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Authors

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

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Performance Measurement Evaluation Framework and Co-Benefit/Tradeoff Analysis for Connected and Automated Vehicles (CAV) Applications: A Survey

Abstract—A number of Connected and/or Automated Vehicle (CAV) applications have recently been designed to improve the performance of our transportation system. Safety, mobility and environmental sustainability are three cornerstone performance metrics when evaluating the benefits of CAV applications. These metrics can be quantified by various measures of effectiveness (MOEs). Most of the existing CAV research assesses the benefits of CAV applications on only one (e.g., safety) or two (e.g., mobility and environment) aspects, without holistically evaluating the interactions among the three types of MOEs. This paper first proposes a broad classification of CAV applications, i.e., vehicle-centric, infrastructure-centric, and traveler-centric. Based on a comprehensive literature review, a number of typical CAV applications have been examined in great detail, where a categorized analysis in terms of MOEs is performed. Finally, several conclusions are drawn, including the identification of influential factors on system performance, and suggested approaches for obtaining co-benefits across different types of MOEs.

**Danyang Tian, Guoyuan Wu,
Kanok Boriboonsomsin, and Matthew J. Barth**
*The Center for Environmental Research
& Technology, UC Riverside, CA 92507 USA.
E-mail: dtian001@ucr.edu, gywu@cert.ucr.edu,
kanok@cert.ucr.edu, barth@ece.ucr.edu*

I. Introduction

Since Connected and/or Automated Vehicle (CAV) technology has emerged rapidly as a key component of Intelligent Transportation Systems (ITS) and a major pillar of the Smart City Challenge in the U.S. [1], a great quantity of relevant applications have been developed by automobile manufacturers, such as Volvo Cars' autonomous driving mode research, Toyota Motor Corporation's investment in Artificial Intelligence (AI) to reduce car accidents and showcase Vehicle-to-Everything (V2X) systems, BMW's Enlighten application showing traffic signal status ahead [2], and Honda's early deployment and effectiveness evaluation of V2X applications [3]. Also, the U.S. Department of Transportation (USDOT), with support from both public and private sectors, has developed the Connected Vehicle Reference Implementation Architecture (CVRIA) [4], which lays the foundation for many CAV application development and implementation. In Europe, the European Commission has invested in CAV research through programs such as seventh Framework Program and Horizon 2020 [5]. At the same time, there have been significant research activities in the area of CAV technology in Asia as well. For example, Japan is setting up Robot Taxi Inc. to operate driverless cars and an online service to transport passengers to stadiums of the 2020 Summer Olympics [6].

To better understand the different CAV applications in a systematic way, we have conducted an extensive survey of the literature and attempted to classify them. In a broad sense, the CAV applications may be classified into three categories, depending on the type of objects targeted by the applications.

a) *Vehicle-centric*: Vehicle-centric applications are primarily driven by on-board sensors and communication technologies, aimed at the ego-vehicle and/or the surrounding traffic. This type of CAV applications is mainly designed to adjust the ego vehicle's operations (e.g., longitudinal control), or to respond to its surroundings. Examples of vehicle-centric applications include adaptive cruise control and lane departure warning.

b) *Infrastructure-centric*: Infrastructure-centric applications enhance roadway performance by means of centralized surveillance, control, and analysis of roadway infrastructure via inductive loop detectors, communication-capable roadside units, and Traffic Management Centers (TMC). Examples of infrastructure-centric applications are ramp metering and variable speed limit systems.

c) *Traveler-centric*: Other than vehicles, travelers can also supply and receive information through connectivity to protect themselves from collisions and accidents or receive valuable information, such as route guidance. These travelers include drivers, transit riders, pedestrians, bicyclists, and even wheelchair users. Traveler-centric applications connect a variety of travelers with information regarding other objects in the traffic network, e.g., vehicles and infrastructure. Examples include advanced traveler information system and pedestrian collision warning.

There are numerous research activities all over the world focusing on CAV application development and a large number of studies on impact assessment and cost-benefit analysis of Advanced Driver Assistance Systems (ADAS) and CAV applications have been conducted, especially in Europe. However, there have been very few research effort looking into all possible benefits of these applications simultaneously. In this paper, we first present a benefit evaluation framework for CAV applications and a performance-oriented taxonomy based on key performance metrics in Section II. A category summary is then discussed in Section III, followed by the detailed analysis of potential co-benefits of some CAV applications in Section IV. Section V concludes this paper.
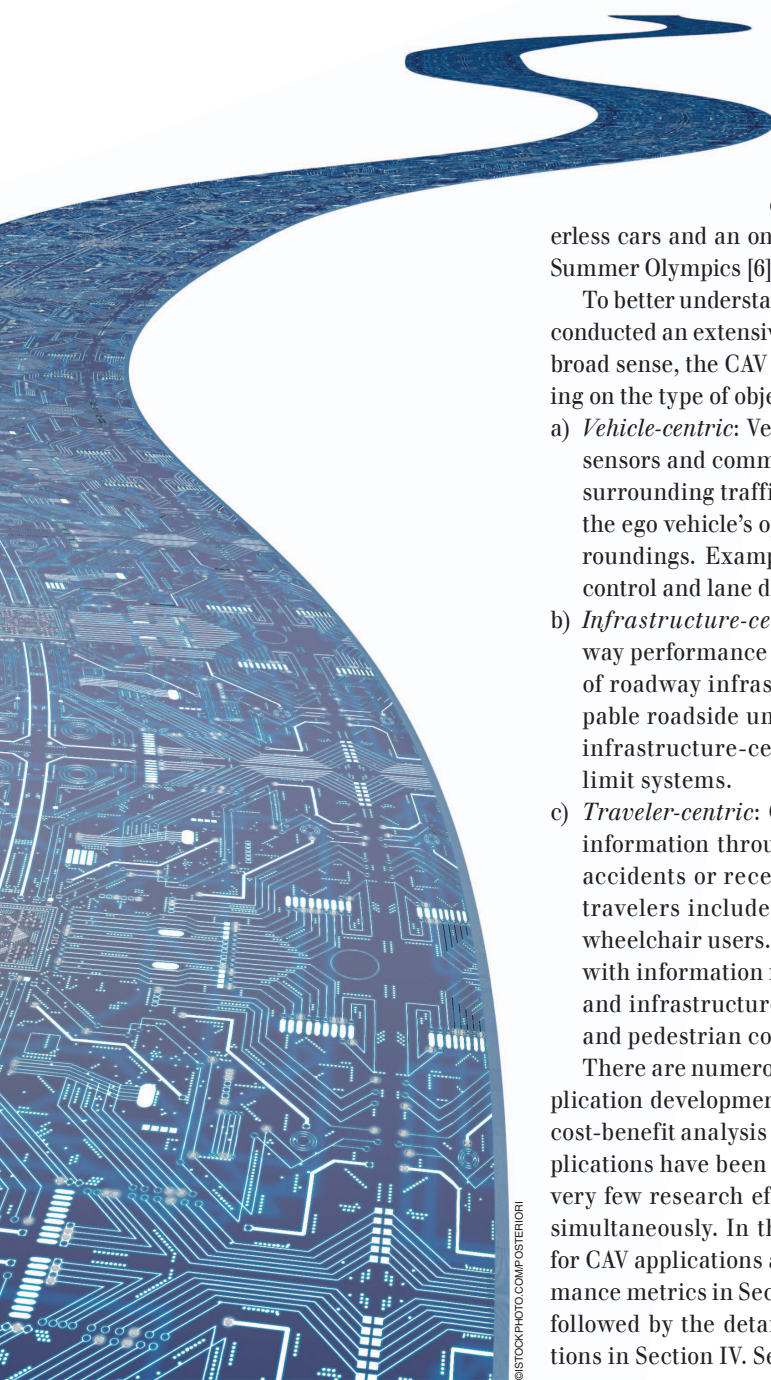
II. Performance-Oriented Taxonomy of CAV Applications

