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16. ABSTRACT

As part of Intelligent Transportation Systems (ITS) development, a significant number of Connected and Automated Vehicles (CAV) applications are now being designed to improve a variety of transportation-related Measures of Effectiveness (MOEs). Safety, mobility and environmental sustainability typically represent the three cornerstones when evaluating the effectiveness of a CAV application system. These key MOEs can be evaluated through various performance indicators, many that are described in the literature. Most CAV applications are typically developed with the major goal of improving one of these key elements. As examples: 1) crash avoidance systems on vehicles are being developed specifically for improving safety; 2) adaptive signal control systems are being put into place to improve mobility; and 3) ecoapproach and departure systems at signalized intersections are now being contemplated to reduce vehicle energy and emissions. To date, very few studies on CAV applications have been conducted that provide a holistic assessment of all three of these MOE elements. Many CAV applications may have co-benefits in the sense that they can improve a combination of safety, mobility and environmental sustainability. On the other hand, some CAV applications may actually have tradeoffs between these elements.

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Examining the Safety, Mobility and Environmental Sustainability Co-Benefits and Tradeoffs of Intelligent Transportation Systems

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A White Paper from the National Center for Sustainable Transportat

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Examining the Safety, Mobility and Environmental Sustainability Co-Benefits and Tradeoffs of Intelligent Transportation Systems

A National Center for Sustainable Transportation Research Report

March 2017

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EXECUTIVE SUMMARY

As part of Intelligent Transportation Systems (ITS) development, a significant number of Connected and Automated Vehicles (CAV) applications are now being designed to improve a variety of transportation-related Measures of Effectiveness (MOEs). Safety, mobility and environmental sustainability typically represent the three cornerstones when evaluating the effectiveness of a CAV application system. These key MOEs can be evaluated through various performance indicators, many that are described in the literature. Most CAV applications are typically developed with the major goal of improving one of these key elements. As examples: 1) crash avoidance systems on vehicles are being developed specifically for improving safety; 2) adaptive signal control systems are being put into place to improve mobility; and 3) eco-approach and departure systems at signalized intersections are now being contemplated to reduce vehicle energy and emissions.

To date, very few studies on CAV applications have been conducted that provide a *holistic* assessment of all three of these MOE elements. Many CAV applications may have co-benefits in the sense that they can improve a combination of safety, mobility and environmental sustainability. On the other hand, some CAV applications may actually have tradeoffs between these elements.

As part of an initial research project, we conducted an in-depth literature review across a wide range of CAV applications and have broadly classifying these applications into vehicle-centric, infrastructure-centric, and traveler-centric CAV applications. This classification is dependent on the "focus" of the objects that have been involved in the application's developing and deploying process.

In this whitepaper, we briefly describe the three major MOEs, followed by a categorization summary based on the most recent literature. Next, a number of typical CAV applications have been examined in depth, providing a detailed analysis of the different MOEs co-benefits and tradeoffs.

Further, three representative CAV applications have been examined in detail in order to show the association between the application focus and tradeoffs/co-benefits of different performance measures. The CAV applications include High Speed Differential Warning (safety-focused), Lane Speed Monitoring (mobility-focused), and Eco-Speed Harmonization (environmental impacts-focused). We then highlight several future research directions, including the identification of key influential factors on system performance and how to obtain

co-benefits across all key MOEs. The overall intent of this whitepaper is to inform practitioners and policy makers on the potential interactions between the safety, mobility, and environmental sustainability goals of implementing specific CAV applications as part of their ITS programs.

Introduction

Connected and Automated Vehicle (CAV) technology is emerging rapidly as a key component of Intelligent Transportation Systems (ITS) development. There are a number of U.S. Department of Transportation (USDOT) pilot programs that highlight CAV technology; these technologies are also playing a major role in a variety of "Smart City" initiatives across the U.S. [USDOT, 2017]. Further, many automobile manufacturers are developing relevant CAV applications [Uhlemann, 2016], such as Volvo's autonomous driving mode research, Toyota Motor Corporation's investment in Artificial Intelligence (AI) to reduce car accidents (part of their ITS Vehicle-to-Everything (V2X) system), BMW's Enlighten application showing traffic signs status ahead, and Honda's early deployment and effectiveness evaluation of V2X applications [Honda, 2016].

