Title
A co-benefit and tradeoff evaluation framework for connected and automated vehicle applications

Authors
Tian, Danyang
Wu, Guoyuan
Boriboonsomsin, Kanok
et al.

Publication Date
2017-07-31

DOI
10.1109/IVS/2017/7995838

Peer reviewed

2017 IEEE Intelligent Vehicles Symposium (IV)
June 11-14, 2017, Redondo Beach, CA, USA

A Co-Benefit and Tradeoff Evaluation Framework for Connected and Automated Vehicle Applications

Danyang Tian, *Student Member, IEEE*, **Guoyuan Wu**, *Senior Member*, *IEEE*, **Kanok Boriboonsomsin**, *Member, IEEE*, **Matthew J. Barth**, *Fellow*, *IEEE*

***Abstract*—A large number of Connected and Automated Vehicle (CAV) applications have been emerging that benefit transportation systems in terms of safety, mobility and the environment. These benefits can be quantified by a variety of performance indices (PIs) as described in recent literature. However, there has been very little research in analyzing the potential *co-benefits and tradeoffs* among all these PIs for the various CAV applications. In this paper, we examine a number of CAV applications whose system effectiveness focus is targeted on the three key areas of safety, mobility and environment, and then examine whether some PIs are synergistic or antagonistic. Using the Lane Speed Monitoring application as a specific example, we explore the in-depth relationship between different types of measures of effectiveness (MOEs) under different penetration rates of the technology, in order to show the association between the application focus and tradeoffs to be made among different performance measures. As part of the analysis, several future research directions are discussed, including the identification of key influential factors on system performance to obtain co-benefits in terms of different types of MOEs.**

I. Introduction

Connected and Automated Vehicle (CAV) technology has been rapidly emerging as a key component of Intelligent Transportation Systems (ITS) and a major pillar of the Smart City Challenge in the U.S. [1]. Thus far, a large number of relevant applications have been developed by researchers and engineers [2], with the support from both public and private sectors. In particular, the Connected Vehicle Reference Implementation Architecture (CVRIA) program [3] has laid out the foundation and provides detailed description of many CAV applications.

In general, CAV applications may be broadly classified into three categories, namely vehicle-centric, infrastructure-centric and traveler-centric, depending on the type of focused objects and the type of principles that have been involved in the developing and deploying process of the application. Among other, the vehicle-centric applications refer to the ones based on on-board sensors and communication technologies, aiming at improving the performance of ego-vehicle as well as entire transportation system. This type of CAV applications mainly focus on the vehicles' ego states (e.g., powertrain dynamics) during the operation, or the control schemes (longitudinally and laterally, or even at the route level) of application-equipped vehicles that interacting with their surrounding vehicles.

There are a considerable number of studies all over the world focusing on Vehicle-to-Vehicle (V2V)-based CAV applications and the evaluation of their effectiveness from different perspectives, i.e., safety, mobility and environment, such as the PReVENT project [4], the interactIVe project [5], the AdaptIVe project [6] and the DriveC2X project [7]. However, very few research efforts are investigating all possible MOEs simultaneously and diving deeper into how it is possible to fine tune the system parameters of these applications to achieve co-benefits from different types of measures of effectiveness (MOEs). To get further insight into these emerging CAV applications in a systematic way, we mainly introduced three key measures of effectiveness (Section 2). A detailed survey of the relevant studies is then provided in Section 3, followed by an in-depth case study of the Lane Speed Monitoring application on the trade-offs among different types of MOEs in Section 4. Section 5 concludes this paper.