By incorporating advanced sensors, communication technologies and autonomous control into today's vehicles, CAV applications are able to greatly benefit the transportation systems and significantly enhance safety, improve mobility, and reduce environmental impacts. Inspired by some existing performance measure analysis [7] and surveys [8] [9], we developed a comprehensive performance measure evaluation framework, by including additional performance indicators used in other papers, of which the overview is shown in Figure 1. A brief description of the three major performance metrics, i.e., safety, mobility and environmental impacts is provided below. Examples of CAV applications that target one or more of the three performance metrics are given in Figure 2. Several of these applications are from the recent literature in 2015 and 2016. Some of these applications are also examined in detail in Section IV of the paper.

A. Safety

Safety is the primary goal of many ITS and CAV applications. Safety-oriented CAV applications enable vehicles to mitigate movement conflicts on roadways. Notifications or warnings for collision avoidance are issues through infrastructure-based and/or vehicle-based cooperative safety systems [10]. Examples include forward collision warning and lane keeping assistance.

B. Mobility

Mobility-oriented CAV applications employ methods and strategies aiming at increasing the operational efficiency of transportation systems and thus improving the mobility of individual travelers. Transportation system efficiency is referred to as the good use of transportation resources such as roadway capacity and travel time, with the objective of producing an acceptable level of transportation outputs such as roadway throughput and travel distance. Examples of mobility-oriented CAV applications are platooning and traffic signal coordination.

C. Environmental Impacts

The transportation sector has been a major contributor to air pollution and greenhouse gas emissions. It has now
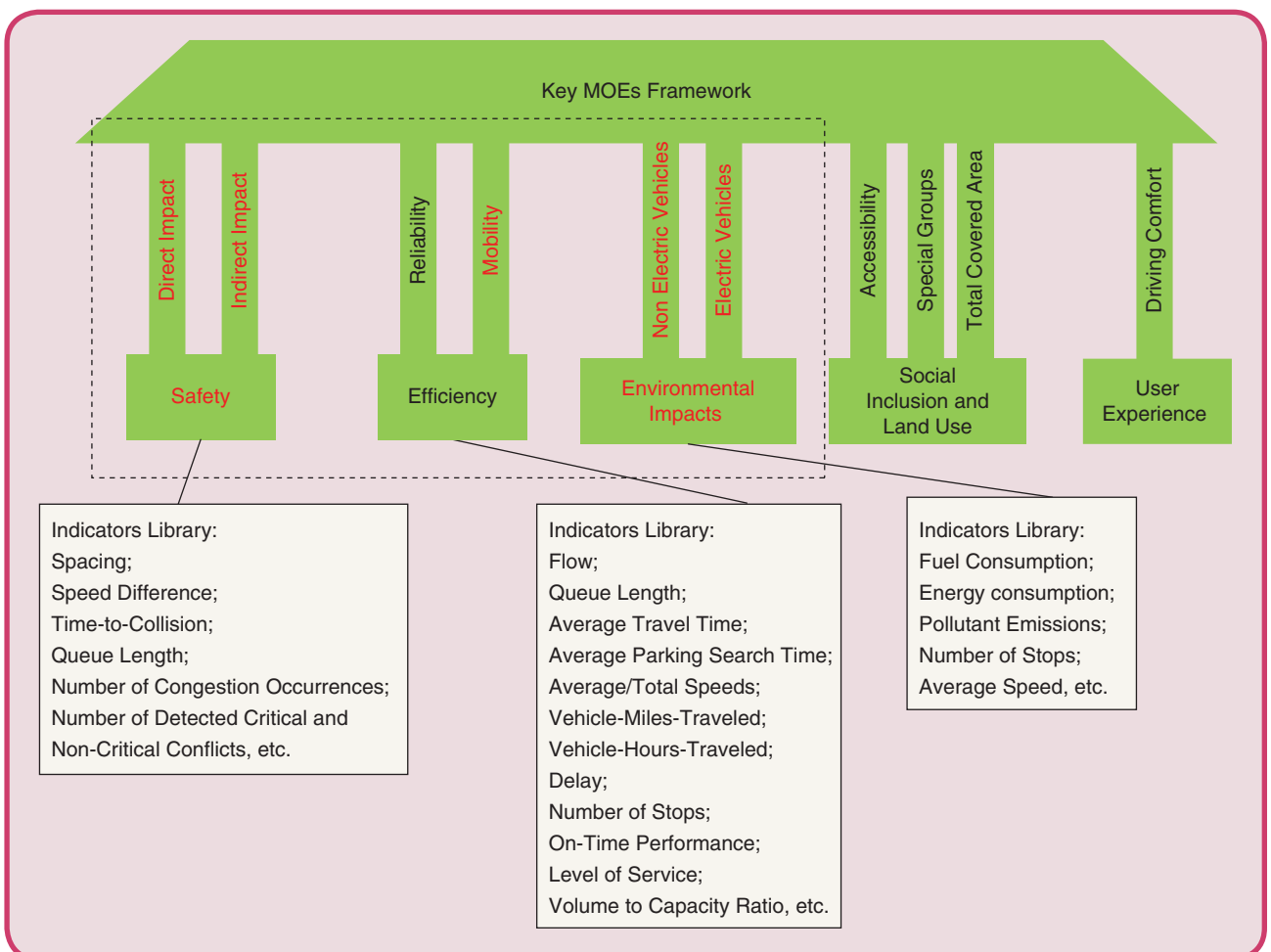

FIG 1 Overview of the performance measurement framework (MOEs in red are focused in this paper).

been widely accepted that ITS and CAV technologies can help significantly reduce transportation-related emissions. Over the last several years, a number of CAV applications have been developed that are focused on reducing energy and emissions associated with transportation activities. Examples include eco-routing navigation and eco-driving assistance.