With the proliferation of CAV applications, the U.S. Department of Transportation, along with support from both public and private sectors, has developed a *Connected Vehicle Reference Implementation Architecture* (CVRIA, see [Iteris, 2015]), which categorizes and describes the foundation of many CAV-based applications. In addition, Europe has also been funding CAV-related projects as part of their Seventh Framework Programme [European Commission, 2016]. These projects tackle a number of traffic improvements, including safety, mobility enhancement, minimization of environmental impacts, energy efficiency, security, and public health. In Asia, many researchers are also developing CAV-based ITS applications. For example, Japan is actively setting up a Robot Taxi system to operate driverless cars and an online service to transport passengers to stadiums for the Olympics of the future [Futurism, 2016].

To better understand the impacts of emerging CAV applications in a systematic way, we have carried out a comprehensive literature review over many CAV applications that may be broadly classified into three major categories, depending on the type of focused objects that have been involved in the application's developing and deploying process. These categories include:

Vehicle-centric: Vehicle-centric applications refer to CAV applications that benefit the vehicle itself (i.e., ego-vehicle) and/or the entire transportation system, using advanced sensors and communications technologies. These CAV applications are typically designed to adjust a vehicle's endogenous operational parameters (e.g., powertrain and vehicle dynamics), based on sensing of the environment and communicating with other vehicles.

***Infrastructure-centric*:** Infrastructure-centric CAV applications enhance roadway transportation performance by means of centralized surveillance, management, and analysis via roadway infrastructure systems. There are a wide-variety of components that are utilized, including inductive loop detectors, communication-capable roadside units, and intelligent Traffic Management Centers (TMC).

***Traveler-centric*:** Other CAV applications are focused on the traveler themselves; for example, some on-road active users could provide input on trip parameter information (using connectivity technologies), as well as receiving routing guidance based on advanced traveler information system technology. These connected travelers may include pedestrians, bicycles, and even wheelchairs. The traveler-centric applications focus on bridging travelers to other objects in the traffic network, e.g., vehicles and infrastructure.

There are numerous studies all over the world focusing on V2X-based CAV applications development and a large number of research activities on impact assessment and cost-benefit analysis. Most projects define specific performance measures and carry out some type of evaluation. This is very typical of the USDOT-sponsored projects, as well as European projects. However, very few research efforts examine a *comprehensive set* of MOEs simultaneously. Further, there are only a few projects that actually fine-tune their system parameters in order to achieve a wide range of co-benefits across different types of measures of effectiveness (MOEs).

To get further insight into the impacts of emerging CAV applications in a systematic way, we have established an evaluation framework and developed a performance-oriented taxonomy based on the key measures of effectiveness. In this whitepaper, we present the framework along with a possible parameter tuning strategy. This is followed by a detailed analysis on the potential co-benefits of some typical CAV applications. Three specific example CAV applications are then analyzed in detail: High Speed Differential Warning (vehicle-centric safety-focused), Lane Speed Monitoring (vehicle-centric mobility-focused) and Eco-Speed Harmonization (infrastructure-centric environmental impacts-oriented). For each of these examples, we describe the existing tradeoffs and co-benefits of different types of MOEs. The last section of this whitepaper provides conclusions and highlights future research directions.

Measure of Effectiveness (MOE) for CAV Applications

By incorporating advanced sensors, communication technologies and automated control into today's vehicles, CAV applications are enhancing safety, improving mobility, and reducing environmental impacts. To evaluate these different impacts, we have developed a performance measure framework to define all of the different measures of effectiveness (styled after similar cost-benefit analyses, e.g., [Kaparias and Bell, 2011; Bila et al., 2016; Chen and Cheng, 2010]). The overall performance measure framework is shown in Figure 1, based around the three major performance areas of safety, mobility and the environment.

Safety

Safety-focused CAV applications enable vehicles to mitigate roadway conflicts by developing notification and warning mechanism of collision avoidance with regard to both infrastructure-based and vehicle-based cooperative safety systems (see, e.g., [Barbaresso et al., 2014]). A portion of these applications focus directly on safety benefits to avoid crashes and accidents (e.g., [Li et al., 2016]) or even to detect and predict on-road irregular driving behavior (e.g., [Sun et al., 2015]). Other non-safety oriented CAV applications (e.g., mobility improvement and/or pollutant emissions reduction) may affect safety indirectly, either positively or negatively, which we view as co-benefits or tradeoffs among the different MOEs.