II. Measure of effectiveness perspective

By integrating advanced autonomous control and Information and Communication Technologies (ICT) into today's vehicles, Advanced Driving Assistance Systems (ADAS) as well as CAV applications help enhance safety, improve mobility, and reduce environmental impacts. Different applications have various orientations in terms of performance measure and improvement. After a brief description of three major performance measures (inspired by [8] [9] [10]), i.e., safety, mobility and environmental impacts, we provide some selected examples, which are listed in a tabular format with information of categories, project/application name, MOE focus, and contributions.

a) Safety. Safety-focused CAV applications enable safer vehicles and roadways by developing collision avoidance, notification and warning mechanism considering both infrastructure-based and vehicle-based cooperative safety systems [11]. Some applications focus directly on safety impacts to avoid crash and accidents [12] or even on-road irregular driving behaviors [13], while some others focus on goals other than safety (e.g., mobility and environmental impacts improvement). These mobility and environmental

*This research is funded by the California Department of Transportation as part of a National Center for Sustainable Transportation research project.

D. Tian is with the Center for Environmental Research & Technology, UC Riverside, CA 92507 USA (phone: 951-323-9347; fax: 951-781-5790; e-mail: dtian001@ucr.edu).

G. Wu is with the Center for Environmental Research & Technology, UC Riverside, CA 92507 USA (e-mail: gywu@cert.ucr.edu).

K. Boriboonsomsin is with the Center for Environmental Research & Technology, UC Riverside, CA 92507 USA (e-mail: kanok@cert.ucr.edu).

M. J. Barth is with the Center for Environmental Research & Technology, UC Riverside, CA 92507 USA (e-mail: barth@ece.ucr.edu).

978-1-5090-4804-5/17/$31.00 ©2017 IEEE

applications may have a positive or negative indirect safety impacts in the traffic environment, which could be viewed as co-benefits or trade-offs among different MOEs. The direct and indirect impacts argument may apply to the mobility-focused and environment protection-focused applications as well.

b) Mobility. Mobility-oriented applications explore methods and management strategies aiming at increasing operational efficiency and improving individual mobility. Operational/system efficiency is an essential constituent referring to the good resources organization with the objective of producing an acceptable level of transportation throughput [8]. Similar to mobility, reliability is another important function of transportation efficiency, concerned with things such as travel time variability, system usage and capacity.

c) Environmental Impacts. As one of the largest significant contributors to air pollution and greenhouse gas emissions, the transportation sector attracts increasing awareness that ITS and CAV technologies can enhance sustainable development leading to improved air quality and climate change mitigation. A significant number of ITS applications focus on how to reduce the traffic emission of pollutants, which is associated with vehicle data and can be assessed by fleet data, traffic condition and route data [8].

III. VEHICLE-CENTRIC APPLICATIONS

The information exchange between two communication-capable vehicles could supply a users' basic motion dynamics parameters (e.g., position, velocity, acceleration and moving direction), which enables the CAV applications to increase the users' environmental awareness in order to achieve the preset objectives in terms of transportation performance improvement [14] [15] [16]. Moreover, safety benefits are generally represented as conflict risk reductions in this section. Table I lists symbols representing MOE focus used in Table II. Table II lists some of the vehicle-centric related projects/applications.

A. Safety & Mobility Co-Benefits

A large collection of valuable research has been studied focusing on road environment awareness with the aim of enhancing traffic safety by utilizing inter-vehicular communication-based CAV applications. Fullerton *et al*. [17] proposed a lane closure alert based on modern communications technologies, which allows drivers to be warned sooner about emergency situations, such as motorway vehicle breakdowns or a sudden lane drop. The driver advice system was tested using the microscopic traffic simulation tool VISSIM with a built-in radio communication simulator. Based on the simulation results, the authors state that a gradual slow-down ought to be enough to reduce the risk of follow-on rear-end collisions. Due to the relief of bottlenecks congestion, this alert system has great potential to improve the traffic flow through lane closure areas. Another example of an ADAS application which aims to improve both traffic flow and safety is the Cooperative Adaptive Cruise Control (CACC) system [18] [19]. Dey *et al*. [19] provided an overall review of CACC-related performance and reported that the CACC application has the potential to improve the traffic flow by increasing the traffic capacity under high penetration rates and by harmonizing the speed of platoons in a safe manner.