III. Category Summary

According to Figure 2, most of the current CAV applications are not designed to be capable of achieving the three aims at the same time and most of the applications listed are safety-oriented. While these applications are focused primarily on avoiding crashes and accidents [11] or even detecting and predicting on-road irregular driving behavior [12] resulting in direct safety benefits, many of them also provide indirect or co-benefits (e.g., mobility improvement and/or pollutant emissions reduction). On the other hand, some safety-oriented applications may result in negative indirect impacts on mobility and environment, which can be viewed as tradeoffs among the different metrics. These arguments also apply to the mobility-oriented and environment-oriented CAV applications as well. Table I summarizes these co-benefits and tradeoffs. It can be seen that safety is the most common target among all the CAV applications reviewed in this survey. Please note that the criteria of whether the aims are achieved also depends on what the baseline is. The performance is usually compared under the same traffic situation with and without such CAV application. For instance, a queue-end warning application may improve "safety" in highway work zones due to the potential reduction in rear-end collision, even though the collision risk in work zones may still be higher than in other areas.
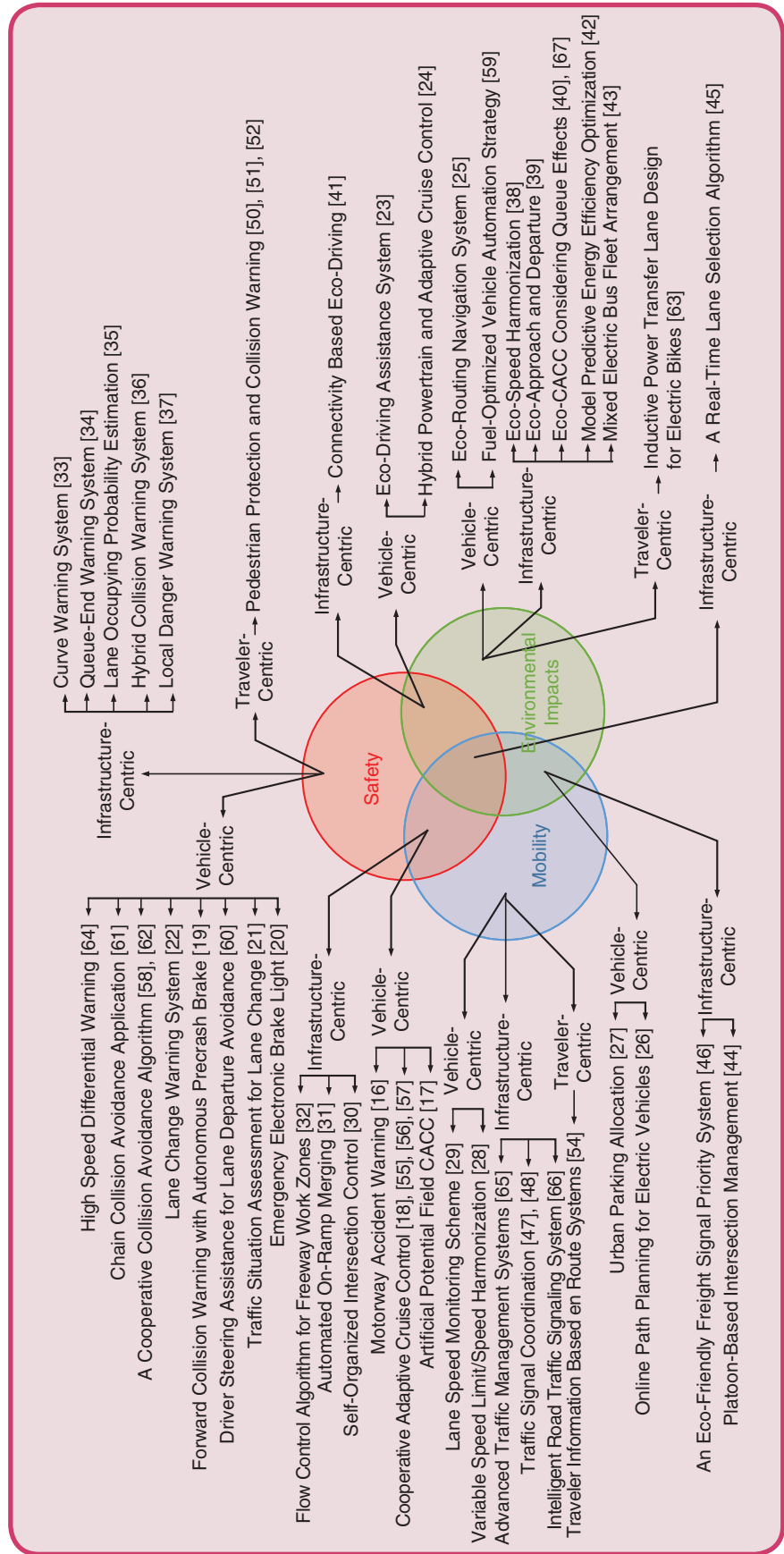

FIG 2 Taxonomy of CAV applications.

Table I. Category Summary of CAV Applications in Terms of Different MOEs.

Safety focused (25)	S↑ M? E?	S↑ M↑ E?	S↑ M? E↑	S↑ M↑ E↑
	15 out of 25 (60%)	6 out of 25 (24%)	3 out of 25 (12%)	1 out of 25 (4%)
Mobility focused (18)	S? M↑ E?	S↑ M↑ E?	S? M↑ E↑	S↑ M↑ E↑
	7 out of 18 (39%)	6 out of 18 (33%)	4 out of 18 (22%)	1 out of 18 (6%)
Environmental impacts focused (15)	S? M? E↑	S↑ M? E↑	S? M↑ E↑	S↑ M↑ E↑
	7 out of 15 (47%)	3 out of 15 (20%)	4 out of 15 (27%)	1 out of 15 (7%)

S: Safety; **M**: Mobility; **E**: Environmental impacts; ↑: Improvement; ?: Unknown, Neutral or Deteriorate.

There are very few studies that evaluate all three MOEs, and the co-benefits and tradeoffs among the three MOEs of CAV applications are rarely analyzed. Although a portion of CAV applications are designed to improve more than one MOE (usually two), very few of them improve all the three MOEs. Several CAV applications can be combined to achieve a comprehensive performance. For instance, vehicle platooning (increasing throughput) and collision avoidance functions (enhancing safety) can be incorporated into the intelligent energy management function in hybrid electric vehicle or plug-in hybrid electric vehicle platform (reducing fuel consumption). In terms of multiple MOEs, this combined CAV application will likely outperform the case where only individual applications are applied. In general, multiple CAV applications tend to be combined to achieve improvements of transportation systems in a more holistic way.

IV. Co-Benefit Analysis Of Typical V2X Based CAV Applications

All on-road communication-capable objects could share their information via wireless connectivity technologies, such as the Dedicated Short-Range Communication (DSRC) devices mounted on on-road units [13], and/or mobile devices enabled by cellular technologies (e.g., smart phones with built-in sensors) [14], [15]. The exchange of information between two terminals could supply users' basic motion

dynamics to the CAV applications and help increase the users' environmental awareness to benefit the transportation system, achieving the preset objectives in terms of transportation performance improvement.

Some typical examples of various CAV applications in the latest literature are addressed in this section. At the same time, co-benefits/tradeoffs among the three major MOEs are analyzed, under the categories introduced in Section I. Table III lists the vehicle-centric applications, and the symbols used in Table III, Table IV and Table V are listed in Table II.

A. Vehicle-Centric CAV Applications

1) Safety & Mobility Co-Benefits

Aimed at enhancing traffic safety, there are plenty of valuable research activities on CAV applications that have been carried out, focusing on road environment awareness. Based on modern communications technologies, a lane closure alert has been proposed by Fullerton et al., allowing drivers to be notified sooner to emergency situations, e.g., a sudden lane drop or motorway vehicle breakdowns [16]. Based on the simulation results of this warning system, the authors concluded that a gradual slow-down ought to be enough to reduce the potential risk of follow-on rear-end collisions. For this safety-focused driver advice system, the relief of bottlenecks congestion has great potential to increase the capacity of lane closure areas to some extent, leading to mobility co-benefit. Another typical example of CAV applications which aims to improve both traffic flow and safety is the Cooperative Adaptive Cruise Control (CACC) system [17]. Dey et al. presented an overall review of CACC system-related performance evaluation. Besides the front radar used to prevent potential conflicts, it was concluded that the CACC application also has the capability of enhancing mobility by increasing the traffic capacity (improving traffic flow) under certain penetration rates, and by harmonizing the speeds of platoons in a safe manner [18].