The common safety performance measures include:

- Probability of collision;
- Time-to-collision;
- Vehicle spacing;
- Speed differences between vehicles;
- Queue length;
- Number of congestion occurrences; and
- Number of detected vehicle conflicts.

Mobility

To better manage the overall transportation system, mobility-oriented CAV applications utilize a variety of strategies aimed at increasing operational efficiency and improving individual mobility. System efficiency is an essential component for good resource management with the objective of producing an acceptable level of transportation throughput [Kaparias and Bell, 2011]. Similar to mobility, *reliability* is another key factor of system efficiency, concerned with things such as travel time variability, system usage and transportation system capacity.

The common mobility performance measures include:

- Average travel time;
- Overall Delay;
- Vehicle-to-Capacity ratio;
- Level of Service;
- Average/total speed;
- Vehicle-Miles-Traveled (VMT)/Vehicle-Hours-Traveled (VHT);
- Vehicle flow;
- Queue lengths;
- Average parking search time;
- Number of total stops; and
- On-Time Performance.

Environmental Impacts

The transportation sector is a major contributor to air pollution and greenhouse gas emissions. This has put increased attention on ITS and CAV technologies to potentially reduce negative environmental impacts, including energy consumption. Indeed, a significant number of CAV applications now focus on how to reduce the traffic emission of pollutants and reduce energy use (e.g., see [Barth et al., 2008; Kaparias and Bell, 2011]).

The common environmental impact performance measures include:

- Energy consumption;
- Criteria pollutant emissions (CO, HC, NO_x, PM)
- GHG emissions (CO2, N_2O, etc.)
- Fuel use.