B. Safety Benefits

As an important situation awareness and safety enhancement approach, the Forward Collision Warning application is attracting more and more attention. Kusano and Gabler [20] examined the effectiveness among several pre-collision system algorithms using Time-to-Collision (TTC) as a surrogate collision-risk-evaluation measure and proved that forward collision warning in combination with a pre-crash brake assistance and autonomous pre-crash braking outperforms the conventional forward collision warning. Likewise, Szczurek *et al*. [21] presented a learning based relevance determination algorithm of the Emergency Electronic Brake Light application, and showed the safety benefits in terms of the average number of collisions. Other than potential safety benefits, potential mobility and environmental impacts gains/costs still remain to be shown in both [20] and [21], in which safety enhancement is probably achieved at the cost of larger greenhouse gas (GHG) emissions due to increased stop-and-go behavior. This might occur in other similar safety-focused collision avoidance applications, e.g., intersection collision warnings, curve speed warnings and pedestrian warning systems, where stop-and-go activity will likely increase.

Lane change warning systems and lane-change assist systems are also becoming increasingly popular (see, e.g., [22] [23]). The study in [22] takes advantage of the fusion of on-board cameras and tracking algorithms as well as a decision-making approach to execute automatic lane-change maneuvers, which was implemented on a concept vehicle called Carai. However, a detailed quantitative effectiveness evaluation in terms of post-processing false alarms, traffic safety and comfort was not carried out in [22]. Dang *et al*. [23] proposed a real-time minimum safe distance model taking into consideration the drivers' reaction delay and brake time based on V2V communications. The simulation results using Simulink show that this system could provide lane change warning through TTC analysis, but it did not mention any other MOEs evaluation other than potential safety improvements.

Table I Symbols used in the review in Table II

	Performance Validated		Performance Non-validated		
	Improvement	Deterioration	Improvement	Deterioration	Unknown
Targeted	●↑	●↓	◑ ↑	◑ ↓	
Non-targeted	◐ ↑	◐ ↓	○↑	○↓	○

Table II Example Vehicle-Centric CAV applications (S: Safety; M: Mobility; E: Environment)

Categories	Platform	Project or Application name & Ref	MOE focus			Contributions
			S	M	E	
vehicle-centric	Non-EV	EU 7th Seventh Framework Programme research project SOCIONICAL [17]	◑ ↑	●↑	○	An emergency situation alert system which leads into a larger "buffer zone" of reduced and harmonized speed in the vicinity of motorway bottlenecks in order to ensure a smoother and safer traffic flow
		FP7 European project ecoDriver [24]	◑ ↑	◐ ↓	●↑	An Android based application taking into account upcoming events, evaluation and analysis of driver behavior to advise drivers the best actions for lower energy consumption
		MINECO/FEDER Project [31]	●↑	○	○	A stochastic model as the surrogate measure for accidents evaluation of cooperative chain collision warning applications
		Cooperative Adaptive Cruise Control [18]	◑ ↑	◑ ↑	○	An analysis on gap closing and collision avoidance functionality of the Cooperative Adaptive Cruise Control system
		Advanced Forward Collision Warning [20]	●↑	○↓	○↓	A pre-collision system integrating forward collision warning, pre-crash brake assist and autonomous pre-crash brake to reduce severe highway crashes
		Emergency Electronic Brake Light [21]	● ↑	○↓	○↓	A machine learning approach-based emergency brake warnings relevance-decision estimation for safety applications
		Automatic Lane-Change [22]	◑ ↑	○	○	A situation awareness-based automatic lane-change scheme based on image processing, Kalman filtering and Bayesian networks approaches
		Eco-routing navigation system [26]	○	◐ ↓	●↑	An eco-routing navigation system accommodating origin-destination inputs through user interfaces to assist the driver to find the most eco-friendly route
		Urban parking management [27]	○	◑ ↑	◑ ↑	Online localized cooperative resource allocation models for urban parking management to decrease available parking spots search time
		Connected Vehicles Harmonizer [29]	○↑	●↑	○↑	A connected vehicle-based shockwave propagation control system using an optimization program to reduce travel time in the freeway work zone bottleneck
		Lane Speed Monitoring [30]	◐ ↓	●↑	◐ ↓	A lane speed monitoring system using basic safety message exchange between communication-capable vehicles to advise the driver faster lane to change to
	EV	Adaptive Cruise Control [25]	◑ ↑	○	●↑	An intelligent hybrid electric vehicle (i-HEV) platform incorporating a hybrid powertrain scheme with the adaptive cruise control application to achieve comprehensive performance
		Online Path Planning [28]	○	◐ ↑	●↑	A real-time micro path planning algorithm tested on the robotic electric vehicle research platform ROboMObil together with the velocity profile generation to make the energy saving capabilities achievable