2) Safety Benefits

The Forward Collision Warning application is a relatively mature application, which is commonly used to improve situation awareness and enhance safety performance. The effectiveness among several pre-collision system algorithms was examined using Time-to-Collision (TTC) as a surrogate collision risk evaluation in [19], where Kusano & Gabler proved that performance of the conventional forward collision warning was significantly improved by integrating a pre-crash brake assistance as well as an autonomous pre-crash braking scheme. Likewise, Szczurek et al. presented an Emergency Electronic

Table II. Symbols for MOEs Co-Benefits and Tradeoffs in the Literature Review Tables.

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

Table III. Vehicle-Centric CAV Applications.

Categories	Platform	Project/Application Name & Ref	MOE Focus			Contributions
			S	M	E	
Vehicle-centric	Non-EV	EU 7th Seventh Framework Programme research project SOCIONICAL [16]	◐↑	●↑	○	An emergency situation alert system leading to reduced and harmonized speed in the vicinity of motorway bottlenecks in order to ensure a smoother and safer traffic flow
		FP7 European project ecoDriver [23]	◐↑	◐↓	●↑	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 [61]	●↑	○	○	A stochastic model regarding the surrogate measurement for accidents evaluation of cooperative chain collision warning applications
		Cooperative Adaptive Cruise Control [17]	◐↑	◐↑	○	An analysis on gap closing and collision avoidance functionality of the Cooperative Adaptive Cruise Control system
		Cooperative Adaptive Cruise Control [18]	◐↑	◐↑	○	A review of Cooperative Adaptive Cruise Control systems which have the potential to improve traffic throughput by increasing the roadway capacity and to harmonize the speeds of moving vehicles in the platoon in a safe manner
		Advanced Forward Collision Warning [19]	●↑	○↓	○↓	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 [20]	●↑	○↓	○↓	A machine learning approach-based emergency brake warnings relevance-decision estimation for safety applications
		Automatic Lane-Change [21]	◐↑	○	○	A situation awareness-based automatic lane-change scheme based on image processing, Kalman filtering and Bayesian networks approaches
		Lane Change Warning [22]	◐↑	○	○	A V2V-based lane change warning system, analyzing safe distance between the ego vehicle and its surrounding vehicles in both the original lane and the target lane
		Eco-routing navigation system [25]	○	◐↓	●↑	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 [28]	○↑	●↑	○↑	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 [29]	◐↓	●↑	◐↓	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 [24]	◐↑	○	●↑	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 [26]	○	◐↑	●↑	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

S: safety; M: mobility; E: environmental impacts.

Brake Light application-related algorithm, and showed safety benefits represented by the lower average number of collisions [20]. However, besides potential safety benefits, potential mobility and environmental impacts gains/costs still remain to be shown in both [19] and [20], where safety benefits are probably achieved at the expense of larger greenhouse gas (GHG) emissions due to increased stop-and-go behavior. This might happen in other similar safety-oriented collision avoidance applications, e.g., intersection collision warnings, curve speed warnings and

Table IV. Infrastructure-Centric CAV Applications.

Categories		Project/Application Name & Ref	MOE Focus			Contributions
			S	M	E	
Infrastructure-centric	Decentralized	A*STAR SERC "Complex Systems" [30]	◑↑	●↑	○↑	A self-organized intersection control algorithm with safe and efficient operations on individual vehicle dynamics control to smoothen intersection traffic flow and to increase the intersection capacity in urban area
		The 11th Five National Science and Technology Research Item [32]	●↑	●↑	○↑	An intelligent lane merge control system using traffic information collection, state estimation and variable merge strategy to improve safety and traffic flow in freeway work zones
		REM 2030 [42]	○	○	●↑	A model predictive energy efficiency minimization system implemented on the electric vehicle
		SAFESPOT [35]	◑↑	○	○	An intersection safety-critical situation awareness application based on lane occupying estimation via vehicle-to-infrastructure communication
		AERIS [38]	○↑	○	●↑	An eco-speed harmonization scheme using V2I and I2V to smooth the individual vehicle's speed profile and to reduce the overall energy consumption
		AERIS [39]	○↑	○↑	●↑	An eco-approach departure application which utilizes SPaT and preceding vehicles information to guide drivers to pass through intersections smoothly
		AUTOPIA [31]	◑↑	◑↑	○↑	An automated on-ramp merging system which consists of the distance reference system and a fuzzy control on vehicle's longitudinal control to improve traffic flow and congestion in a merging situation
		Queue-end warning [34]	◑↑	○	○	A queue-end location prediction algorithm using artificial neural network together with sensors and on-road message signs to reduce rear-end collisions in highway work zones
		Eco-CACC-Q [40]	○↑	○↑	●↑	An eco-cruise control system using shockwave prediction by SPaT messages and V2I information to refer the driver a fuel-optimal trajectory at the signalized intersections
		Connected eco-driving [41]	◑↑	○	●↑	A vehicle's longitudinal control system considering the inner driving operation and outer on-road factors to increase energy efficiency in a safe manner
		Curve warning system [33]	◑↑	○	○	A speed limitation algorithm integrating the upcoming road geometry and a safe speed decision scheme to achieve safe driving in sharp-curve roads
		Platoon-based MAS-IMA [44]	○↑	●↑	●↓	A multi-agent intersection management system based on the formation of platoons to increase mobility performance
		Optimal lane selection [45]	◑↑	●↑	●↑	An optimal lane change selection algorithm using on-road information and desired speed of individual vehicles to regulate traffic flow and reduce negative impacts induced by uncoordinated lane changes
		MA based Freight Signal Priority [46]	○↑	●↑	●↑	A regulation scheme of the signal timing for the priority of freight vehicles to decrease travel time and reduce fuel consumption
	Centralized	ADIS/ATMC Applications [65]	○	●↑	○	A dynamic traffic assignment model, seeking optimal assignment of vehicles to the network and supplying proper route guidance
		Hybrid collision warning system [36]	●↑	○↓	○↓	A hybrid collision warning system with integration of NGSIM loop detectors data, vehicle-to-vehicle information and the cloud center to offer the driver potential collision warnings in order to decrease collision risks
		Local Danger Warning System [37]	◑↑	○	○	A central information service and smartphone-based on-road dangerous situation awareness system to alleviate further dangers caused by congestion, full braking and tight bend

S: safety; M: mobility; E: environmental impacts.

Categories	Project/Application Name & Ref	MOE Focus			Contributions
		S	M	E	
Traveler-based	WATCH-OVER [50]	◑ ↑	○	○	A cooperative system framework integrating sensors and V2X communications to prevent road accidents that involve vulnerable active road users
	V2ProVu [51]	◑ ↑	○	○	A pedestrian protection application using Wi-Fi based NexCom devices for V2P communication for vehicle presence informing and/or hazard alarming
	Path2Go [54]	○	◑ ↑	○	A context-awareness routing service based on real-time Multi-Model traveler information to match proper travel modes and to provide users further route information
	WiFiHonk [52]	●↑	○	○	A collision estimation algorithm between providing issue warnings using the beacon stuffed Wi-Fi communication
	[63]	○	○	◑ ↑	A dynamic inductive power transfer lane designed for electric bikes

S: safety; M: mobility; E: environmental impact.

pedestrian warning systems, where stop-and-go activity will likely increase.

