent needs to gain knowledge about the environment. All information on other agents, obstacles etc form agent beliefs (and can be acquired using sensors). Desires represent rules that a vehicle obeys and general requirements it is committed to fulfill (e.g., reaching a destination point, preventing collision). A single intention describes the required vehicle's state which consists of all vehicle's dynamic data (e.g., position, speed). A single simulation step involves:

- communication - vehicles retrieve information on the environment
- deliberation - planning actions which should be executed in the next step
- execution - actions planned for the current step are performed, vehicles move forward

Originally, deliberation was implemented as a set of hard-coded rules, but potentially, methods based on artificial intelligence may be involved as well.

In [33], Jaworski et al. proposed a microscopic traffic simulation model with nanoscopic components. The vehicles can be simulated down to basic physical properties including, e.g., throttle and brake settings, fuel consumption. This allows in-depth behavioral analysis of individual vehicles and the whole traffic flow as a result of use of different traffic management systems. It doesn't introduce a new model for autonomous vehicles, but it allows investigating inter-vehicle interactions including platooning behavior and its consequences such as the string stability problem. The major application of this simulator is assessing performance of ITS and vehicle control systems, which was used in a cloud-based traffic management system operating in a connected environment [34].

Similar approaches for traffic management in connected environments were presented, e.g., in [35], [36], and microscopic simulation models involved were implemented in VISSIM (but without autonomy) and in Traffic Simulation Framework, respectively.

VISSIM is a widely used tool for running microscopic simulations, also in cases with autonomous vehicles. The default underlying model is a Wiedemann model [3] which can be further extended for the purpose of simulating traffic including CAVs [37]. VISSIM provides 3 interfaces (DriverModel.dll, DrivingSimulator.dll, COM Interface), which allows to adapt internal driving parameters: car following model, speeds and lane change behavior. [3] includes information on how to modify specific Wiedemann model parameters to achieve a desired behavior. VISSIM has been already used in several researches concerning CAVs, e.g., in modelling parking behavior of AVs [38] Wiedemann model was used with default settings as per manual, flatter speed distribution and an acceleration distribution were set according to Le Vine et al. [39]. They investigated the impact of various penetration rates of AVs, demand, number of lanes and various configurations of parkings on average delay, average stops, total travel time and average speed. They observed, e.g., a slow improvement in network performance until 40% AV penetration rate and a reduction in network performance after 60% AV penetration rate. Zhixia Li et al. [40] used simulation based on VISSIM with implemented ACUTA system (autonomous control of urban traffic). It was tested on an isolated intersection to get adequate results of autonomous intersection control, which could be helpful in managing different AV penetration rates. Felicia Bohm et al. [41] simulated a large urban area in VISSIM with Enviver to estimate and compare vehicle emissions in different scenarios. They match various parameters with vehicle delays, number of stops and speed to find the best solution. This study shows that AVs are likely to lower the fuel consumption and minimise emissions in cities.

Finally, another popular traffic simulator used in CAVs research is "Simulation of Urban MObility" (SUMO) [42], a microscopic, space-continuous road traffic simulation. For instance, it was used to study the effect of different platoon configurations on travel time of the delivery CAVs [43] and to study road capacity with CAVs [44].

3. Conclusions and future work

The presented analysis of papers related to microscopic models of CAVs showed a large amount of approaches. Although some models are applied more often, there are no universal methods and it is difficult to compare different models and draw proper conclusions regarding the outcomes. One of the important reasons is the lack of empirical CAVs data which could be used for a precise calibration and validation of models. Also, the algorithms for CAVs are still under development, so it is not obvious which models may eventually become the most accurate and useful. It may turn out that the development of microscopic simulation models of CAVs may also lead to the development of better control algorithms of CAVs in real traffic.

To tackle the aforementioned challenges, we recommend: building a repository of real-world data (e.g., trajectories) for CAVs, establishing standards for building, calibrating and validating traffic models of CAV using real-world data, building scenarios (e.g., standard road networks) to conduct experiments for CAVs, developing a generic, open, software-agnostic benchmarking platform for the evaluation of alternative modelling approaches and conducting further metaresearch to build a database of models and research works with information about their assumptions, inputs, outcomes, scope of applicability, in order to ensure comparability and reproducibility of results.

Regarding future research, mesoscopic and macroscopic simulation models of CAVs will be also investigated, more focus on applications of models and on comparison of outcomes from different researches which use simulation models for CAVs will be given. Lastly, datasets and input parameters used in different studies will be thoroughly reviewed to provide better understanding of applicability and reliability of models and research outcomes.