C. Environmental Impacts & Safety Co-Benefits

Major focus of most current ADAS applications is on both safety and environmental impacts aspects. In this direction, Orfila *et al*. [24] developed an Android system based eco-Driving application which consists of the upcoming road features recognition and crash relevant events identification modules, utilizing the Ant Colony Optimization (ACO) to estimate the recommended speed with the purpose of supplying drivers an eco-friendly speed. The proposed application claimed the potential improvement in terms of fuel savings in the pre-validation experiment. However, the safety performance was not evaluated, even though it was targeted to be improved by the proposed system. Further, the speed with the system is lower than the speed without the system, which means the safe eco-driving system that contributes to the steady-speed, smooth-deceleration traffic results in reduced mobility with longer travel times. Li *et al*. [25] proposed another approach to achieve performance improvement in terms of fuel efficiency/environment protection as well as traffic safety by incorporating a hybrid powertrain with the conventional Adaptive Cruise Control (ACC) that enhances traffic safety and reduces the driver's effort. The velocity profiles of vehicles with and without the proposed system were compared and it was found out that the vehicle with the proposed system has smoother velocity and lower overshoot. Since the study also takes advantage of the high fuel efficiency of hybrid electric systems, the engine torque and fuel improvement were investigated as well.

D. Environmental Benefits

Eco-routing system scheme turns out to be another valuable ADAS algorithm that is beneficial to the environment. An eco-routing navigation system was proposed by Boriboonsomsin *et al*. [26], where the authors made use of the integration of multiple-sources traveler information, a hierarchical fusion approach, the optimal route calculation engine, and the human-machine-interface to contribute to the reductions of fuel consumption and pollutant emissions. The trade-off between mobility and environmental impacts of the proposed system was described in [26]. The authors concluded that significant fuel savings can be well achieved from eco-routes rather than the fastest route, leading to travel time increase, and the trade-off between travel time and fuel consumption can be comparable, especially for long trips.

E. Environmental Impacts & Mobility Co-Benefits

Some representative applications for environmental impacts & mobility improvement are developed from the perspective of resource allocation. Zargayouna *et al*. [27] proposed the modeling of the resource allocation problem to achieve the management of parking spots in an urban area taking into account both the location and the resources availability moment. Even though the mobility and energy consumption performance was not tested directly in [27], the urban parking management is assumed to reduce fuel consumption by decreasing parking spots search time. Winter *et al*. [28] presented an online micro geometric path planning methodology based on curvature minimization algorithm together with the velocity profile generation design implemented on the maneuverable robotic electric vehicle research platform ROboMObil to achieve the energy saving.

F. Mobility Benefits

There are very few ADAS applications purely focusing on mobility improvement to date. Ramezani and Benekohal [29] study connected vehicle-based harmonizer, which was designed to control shockwave propagation to reduce travel time delay in the freeway work zone, by using a travel time minimization optimization program. The system performance was evaluated in terms of congestion duration and travel time delay, and it was found out that there is a minimum penetration rate of equipped vehicles that guarantees the satisfactory efficiency of the proposed system. Another application targeting travel time improvement has been studied in [30], where a Lane Speed Monitoring (LSM) system is presented, which mainly relies on basic information collection (e.g., position, velocity and lane index) of downstream communication-capable vehicles to estimate traffic state at the lane level and to advise the driver to change to a faster lane. In addition to the average speed of equipped vehicles and unequipped vehicles being compared, the fuel consumption and potential conflict number were also investigated in [30]. It was shown that the higher average speed is achieved for equipped vehicles, while the fuel consumption and potential conflict of equipped vehicles are higher as well due to the encouragement of more aggressive driving behaviors (e.g., frequent lane changes and higher speed).