As the safety of the lane change operation is one of the most concern issues in the transportation system, lane change warning systems and lane change assistance systems have been attracting more and more attention. Schubert et al. fused on-board cameras and a decision-making approach to execute automatic lane-change maneuvers, and tested the algorithm on a concept vehicle Carai [21]. However, detailed quantitative effectiveness evaluation regarding traffic safety was not evaluated in [21]. In addition, Dang et al. take into account the drivers' reaction delay and brake time and proposed a real-time minimum safe distance model [22]. The simulation results obtained from Simulink show that this system generate lane change warning with the assist of TTC analysis, however, no other MOEs evaluation was mentioned other than potential safety improvements.

3) Environmental Impacts & Safety Co-Benefits

As aforementioned, safety and environment protection are always the first two of the most concerned issues concerning CAV applications preset objectives. Some co-benefits in terms of safety aspects can be well achieved by environmental impacts-oriented CAV applications. In this direction, an Android system based eco-Driving application was developed by Orfila et al., comprising the integration of upcoming road features recognition and crash relevant events identification modules, estimating the recommended speed with the purpose of supplying drivers an eco-friendly speed [23]. Even though one of the objectives was to improve the safety performance, potential safety effectiveness was not evaluated other than fuel savings results. Furthermore, the speeds with the proposed system are slower probably due to the safe eco-driving system that contributes to the steady-speed, smooth-deceleration behavior, therefore resulting

in reduced mobility with longer travel times. Another approach was proposed by Li et al. with the aim of achieving environment impacts improvement as well as safety improvement. A hybrid powertrain was incorporated with the conventional Adaptive Cruise Control (ACC) in [24], aiming to enhance traffic safety and to reduce the driver's effort. By comparing velocity profiles of vehicles without and with the proposed system, Li et al. show that vehicles' velocity profiles of the proposed system are smoother with lower overshoot. Moreover, since the study takes advantage of the high fuel efficiency scheme of hybrid electric systems, the engine torque and fuel improvement were investigated in [24] as well.

4) Environmental Impacts Benefits

As for the environmental impacts-focused CAV applications, Eco-routing system scheme turns out to be a very valuable algorithm that is beneficial to the environment. Boriboonsomsin et al. proposed an eco-routing navigation system, fusing multiple sources traveler information, incorporating the optimal route calculation engine and the human-machine-interface to reduce fuel consumption and pollutant emissions [25]. The trade-off between mobility and environmental impacts of the proposed system was described in [25]. 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.

5) Environmental Impacts & Mobility Co-Benefits

Some mobility improvement-oriented CAV applications are developed from the angle of path planning. For example, Winter et al. presented an online micro geometric path planning methodology using curvature minimization algorithm

to decrease travel time. Simultaneously the maneuverable robotic electric vehicle research platform ROboMObil was used to achieve the energy saving [26]. On the other hand, resource allocation is another approach to improve both mobility and environmental impacts. Zargayouna et al. proposed the resource allocation model to achieve the management of parking spots in an urban area taking into consideration both the location and the resources availability moment [27]. The urban parking management is expected to reduce fuel consumption by decreasing parking spots search time.

6) Mobility Benefits
There are very few CAV applications purely focusing on mobility improvement to date. A freeway work zone harmonizer was proposed, which was mainly designed to control shockwave propagation to reduce travel time delay [28]. The congestion duration and travel time delay were evaluated and it turned out that a minimum penetration rate of equipped vehicles must exist to guarantee the satisfactory efficiency of the proposed system. Another application called Lane Speed Monitoring (LSM) system has been studied in [29], which was proposed to estimate lane-level traffic state and to advise the driver to change to a faster lane, targeting to improve travel time. The average speed of equipped vehicles and unequipped vehicles were compared, and the fuel consumption and potential conflict number were also investigated in [29]. Higher velocity is achieved for equipped vehicles, whereas 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).

B. Infrastructure-Centric CAV Applications
Infrastructure-centric CAV application is another one of the key components regarding the traffic performance improvement and is well studied in the literature. Those infrastructure-centric applications can be further divided into two groups based on the control strategy implemented: decentralized (controlled by a localized infrastructure) and centralized (controlled by a traffic management center).

1) Safety & Mobility Co-Benefits
The fundamental task of localized infrastructure in the decentralized infrastructure-centric CAV applications is to collect and relay the vehicles information within a certain range. A number of studies have explored the decentralized control strategies. Yang and Monterola proposed a self-organized approach where each individual vehicle approaching the intersection governs its own motion dynamics by using the equipped intersection cruise control device together with the beacon as the information relay of approaching vehicles in the intersections of urban area [30]. Since fully stopping right before crossing the intersection reduces the

capacity of the intersection, the proposed decentralized traffic control system smoothens the individual vehicle dynamics and actively helps eliminate human driver errors to guarantee the overall safety when vehicles pass through the intersections. Fundamental traffic flow diagrams were plotted and compared in [30], and Yang and Monterola show the proposed control scheme's positive effects to the intersection capacity. Direct tests on safety, environmental impacts and other mobility-related indicators were not investigated. However, based on our analysis, it is expected that the fuel consumption likely decreases since there are smoother traffic flows in the intersections and more efficient braking operations. Considering the lane merging control schemes in the decentralized manner, Milanés et al. proposed an on-ramp merging system, which consists of a reference distance decision algorithm and a fuzzy controller to operate the vehicle's longitudinal control, based on information acquired from the localized infrastructure [31]. The study investigated the performance of the proposed system through real-world experiments, and Milanés et al. showed how three vehicles coordinate in order to alleviate the congestion and improve traffic flow in a merging situation by presenting the trajectories, speed profiles and relative distances results. In the same direction, Pei and Dai presented an intelligent lane merge control system for freeway work zones [32]. Pei and Dai used a traffic information collection system to comprehensively identify traffic states (e.g., traffic volume, velocity and occupancy) and implemented a variable lane merge strategy in VISSIM simulation software to produce mobility-related performance indices, such as capacity, delay and queue length. Moreover, performance in terms of the observed collisions number was compared among several merge control strategies.

2) Safety Benefits
As aforementioned, most reported infrastructure-centric applications are also focused on safety benefits in terms of collision mitigation. A safety-oriented application based on vehicle-infrastructure-driver interaction, an advanced curve warning system, was proposed in [33] as speed limitation/harmonization scheme on sharp roadways. The proposed system was tested in Matlab/Simulink, integrating the upcoming road geometry feature and a safe speed implementation module. Similar to [16], a queue-end warning system was presented in [34] where numerous sensors and an artificial neural network model-based algorithm were used to predict queue-end location. The information was displayed on portable variable message signs to avoid rear-end collisions in highway work zones. VISSIM was utilized to test the queue formation and dissemination in highway work zones. Another example of safety-focused applications has been presented in [35], where a safety-critical situation awareness warning system based on lane occupying probability estimation algorithm via vehicle-to-infrastructure

communication was proposed with the purpose of improving road users' safety at intersections.

As underlined in many studies, a management center tactic is inevitable in the centralized control strategy. As reported in [36], a hybrid collision warning system, integrating macroscopic data acquired from loop detectors and microscopic inter-vehicle information data obtained from on-board smartphones, was proposed to describe potential collision risks in divided road segments using a deceleration-based surrogate safety measurement. Benefited from the cloud center tactic, the system efficiency can be increased by loading computation tasks on individual smartphones. The collision risks, herein defined as a ratio between the required deceleration and the representative maximum braking performance, were compared among several collision warning systems. Tak et al. concluded that the proposed system outperforms other collision warning systems because of higher accuracy due to data fusion from multiple sources [36]. Other than driving behavior data (e.g., space headway difference, velocity difference and acceleration difference between the subject vehicle and the lead vehicle), mobility and environment impacts performance were not measured in [36]. Another typical example of safety-focused CAV application is the danger notification/dissemination application. Haupt et al. presented a local danger warning system, which used a central information service and equipped smartphones with built-in sensors to collect local abnormal situations (e.g., collective full braking behaviors, congestion and tight bend) to disseminate warnings to app-enabled vehicles in the vicinity of hazards [37]. It was concluded that the potential congestion and collision risks caused by the dangerous situations should be avoidable and reduced, whereas no direct results were investigated in [37].