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References

[1] "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles" https://www.sae.org/standards/content/j3016_201806
[2] Gipps P.G., A behavioural car-following model for computer simulation. Transp. Research Part B, 15, 1981, pp. 105-111.
[3] Fellendorf, M., Vortisch, P: Microscopic Traffic Flow Simulator VISSIM. Fundamentals of Traffic Simulation. International Series in Operations Research and Management Science, 2010, pp. 63--93.
[4] Nagel, K.; Schreckenberg, M., A cellular automaton model for freeway traffic. *Journal de Physique I.* **2** (12), 1992, pp. 2221-2229.
[5] Treiber M.; Hennecke A., Helbing D., Congested traffic states in empirical observations and microscopic simulations, *Physical Review E*, **62** (2), 2000, pp. 1805–1824.
[6] Gáspár P., Németh B.. Design of adaptive cruise control for road vehicles using topographic and traffic information. IFAC Proc. Vol., 19th IFAC World Congress 47, 2014, pp. 4184–4189.
[7] Chin H., Okuda H., Tazaki Y., Suzuki T.. Model predictive cooperative cruise control in mixed traffic, in: IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, 2015, pp. 003199–003205.
[8] Xiao L., Wang M., van Arem B. Realistic Car-Following Models for Microscopic Simulation of Adaptive and Cooperative Adaptive Cruise Control Vehicles. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, 2017.
[9] Li L., Ma W. A Collision-Free Car-Following Model for Connected Automated Vehicles. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, 2017
[10] Newell G.F. A simplified car-following theory: a lower order model. Institute of Transportation Studies, University of California, Berkeley, 2002
[11] Lu X.-Y., Kan X., Shladover S.E., Wei D., Ferlis R.A. An Enhanced Microscopic Traffic Simulation Model for Application to Connected Automated Vehicles. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, 2017.
[12] Rahman M., Chowdhury M., Dey K., Islam R., Khan T. An Evaluation Strategy for Driver Car-Following Behavior Models for CACC Controllers. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, 2017.
[13] Bando M., Hasebe K.., Nakayama K., Nakayama A., Shibata A., Sugiyam Y., Phenomenolical Study of Dynamical Model of Traffic Flow, Physical Review E, 51, 1995, pp. 1-18.
[14] Khan M.U., Basaras P., Schmidt-Thieme L., Nanopoulos A., Katsaros D. Analyzing cooperative lane change models for connected vehicles, 2014 International Conference on Connected Vehicles and Expo, 2014, pp. 565-570.
[15] Kesting A., Treiber M., Helbing D., General lane-changing model mobil for car-following models, Transportation Research Record: Journal of the Transportation Research Board, vol. 1999, 2007, pp. 86-94.
[16] Sangjae B., Kim Y., Guanetti J., Borrelli F., Moura S., Design and Implementation of Ecological Adaptive Cruise Control for Autonomous Driving with Communication to Traffic Lights. 2018, *CoRR* abs/1810.12442.
[17] Liu L., Li C., Li Y., Peeta S., Lin L., Car-following behavior of connected vehicles in a mixed traffic flow: modeling and stability analysis. 8th Annual IEEE Int. Conf. on CYBER Technology in Automation, Control, and Intelligent Systems. https://arxiv.org/abs/1809.05754.
[18] Jie S., Zuduo Z., Jian S. Stability analysis methods and their applicability to car-following models in conventional and connected environments. Transp. Research Part B: Methodological, vol. 109C, 2018, p. 212-237.
[19] Talebpour A., Mahmassani H.S. Influence of connected and autonomous vehicles on traffic flow stability and throughput. Transp. Res. Part C Emerg. Technol. 71, 2016, pp. 143–163.
[20] Talebpour A., Mahmassani H., Hamdar S., Multiregime sequential risk-taking model of car-following behavior. Transport. Res. Rec.: J. Transport. Res. Board 2260 (1), 2011, pp. 60–66.
[21] Van Arem B., van Driel C.J.G., Visser R.. The impact of cooperative adaptive cruise control on traffic-flow characteristics. IEEE Trans. Intell. Transport. Syst. 7 (4), 2006, pp. 429–436.
[22] Reece D.A., Shafer S.A. A computational model of driving for autonomous vehicles. Transport. Res. Part A: Policy Pract. 27 (1), 1993, pp. 23–50.
[23] Talebpour A., Mahmassani H. S., Bustamante F. E., Modeling driver behavior in a connected environment: Integrated microscopic simulation of traffic and mobile wireless telecommunication systems. *Transportation Research Record*, *2560*, 2016, pp. 75-86.