IV. CASE STUDY

As a key example, we choose a vehicle-centric ADAS application recently investigated by the authors (i.e., Lane Speed Monitoring or LSM). In this section, we examine this application in great detail as a case study, aiming at observing the tradeoffs among different perspectives of MOEs, e.g., safety, mobility and environmental sustainability. To be specific, the LSM application was mainly designed for mobility improvements in terms of increasing a vehicle's average speed (or reducing average trip travel time) by monitoring real-time lane-level traffic state in the downstream and advising the driver the faster lane to travel in. Other than mobility impacts, the other two MOEs (i.e., safety and environmental impacts) were expected to worsen due to the higher speeds and frequent lane change operations of the LSM application-equipped vehicles, which is viewed as a tradeoff between mobility and safety/environmental impacts. For more details please see the review in Section 3 and refer to [30].

The average conflict number, average speed and average fuel consumption are selected as the indicators of the three aspects of MOEs, i.e., safety, mobility and environmental impacts. The performance measure results were tested using the microscopic traffic simulation software PARAMICS [32], which was developed to model the individual vehicles dynamics behavior, and to bridge control schemes and on-road users in simulation through an API in C/C++. API calculates the aggregated travel time results and tailpipe emissions based on the USEPA MOVES [33] model. Another software called Surrogate Safety Assessment Model (SSAM) [34] was then utilized to post process trajectory files produced from PARAMICS in order to generate potential conflict number results for individual vehicles. Regarding the simulation scenario, the freeway SR-91E in California was selected as the network model which has been calibrated in terms of traffic demand and driving behavior based on data of a typical weekday morning in the summer [35]. The overall traffic demand is 25,000 vehicles per simulation run, which is categorized as the Level of Service (LOS) D according to the Highway Capacity Manual (HCM) 2010 [36].

The penetration rate of equipped vehicles is another dimension when evaluating the traffic flow impacts and overall performance measure. Four penetration rate cases were selected: 10%, 20%, 50% and 80% to generally observe the tradeoffs among three MOEs. The numerical results are listed in Table III. Figure 1 shows radar plots, where the quantitative tradeoffs among different MOEs can be observed and compared, and each performance measurement in radar plots is normalized for comparison purpose. To be specific, the normalized values in Figure 1 are obtained by choosing the largest value of the certain group of data in Table III as one and the others in that group are calculated in accordance with the relative proportions. Moreover, the average speed indicator is replaced by the average trip travel time, and each radar plot in Figure 1 is on a scale of 0 to 1, where 1 represents the "worst" quality in terms of each MOE. The baseline case is 0% penetration rate of application-equipped vehicles. Besides the baseline, the performance measure results of the other scenarios in Table III are for application-equipped vehicles.

Table III and Figure 1 illustrates the tradeoff among travel time decreases, conflict number increases and fuel consumption increases and shows:

a) 10% penetration rate: the mobility-focused LSM application provides lower travel time due to faster-lane change behavior, but is exposed to higher potential conflicts and fuel consumption because of the lane change operations and higher traveling speed. With regard to the tradeoff, LSM application would provide 8% travel time decrease while increasing fuel consumption by 3% and introducing higher potential conflict risks.

b) 20% penetration rate: As the penetration rate of LSM-equipped vehicles increases to 20%, the tradeoff is similar to the case where the penetration rate is 10%.

c) 50% penetration rate: Both the fuel consumption and average conflict number of the LSM-equipped vehicles group continue increasing compared to the baseline, while the travel time barely decreases when the penetration rate increases to 50% because of highly mixed traffic.

d) 80% penetration rate: As the penetration rate increases to 80%, where the majority of the on-road users are LSM-application-equipped vehicles, all the performance of the LSM-equipped vehicles deteriorates compared to the baseline since most vehicles in roadway transportation were trying to operate lane changes, which leads to more traffic chaos. Since the traffic system is disturbed by extra lane changes, the LSM application does not benefit equipped vehicles any longer in this high-penetration-rate scenario.