3) Environmental Impacts Benefits

To achieve pollution emissions reduction of transportation systems, Wu et al. proposed an eco-speed harmonization scheme to reduce the overall fuel consumption on freeways using mutual vehicle-to-infrastructure communication [38]. In the proposed method, individual vehicles communicate with infrastructure on the associated road segment and calculate a safe eco-friendly speed based on a speed determination scheme. It is interesting to note that even the proposed strategy was proposed with a focus on environment protection, the rear collisions might be mitigated as well due to the harmonized speeds. In the same direction, an environmental impacts-focused application, namely the eco-approach departure system, was proposed in [39], where the signal phase and timing information from the traffic signal controller together with preceding vehicles information was utilized to supply speed and acceleration guidance to the driver in an eco-friendly way. The fuel savings generated by the Comprehensive Modal Emissions Model (CMEM) were compared, and results show that there are higher fuel

savings as the penetration rate of equipped vehicles increases. The mobility and safety performance were not estimated specifically in [39], whereas the individual vehicle's speed is smoothened when passing through the intersection, possibly leading to a decrease of potential rear-end collisions.

Yang et al. proposed an eco-CACC system to obtain fuel savings at signalized intersections [40]. The proposed system used a queue length prediction algorithm and formulated a fuel efficiency optimization problem, recommending the vehicle trajectory and advising the driver when to approach the intersection stop bar (right after the last queued vehicle is discharged) and how to stop (e.g. supplying speed and acceleration advice). A minimum penetration rate value is required for the overall fuel efficiency improvement for the multi-lane intersection scenario. Besides trajectory and fuel savings, safety-related and mobility-related results were not mentioned, however, potential conflicts and congestion are supposed to be mitigated due to a decrease of the queue length. Another eco-driving approach has been proposed in [41], where a longitudinal control approach based on energy consumption-minimized was used, taking into account both the inner vehicle's operations and the outer traffic and roadway conditions to evaluate the fuel savings. At the same time, a safe headway principle was embedded into this proposed system as well to achieve safety benefits.

Saving fuel by taking advantages of (hybrid) electric vehicle is an emerging and attractive research topic as well. A variety of research activities on electric vehicles and electric buses have been carried out, with the purpose of increasing energy efficiency and reducing emissions. Guan and Frey presented a model predictive energy efficiency optimization system using a power-train model and traffic lights sequences information to increase energy efficiency of the electric vehicles [42], [43].

4) Environmental Impacts & Mobility Co-Benefits

Multi-agent systems (MAS) approach turns out to be another frequently used method to regulate traffic flow and to save fuel consumption [44]–[46]. A platoon-based intersection management system was proposed in [44], aiming to improve mobility and environmental sustainability by the formation of vehicle platoons using connected vehicles technologies. The intersection capacity is increased due to the vehicle platoons, therefore the travel time is reduced compared to traditional traffic light control and non-platoon intersection management schemes, and safety might be improved due to the formation of platoons as well, however, slightly higher fuel consumption is introduced (validated). MAS can be applied to not only longitudinal maneuvers but also lateral ones. Also, Jin et al. proposed a real-time optimal lane selection algorithm which also regulates the uncoordinated lane changes of vehicles on a localized road segment based on the lane

occupied, speed, location and desired driving speeds of individual vehicles [45]. The overall conflict number was targeted to be zero in an optimization problem and it has been validated that the average travel time and fuel consumption are reduced at the same time. Making use of the freight signal priority on the basis of a connectivity-based signal control algorithm, Kari et al. addressed the issue of high NOx emissions from freight vehicles at intersections. Compared to fixed signal timing cases, both the fuel consumption and the travel time have been saved due to better traffic regulation, which benefits not only freight vehicles but also other vehicles [46]. Besides the freight vehicle priority algorithm, there are also some studies conducted, leading to a safe and smooth traffic society by using signal preemption systems for emergency vehicles [47], [48]. Table IV lists some of the infrastructure-centric CAV applications from the angle of co-benefits and trade-offs among different MOEs.

C. Traveler-Centric CAV Applications

1) Safety Benefits
Pedestrian protection is one of the urgent issues needed to be addressed, in order to enhance pedestrian safety. An interesting survey in this direction was carried out by Gandhi and Trivedi, which mainly focuses on pedestrian detection using sensors in vehicles and infrastructure, and collision avoidance based on collision prediction with pedestrian dynamics and behavior analysis [49]. Other than those computer vision based pedestrian detection techniques, there are also a few studies on pedestrian protection through V2X communications [50]–[53]. An approach to avoiding accidents by making use of sensors and communication technologies was discussed in [50]. The contributions focus on safety enhancement of active vulnerable road users (pedestrians, cyclists or powered two-wheelers) in a cooperative way. The proposed WATCH-OVER system can be triggered when there is a certain risk level measured by collision trajectories and send an alert to both the equipped vehicle and the active on-road traveler(s) to prevent any road accident. Similar projects V2ProVu and WiFiHonk were investigated in [51], [52], using a communication device NexCom (installed with the IEEE 802.11 g and a conventional GPS chip) and a smartphone-based beacon stuffed with a Wi-Fi based Vehicle-to-Pedestrian (V2P) communication system, respectively. In [52], results are the probability of a collision, defined as the ratio of the required time to stop and the time available for stop. Results of systems with the proposed communication approach and with conventional Wi-Fi communication method were tested and compared.

2) Mobility Benefits
In addition to the presented safety application, multimodal traveler information based traffic situational awareness systems have been developed in order to detect user modes of travel and provide further proper suggestion for routing. Zhang et al. proposed an iPhone/Android-based Path2Go application which was designed to improve the mobility of equipped users, by fusing the GPS data from both transit vehicles and smart phones/detecting mobile users' activity/differentiating the user's travel modes/supplying proper routing advice (including mode choices) to users [54]. The performance test of the proposed application was carried out on CalTrain and several local bus routes, and the correction detection rate is as high as 92%. Table V lists some of the traveler-centric applications from the different MOEs benefits perspective.

V. Conclusions
This paper provides an in-depth literature review on CAV applications related research, and analyses the potential tradeoffs and co-benefits of three key MOEs among various CAV applications in detail. A broad three-level classification of CAV applications has been proposed, i.e., vehicle-centric, infrastructure-centric, and traveler-centric applications. It is concluded that a trend exists that a portion of those CAV applications are being designed to improve more than one MOEs (usually two), however, very few CAV applications improve all the three major MOEs (i.e., safety, mobility and environmental impacts) simultaneously. Based on the literature reviewed, we identify some influential factors on system performance. In combination with co-benefits analysis of some typical CAV applications, we can conclude and identify some key strategies to improve system performance, such as better trajectory planning, increased spacing, capacity increase, speeds/deceleration smoothing, regenerative braking, vehicle's dynamics and exogenous signal phase and timing adjustment, etc. Moreover, some CAV applications may have co-benefits in the sense that they can improve a combination of safety, mobility and environmental sustainability by combining several different-MOE-focused applications.