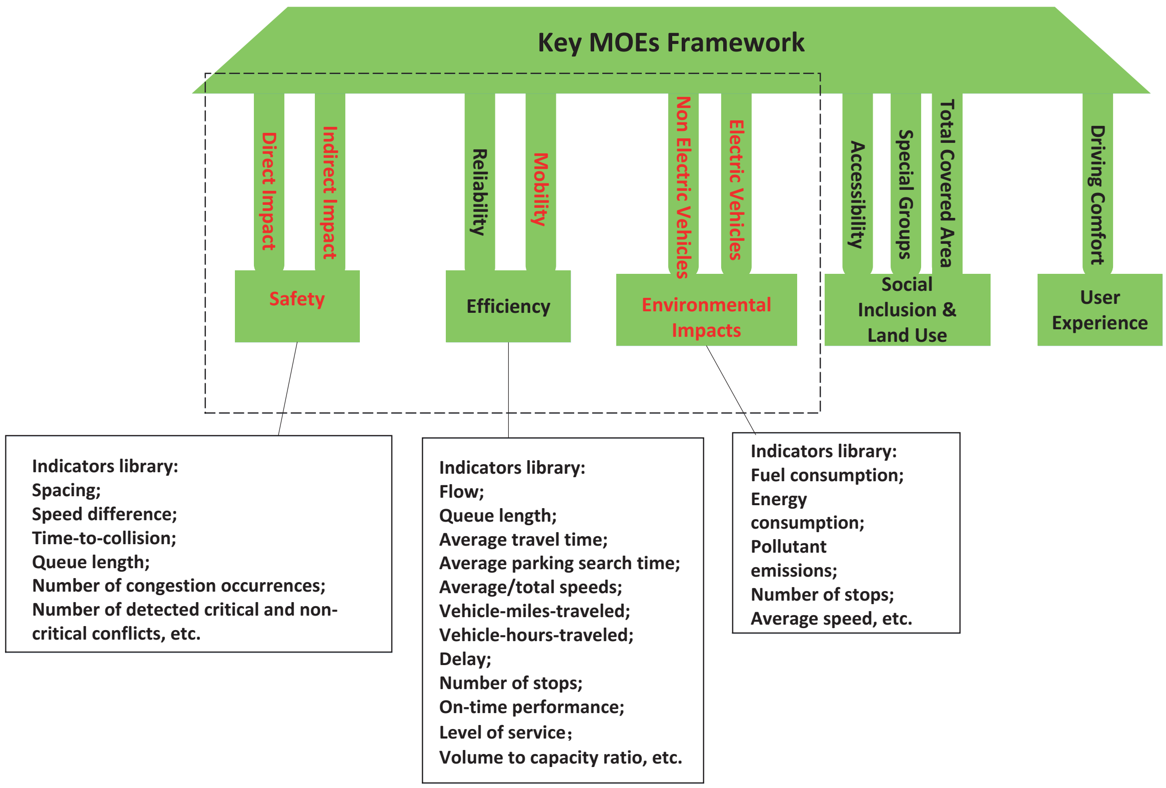


Figure 1. Overview of the Performance Measurement Framework (measures in red are the focus used in this analysis)

Safety, Mobility, Environment Category Summary

As described previously, safety, mobility and environmental sustainability represent the three cornerstones when evaluating the effectiveness of CAV applications. Of particular interest are CAV applications or projects that explicitly account for elements of safety, mobility, and/or environmental factors. To help categorize different applications, we utilize the general Venn diagram shown in Figure 2. This Venn diagram allows us to directly categorize different CAV applications; note that in Figure 2, several examples are given.

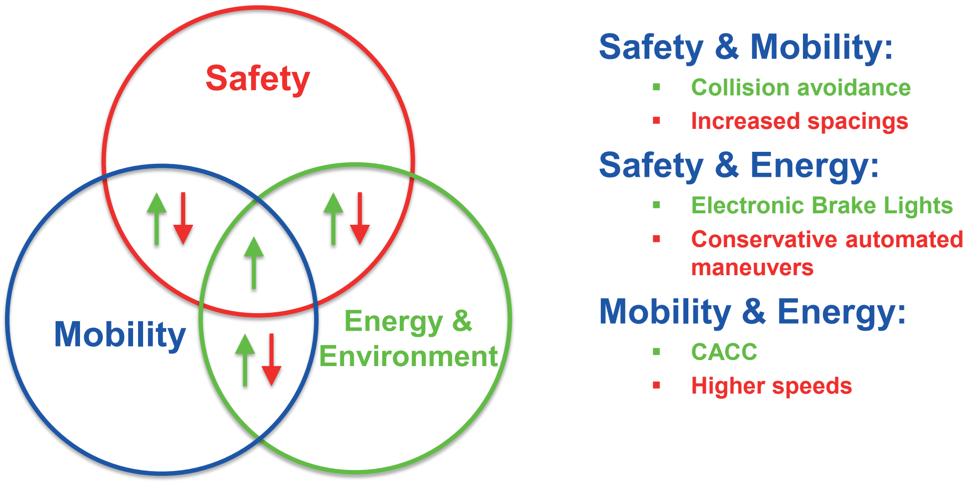


Figure 2. Co-Benefits and Tradeoffs between Safety, Mobility and Environmental factors.

Literature Survey

We have carried out a literature survey, primarily addressing recent CAV literature in 2015 and 2016. The general results of the survey are annotated in Figure 3, and several literature examples are given in Table 1. For each of the pieces of literature, they are categorized into the areas shown in Figure 2.