Table III Numerical results of the case study

	Baseline	LSM			
Penetration rate	0%	10%	20%	50%	80%
Average conflict number per vehicle	0.1673	0.2841	0.3922	1.1029	2.8443
Average speed (mph /vehicle)	60.6	65.5	65.5	59.6	34.8
Average fuel consumption (KJ/mile/vehicle)	4275.3	4398.1	4502.1	5062.6	5917.2

V. Discussions and Conclusions

Connected and Automated vehicles (CAV) centric advanced driver assistance systems applications constitute a huge part of intelligent transportation systems applications.

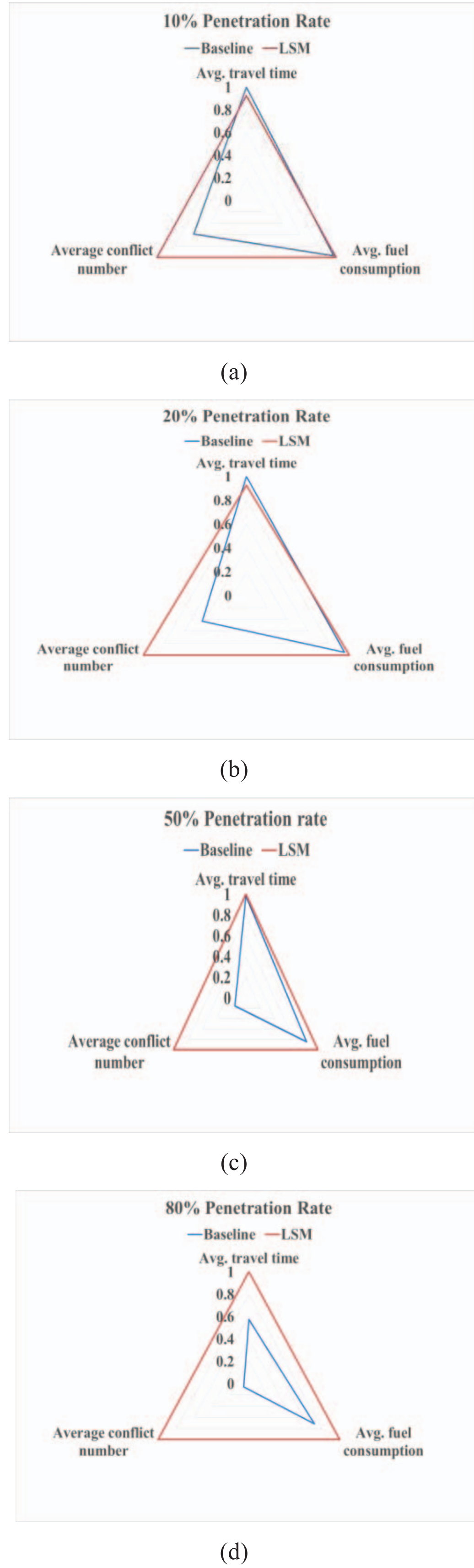

Figure 1. Radar plots of three normalized MOEs for LSM

This paper aims at providing a review on related research in the area of vehicle-centric CAV applications, where the co-benefits and trade-offs of systems performance measurement are examined simultaneously. Three major MOEs co-benefits/tradeoffs of different vehicle-centric applications have been analyzed. Not all the applications can take advantage from every MOE perspective, which is why it is necessary to consider certain tradeoffs. Several key influential factors were identified, such as capacity increase, gap increase, conservative brake, hybrid powertrain and path planning, with the goal of improving all key MOEs, leading to some co-benefits.

VI. Acknowledgement

This research is funded by the California Department of Transportation as part of a National Center for Sustainable Transportation research grant (NCST, see https://ncst.ucdavis.edu/).