Moreover, other than the application itself, many network-wide factors could affect the performance of a specific application. For instance, penetration rate of application-equipped vehicles is one important dimension that should be taken into account when the performance is measured, especially when there is a growing trend toward mixed traffic within the next decade. Other parameters we might also need consider include but not limit to traffic demand, truck percentage and even communication transmission range, etc.

of the authors, who are responsible for the facts and the accuracy of the data presented herein.

About the Authors

Danyang Tian is currently working toward the Ph.D. degree at the Transportation Systems Research Laboratory, Bourns College of Engineering—Center for Environmental Research and Technology, University of California, Riverside, CA. Her research interests include development of advanced driver assistance systems applications such as eco-driving and collision avoidance systems in combination with advanced sensors and connectivity technologies. She is also interested in traffic state prediction models, cooperative and safe lane-changing behavior, and traffic scheduling.

Guoyuan Wu holds an Assistant Research Engineer position in the transportation systems research (TSR) group at Bourns College of Engineering—Center for Environmental Research and Technology (CE-CERT) in the University of California at Riverside. His research focuses on intelligent and sustainable transportation system technologies, optimization and control of transportation systems, and traffic simulation.

Kanok Boriboonsomsin is currently an Associate Research Engineer at the College of Engineering—Center for Environmental Research and Technology, University of California, Riverside, USA. His research interests include sustainable transportation systems and technologies, intelligent transportation systems, traffic simulation, traffic operations, transportation modeling, vehicle emissions modeling, and vehicle activity analysis.

Matthew J. Barth is the Yeager Families Professor at the College of Engineering, University of California-Riverside. He is part of the intelligent systems faculty in Electrical and Computer Engineering and is also serving as the Director for the Center for Environmental Research and Technology (CE-CERT). Dr. Barth's research focuses on applying engineering system concepts and automation technology to Transportation Systems, and in particular how it relates to energy and air quality issues. His current research interests include ITS and the Environment, Transportation/Emissions Modeling, Vehicle Activity Analysis, Advanced Navigation Techniques, Electric Vehicle Technology, and Advanced Sensing and Control.

References

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

[2] E. Uhlemann, "Connected-vehicles applications are emerging," *IEEE Veh. Technol. Mag.*, vol. 11, no. 1, pp. 25–28, Mar. 2016.

[3] "V2X connected vehicle early deployment application analysis," Honda Project Report, Sept. 2016.

[4] Connected vehicle reference implementation architecture, Iteris. [Online]. Available: http://www.iteris.com/cvria/html/applications/applications.html

[5] FP7-COOPERATION-EUROPA research transport, European Commission. [Online]. Available: http://cordis.europa.eu/fp7/transport/home_en.html

[6] Futurism. [Online]. Available: https://futurism.com/images/tokyo-2020-olympics-future/

[7] I. Kaparias and M. G. H. Bell, *Key Performance Indicators for Traffic Management and Intelligent Transport Systems*. London, U.K.: Imperial College London, June 2011.

[8] 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, no. 99, pp. 1–20, 2016.

[9] 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, June 2010.

[10] J. Barbaresso, G. Cordahi, D. Garcia, C. Hill, A. Jendzejec, and K. Wright, *USDOT's Intelligent Transportation Systems (ITS) ITS Strategic Plan 2015–2019*. Washington, D.C.: U.S. DOT, Dec. 2014.

[11] 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 Intelligent Transportation Systems*, Rio, Brazil, 2016, pp. 2273–2278.

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

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

[14] N. Lyamin, Q. Deng, and A. Vinel, "Study of the platooning fuel efficiency under ETSI ITS-G5 communications," in *Proc. 19th IEEE Intelligent Transportation Systems*, Rio, Brazil, 2016, pp. 551–556.

[15] 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 Int. Conf. Connected Vehicles and Expo*, Shenzhen, China, 2015, pp. 385–386.

[16] M. Fullerton, A. Leonhardt, S. Assenmacher, M. Baur, F. Busch, C. Beltrán, J. J. 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 Transport Information and Control Conf. and Intelligent Transportation Systems United Kingdom Members' Conf.*, London, U.K., 2007.

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

[18] 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.

[19] 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.

[20] 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.

[21] 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, Sept. 2010.

[22] 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 Intelligent Transportation Systems*, Qingdao, China, 2014, pp. 1923–1928.

[23] 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, Emerg. Technol.*, vol. 58, no. Part D, pp. 772–782, Sept. 2015.

[24] 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.

[25] 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.

[26] 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.

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

[28] H. Ramezani and R. F. Benekohal, "Optimized speed harmonization with connected vehicles for work zones," in *Proc. 18th IEEE Intelligent Transportation Systems*, Canary Islands, Spain, 2015, pp. 1081–1086.

[29] 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 Intelligent Transportation Systems*, Rio, Brazil, 2016, pp. 1592–1597.

[30] B. Yang and C. Monterola, "Efficient intersection control for minimally guided vehicles: A self-organised and decentralised approach," *Transp. Res. C, Emerg. Technol.*, vol. 72, pp. 283–305, Nov. 2016.

[31] V. Milanés, J. Godoy, J. Villagrá, and J. Pérez, "Automated on-ramp merging system for congested traffic situations," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 2, pp. 500–508, June 2011.

[32] Y. Pei and L. Dai, "Study on intelligent lane merge control system for freeway work zones," in *Proc. 10th IEEE Intelligent Transportation Systems*, Seattle, 2007, pp. 586–591.

[33] S. Glaser, L. Nouveliere, and B. Lusetti, "Speed limitation based on an advanced curve warning system," in *Proc. 18th IEEE Intelligent Vehicles Symp.*, Istanbul, Turkey, 2007, pp. 686–691.

[34] A. M. Khan, "Intelligent infrastructure-based queue-end warning system for avoiding rear impacts," *IET Intell. Transp. Syst.*, vol. 1, no. 2, pp. 138–143, Feb. 2007.

[35] T. Schendzielorz, P. Mathias, and F. Busch, "Infrastructure-based vehicle maneuver estimation at urban intersections," in *Proc. 16th IEEE Intelligent Transportation Systems*, Hague, the Netherlands, 2013, pp. 1442–1447.

[36] S. Tak, S. Woo, and H. Yeo, "Study on the framework of hybrid collision warning system using loop detectors and vehicle information," *Transp. Res. C, Emerg. Technol.*, vol. 73, pp. 202–218, Dec. 2016.

[37] C. Haupt, J. Rohnstock, and S. Wappler, "smartLDW: A smartphone-based local danger warning system," in *Proc. 2th Int. Conf. Connected Vehicles and Expo*, Las Vegas, NV, 2013, pp. 139–144.

[38] G. Wu, D. Kari, X. Qi, K. Boriboonsomsin, and M. J. Barth, "Developing and evaluating an eco-speed harmonization strategy for connected vehicles," in *Proc. 4th Int. Conf. Connected Vehicles and Expo*, Shenzhen, China, 2015, pp. 373–378.

[39] H. Xia, K. Boriboonsomsin, and M. J. Barth, "Dynamic eco-driving for signalized arterial corridors and its indirect network-wide energy/emissions benefits," *J. Intell. Transp. Syst. Technol. Plan. Oper.*, vol. 17, no. 1, pp. 31–41, 2013.

[40] H. Yang, H. Rakha, and M. V. Ala, "Eco-cooperative adaptive cruise control at signalized intersections considering queue effects," *IEEE Trans. Intell. Transp. Syst.*, vol. PP, no. 99, pp. 1–11, 2016.