[24] Talebpour A., Mahmassani H.S., Hamdar H.S. Modeling Lane-Changing Behavior in a Connected Environment: A Game Theory Approach. Transportation Research Procedia, Vol. 7, 2015, pp. 420–440.
[25] Makridis M., Mattas K., Ciuffo B., Raposo M.A., Toledo T., Thiel C. “Connected and Automated Vehicles on a freeway scenario. Effect on traffic congestion and network capacity.”, 2018.
[26] Shladover S., Su. D., Lu X.-Y.. Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow. Transp. Res. Rec. J. Transp. Res. Board 2324, 2012, pp. 63–70.
[27] Hu J., Kong L., Shu W., Wu M.-Y., Scheduling of connected autonomous vehicles on highway lanes, 2012 IEEE Global Communications Conference, 1997.
[28] Antoniotti M., Deshpande A., Girault A., Microsimulation analysis of automated vehicles on multiple merge junction highways. IEEE International Conference on Computational Cybernetics and Simulation, Vol. 1, 1997.
[29] Aria E., Olstam J., Schwietering C. Investigation of Automated Vehicle Effects on Driver’s Behavior and Traffic Performance, Vol. 15, 2016.
[30] Bierstedt J., Gooze A., Gray C., Peterman J., Raykin L., Walters J., Effect of next - generation vehicles on travel demand and highway capacity, 2014.
[31] Gora P., Rüb I., Traffic models for self-driving connected cars, Transportation Research Procedia, vol. 14, 2016, pp. 2207– 2216.
[32] Rao A.S., Georgeff M.P., “Modeling Rational Agents within a BDI-Architecture”, in “Proceedings of the 2nd International Conference on Principles of Knowledge Representation and Reasoning”, pp. 473–484, 1991.
[33] Jaworski P., Edwards T., Burnham K.J. and Haas O.C.L. Microscopic traffic simulation tool for Intelligent Transportation Systems, 15th International IEEE Conf. on Intelligent Transportation Systems, 2012, pp. 552-557.
[34] Jaworski P., Cloud computing based adaptive traffic control and management, 2013.
[35] Goodall N., Smith B.L., Park B. Traffic Signal Control with Connected Vehicles. Transportation Research Record: Journal of the Transportation Research Board. 2013.
[36] Gora P., Simulation-based traffic management system for connected and autonomous vehicles. Road Vehicle Automation 4, 2017, pp. 257-266.
[37] PTV VISSIM & CONNECTED AUTONOMOUS VEHICLES [ONLINE] http://www.sfbayite.org/wp-content/uploads/2017/04/1%20VISSIM_CAV_SFITE_April2017.pdf
[38] Elvarsson, A.B. Modelling Urban Driving and Parking Behavior for Automated Vehicles, Zürich, 2017.
[39] Le Vine S., Zolfaghari A., Polak J.W., Autonomous cars: The tension between occupant experience and intersection capacity, Transportation Research Part C, 52, 2015, pp. 1-14.
[40] Li Z., Chitturi M.V., Zheng D., Bill A.R., Noyce D.A. Modeling Reservation-Based Autonomous Intersection Control in VISSIM, Transportation Research Record: Journal of the Transportation Research Board, Vol. 2381, 2013
[41] Bohm F., Häger K., Introduction of Autonomous Vehicles in the Swedish Traffic System - Effects and Changes Due to the New Self-Driving Car Technology, UPPSALA Universitet, 2015.
[42] Lopez P.A., Behrisch M., Bieker-Walz L., Erdmann J., Flötteröd Y-P, Hilbrich R., Lücken L., Rummel J., Wagner P., Wießner A. Microscopic Traffic Simulation using SUMO, IEEE Intelligent Transportation Systems Conference, 2018.
[43] Haas I., Friedrich B. Developing a micro-simulation tool for autonomous connected vehicle platoons used in city logistics, Transportation Research Procedia, 2017.
[44] Fernandes P., Nunes U. Platooning of autonomous vehicles with intervehicle communications in SUMO traffic simulator, 13th International IEEE Conference on Intelligent Transportation Systems, 2010.