References

[1] U. S. DOT, Jan. 20, 2017. [Online]. Available: https://www.transportation.gov/smartcity

[2] E. Uhlemann, "Connected-vehicles applications are emerging," *IEEE Vehicular Technol. Mag.*, vol. 11, issue 1, pp. 25-28, Mar. 2016.

[3] Iteris, "Connected Vehicle Reference Implementation Architecture," [Online]. Available: http://www.iteris.com/cvria/html/applications/applications.html

[4] European Commission, [Online]. Available: http://www.transport-research.info/project/preventive-and-active-safety-application

[5] European Commission, [Online]. Available: http://www.interactive-ip.eu/

[6] European Commission, [Online]. Available: http://cordis.europa.eu/project/rcn/191624_en.html

[7] European Commission, [Online]. Available: http://www.drive-c2x.eu/project

[8] I. Kaparias and M. G. H. Bell, "Key performance indicators for traffic management and intelligent transport systems," Imperial College London, London, UK, 218636, Jun. 2011.

[9] C. Bila, F. Sivrikaya, M. A. Khan, and S. Albayrak, "Vehicles of the future: A survey of research on safety issues," *IEEE Trans. Intell. Transp. Syst.*, vol. PP, issue 99, pp. 1-20, 2016.

[10] B. Chen and H. H. Cheng, "A review of the applications of agent technology in traffic and transportation systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 2, pp. 485-497, Jun. 2010.

[11] J. Barbaresso, G. Cordahi, D. Garcia, C. Hill, A. Jendzejec, and K. Wright, "USDOT's intelligent transportation systems (ITS) ITS strategic plan 2015-2019," U.S. DOT, Washington, DC, USA, FHWA-JPO-14-145, Dec. 2014.

[12] Y. Li, Y. Zheng, J. Wang, L. Wang, K. Kodaka, and K. Li, "Evaluation of forward collision avoidance system using driver's hazard perception," in *Proc. 19th IEEE Intell. Transp. Syst.*, Rio, Brazil, 2016, pp. 2273-2278.

[13] R. Sun, W. Y. Ochieng, and S. Feng, "An integrated solution for lane level irregular driving detection on highways," *Transp. Res. C, Emerging Technol.*, vol. 56, pp. 61-79, Jul. 2015.

[14] J. B. Kenney, "Dedicated Short-Range Communications (DSRC) standards in the United States," in *Proc. of the IEEE Journal*, vol. 99, no. 7, pp. 1162–1182, Jul. 2011.

[15] N. Lyamin, Q. Deng, and A. Vinel, "Study of the Platooning Fuel Efficiency under ETSI ITS-G5 Communications," in *Proc. 19th IEEE Intell. Transp. Syst.*, Rio, Brazil, 2016, pp. 551-556.

[16] R. Murugesh, U. Ramanadhan, N. Vasudevan, A. Devassy, D. Krishnaswamy, and A. Ramachandran, " Smartphone based driver assistance system for coordinated lane change," in *Proc. 4th Intl. Conf. on Connected Veh. And Expo*, Shenzhen, China, 2015, pp. 385-386.

[17] M. Fullerton, A. Leonhardt, S. Assenmacher, M. Baur, F. Busch, C. Beltrán, JJ. Mínguez, and T. Paadín, "Simulation study on improving traffic safety and traffic flow in the vicinity of a motorway accident through vehicle-to-vehicle communication," in *Proc. 18th IET Road Transp. Info. And Control Conf. and the ITS United Kingdom Members' Conf.*, London, UK, 2007.

[18] E. Semsar-Kazerooni, J. Verhaegh, J. Ploeg, and M. Alirezaei, "Cooperative adaptive cruise control: An artificial potential field approach," in *Proc. 27th IEEE Intell. Veh. Symp.*, Gothenburg, Sweden, 2016, pp. 361-367.