[41] Q. Jin, G. Wu, K. Boriboonsomsin, and M. J. Barth, "Power-based optimal longitudinal control for a connected eco-driving system," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 10, pp. 2900–2910, Oct. 2016.

[42] T. Guan and C. W. Frey, "Predictive energy efficiency optimization of an electric vehicle using information about traffic light sequences and other vehicles," in *Proc. 19th IEEE Intelligent Transportation Systems*, Rio, Brazil, 2016, pp. 919–926.

[43] D. Santos, Z. Kokkinogenis, J. F. de Sousa, D. Perrotta, and R. J. F. Rossetti, "Towards the integration of electric buses in conventional bus fleets," in *Proc. 19th IEEE Intelligent Transportation Systems*, Rio, Brazil, 2016, pp. 90–95.

[44] Q. Jin, G. Wu, K. Boriboonsomsin, and M. J. Barth, "Platoon-based multi-agent intersection management for connected vehicle," in *Proc. 16th IEEE Intelligent Transportation Systems*, Hague, the Netherlands, 2013, pp. 1462–1467.

[45] Q. Jin, G. Wu, K. Boriboonsomsin, and M. J. Barth, "Improving traffic operations using real-time optimal lane selection with connected vehicle technology," in *Proc. 25th IEEE Intelligent Vehicles Symp.*, Dearborn, MI, 2014, pp. 70–75.

[46] D. Kari, G. Wu, and M. J. Barth, "Eco-friendly freight signal priority using connected vehicle technology: A multi-agent systems approach," in *Proc. 25th IEEE Intelligent Vehicles Symp.*, Dearborn, MI, 2014, pp. 1187–1192.

[47] M. Miyawaki, Z. Yamashiro, and T. Yoshida, "Fast emergency preemption systems (FAST)," in *Proc. 2nd IEEE/IEEJ/JSAI Int. Conf. Intelligent Transportation Systems*, Tokyo, Japan, 1999, pp. 993–997.

[48] W. Kang, G. Xiong, Y. Lv, X. Dong, F. Zhu, and Q. Kong, "Traffic signal coordination for emergency vehicles," in *Proc. 17th IEEE Intelligent Transportation Systems*, Qingdao, China, 2014, pp. 157–161.

[49] T. Gandhi and M. M. Trivedi, "Pedestrian protection systems: Issues, survey, and challenges," *IEEE Trans. Intell. Transp. Syst.*, vol. 8, no. 3, pp. 413–430, 2007.

[50] L. Andreone, F. Visintainer, and G. Wanielik, "Vulnerable road users thoroughly addressed in accident prevention: The WATCH-OVER European project," in *Proc.14th World Congr. Intelligent Transportation Systems*, Beijing, China, 2007, pp. 1–8.

[51] J. J. Anaya, P. Merdrignac, O. Shagdar, F. Nashashibi, and J. E. Naranjo, "Vehicle to pedestrian communications for protection of vulnerable road users," in *Proc. 25th IEEE Intelligent Vehicles Symp.*, Dearborn, MI, 2014, pp. 1037–1042.

[52] K. Dhondge, S. Song, B.-Y. Choi, and H. Park, "WiFiHonk smartphone-based beacon stuffed WIFI car2x-communication system for vulnerable road user safety," in *Proc. 79th IEEE Vehicular Technology Conf.*, Seoul, Korea, 2014.

[53] D. Greene, J. Liu, J. Reich, Y. Hirokawa, A. Shinagawa, H. Ito, and T. Mikami, "An efficient computational architecture for a collision early-warning system for vehicles, pedestrians, and bicyclists," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 942–953, Dec. 2011.

[54] L. Zhang, S. D. Gupta, J.-Q. Li, K. Zhou, and W.-B. Zhang, "Path2Go: Context-aware services for mobile real-time multimodal traveler information," in *Proc. 14th IEEE Intelligent Transportation Systems*, Washington, DC, 2011, pp. 174–179.

[55] S. E. Li, Y. Zheng, K. Li, and J. Wang, "An overview of vehicular platoon control under the four-component framework," in *Proc. 26th IEEE Intelligent Vehicles Symp.*, Seoul, Korea, 2015, pp. 286–291.

[56] Y. Zheng, S. E. Li, J. Wang, D. Cao, and K. Li, "Stability and scalability of homogeneous vehicular platoon: Study on the influence of information flow topologies," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 1, pp. 14–26, Jan. 2016.

[57] Y. Zheng, S. E. Li, K. Li, F. Borrelli, and J. K. Hedrick, "Distributed model predictive control for heterogeneous vehicle platoons under unidirectional topologies," *IEEE Trans. Ctrl. Syst. Technol.*, vol. 25, no. 3, pp. 899–910, May 2017.

[58] J. Wang, S. E. Li, Y. Zheng, and X. Lu, "Longitudinal collision mitigation via coordinated braking of multiple vehicles using model predictive control," *Integr. Comput.-Aided Eng.*, vol. 22, no. 2, pp. 171–185, 2015.

[59] S. E. Li, K. Deng, Y. Zheng, and H. Peng, "Effect of pulse-and-glide strategy on traffic flow for a platoon of mixed automated and manually driven vehicles," *Comput.-Aided Civil Infrastruct. Eng.*, vol. 30, no. 11, pp. 892–905, 2015.

[60] N. M. Enache, S. Mammar, M. Netto, and B. Lusetti, "Driver steering assistance for lane-departure avoidance based on hybrid automata and composite Lyapunov function," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 1, pp. 28–39, Mar. 2010.

[61] 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, Emerg. Technol.*, vol. 30, pp. 126–142, May 2013.

[62] T. Liu, Y. Wang, E. Wenjuan, D. Tian, G. Yu, and J. Wang, "Vehicle collision warning system and algorithm at intersection under internet-connected vehicles environment," in *Proc. 12th Chinese Overseas Transportation Association Int. Conf. Transportation Professionals*, Beijing, China, 2012, pp. 1177–1185.

[63] L. A. Lisboa Cardoso, M. Comesaña Martinez, A. A. Nogueiras Meléndez, and J. L. Afonso, "Dynamic inductive power transfer lane design for E-Bikes," in *Proc. 19th IEEE Intelligent Transport Systems*, Rio, Brazil, 2016, pp. 2307–2312.

[64] W. Li, G. Wu, K. Boriboonsomsin, M. J. Barth, S. Rajab, S. Bai, and Y. Zhang, "Development and evaluation of high speed differential warning application using vehicle-to-vehicle communication," in *Proc. 96th Annu. Meeting Transportation Research Board*, Washington, DC, 2017.

[65] H. S. Mahmassani, T. Hu, S. Peeta, and A. Ziliaskopoulos, "Development and testing of dynamic traffic assignment and simulation procedures for ATIS/ATMS applications," U.S. DOT, VA, Tech. Rep. DTFH61-90-R-00074-FG, June 1994.

[66] N. S. Nafi and J. Y. Khan, "A VANET based intelligent road traffic signalling system," in *Proc. Australasian Telecommunication, Networks and Applications, Conf.*, Brisbane, Australia, 2012, pp. 1–6.

[67] Z. Wang, G. Wu, P. Hao, K. Boriboonsomsin, and M. Barth, "Developing a platoon-wide Eco-Cooperative Adaptive Cruise Control (CACC) system," in *Proc. 28th IEEE Intelligent Vehicles Symp.*, Redondo Beach, CA, 2017, pp. 1256–1261.

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