[19] K. C. Dey, L. Yan, X. Wang, Y. Wang, H. Shen, M. Chowdhury, L. Yu, C. Qiu, and V. Soundararaj, "A review of communication, driver characteristics, and controls aspects of cooperative adaptive cruise control (CACC)," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 2, pp. 491-509, Feb. 2016.

[20] K. D. Kusano and H. C. Gabler, "Safety benefits of forward collision warning, brake assist, and autonomous braking systems in rear-end collisions," *IEEE Trans. Intell. Transp. Syst*., vol. 13, no. 4, pp. 1546-1555, Dec. 2012.

[21] P. Szczurek, B. Xu, O. Wolfson, and J. Lin, "Estimating relevance for the emergency electronic brake light application," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 4, pp. 1638-1656, Dec. 2012.

[22] R. Schubert, K. Schulze, and G. Wanielik, "Situation assessment for automatic lane-change maneuvers," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 607-616, Sep. 2010.

[23] R. Dang, J. Ding, B. Su, Q. Yao, Y. Tian, and K. Li, "A lane change warning system based on V2V communication," in *Proc. 17th IEEE Intell. Transp. Syst.*, Qingdao, China, 2014, pp. 1923-1928.

[24] O. Orfila, G. S. Pierre, and M. Messias, "An android based ecodriving assistance system to improve safety and efficiency of internal combustion engine passenger cars," *Transp. Res. C, Emerging Technol.*, vol. 58, Part D, pp. 772-782, Sep. 2015.

[25] K. Li, T. Chen, Y. Luo, and J. Wang, "Intelligent Environment-Friendly Vehicles: Concept and Case Studies," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 1, pp. 318-328, Mar. 2012.

[26] K. Boriboonsomsin, M. J. Barth, W. Zhu, and A. Wu, "Eco-routing navigation system based on multisource historical and real-time traffic information," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 4, pp. 1694-1704, Dec. 2012.

[27] M. Zargayouna, F. Balbo, and K. Ndiaye, "Generic model for resource allocation in transportation Application to urban parking management," *Transp. Res. C, Emerging Technol.*, vol. 71, pp. 538-554, Oct. 2016.

[28] C. Winter. P. Ritzer, and J. Brembeck, "Experimental investigation of online path planning for electric vehicles," in *Proc. 19th IEEE Intell. Transp. Syst.*, Rio, Brazil, 2016, pp. 1403-1409.

[29] H. Ramezani and R. F. Benekohal, "Optimized speed harmonization with connected vehicles for work zones," in *Proc. 18th IEEE Intell. Transp. Syst.*, Canary Islands, Spain, 2015, pp. 1081-1086.

[30] D. Tian, W. Li, G. Wu, K. Boriboonsomsin, M. J. Barth, S. Rajab, and S. Bai, "Evaluating the effectiveness of V2V-based lane speed monitoring application: a simulation study," in *Proc. 19th IEEE Intell. Transp. Syst.*, Rio, Brazil, 2016, pp. 1592-1597.

[31] C. García-Costa, E. Egea-López, and J. García-Haro, "A stochastic model for design and evaluation of chain collision avoidance applications," *Transp. Res. C, Emerging Technol*., vol. 30, pp. 126-142, May 2013.

[32] Paramics, [Online]. Available: http://www.paramics-online.com/

[33] U.S. Environmental Protection Agency, "Motor Vehicle Emission Simulator (MOVES)," [Online]. Available: http://www.epa.gov/otaq/models/moves/

[34] FHWA, "Surrogate Safety Assessment Model (SSAM)," [Online]. Available: http://www.fhwa.dot.gov/publications/research/safety/08049/

[35] M. J. Barth, W. Zhu, K. Boriboonsomsin, and L. Ordonez, "Final report: Analysis of GPS-based data for light duty vehicles," California Air Resources Board, CA, USA, 04-327 UCR, Aug. 2006.

[36] Transportation Research Board, "Highway capacity manual 2010," [Online]. Available: http://onlinepubs.trb.org/onlinepubs/trnews/trnews273HCM2010.pdf