Table 1. Category Summary Results of CAV Application Literature Survey

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

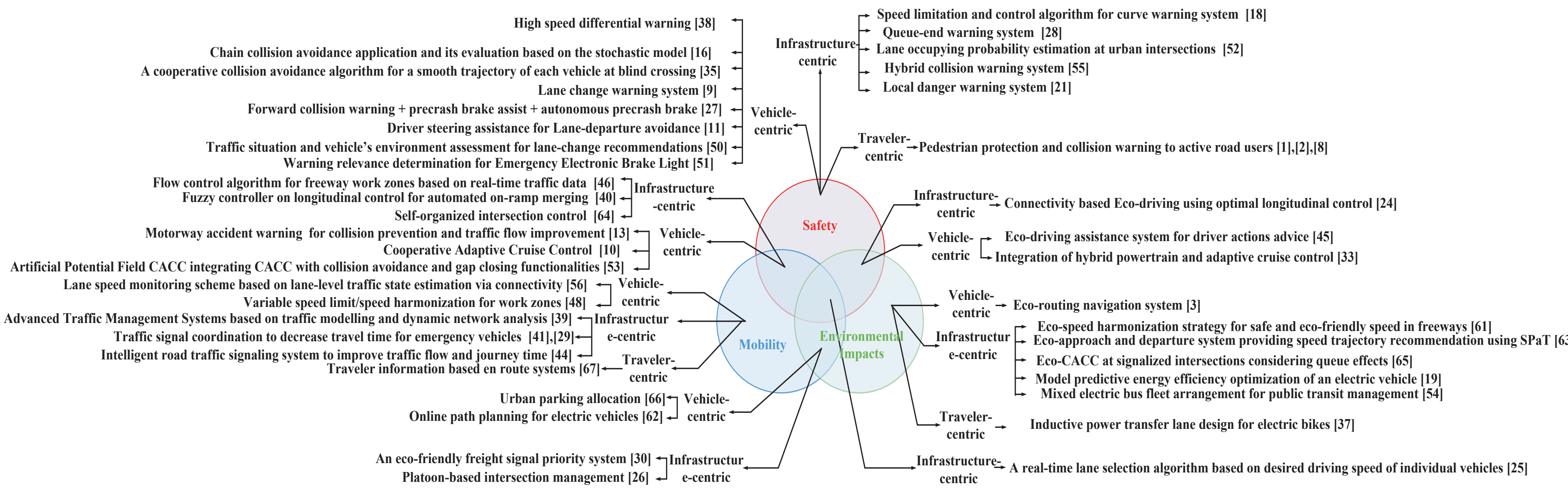


Figure 3. Survey taxonomy in terms of SME categorization.

It can be concluded that safety is the predominant targeted factor among all the CAV applications addressed in the literature. There are very few studies looking into all possible MOEs simultaneously, and synergistic effects (in terms of all MOEs) of the single-MOE-focused applications were rarely addressed in the literature. A recent trend has recently emerged, where a portion of CAV applications are being designed to improve more than one MOE (typically two), however, very few CAV applications address all three MOEs (safety, mobility and environmental impacts) simultaneously. Instead, CAV designers and researchers typically use a combination of different-MOE-focused applications to achieve improvements across several MOEs, instead of potentially fine-tuning the system parameters of a single application.

The next chapter analyzes the potential synergies and tradeoffs overall a variety of CAV applications. As stated earlier, we take an approach in examining applications that are vehicle-centric, infrastructure-centric, and traveler-centric.

Synergies and Trade-Off Analysis of Typical CAV Applications

All on-road communication-capable objects (e.g., vehicles, bicycles, pedestrians) can potentially share information via wireless connectivity technologies, such as using Dedicated Short-Range Communication (DSRC) devices. DSRC receivers can be associated with the infrastructure (see, e.g., [Kenney, 2011]), or with mobile objects. Cellular communication technology (e.g., smart phones with built-in sensors) can also be used (see, [Lyamin et al., 2016; Murugesh, 2015]). The exchange of information between two terminals can vary widely, for example transmitting a users' basic motion dynamics to the infrastructure, helping increase the users' environmental awareness to benefit the transportation system, thereby helping achieve predetermined objectives in terms of transportation performance improvement.

Some typical examples of various CAV applications in the latest literature are addressed in this section, and co-benefits/tradeoffs among the three major MOEs are analyzed. The main results are in Table 3 for the vehicle-centric CAV applications, Table 4 for the infrastructure-centric CAV applications, and Table 5 for the traveler-centric CAV applications. To help understand the symbols used in Tables 3, 4, and 5, Table 2 provides the legend of the symbols.

Table 2. 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			○↑	○↓	○

Vehicle-Centric CAV Applications

Safety & Mobility Co-Benefits

Aiming at enhancing traffic safety, a great deal of research activity on CAV applications has been carried out, primarily 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 regarding emergency situations, e.g., a sudden lane drop or motorway vehicle breakdowns [Fullerton et al., 2007]. 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 a mobility co-benefit. Another typical example of a CAV application that aims to improve both traffic flow and safety are *Cooperative Adaptive Cruise Control (CACC)* systems (see, e.g., [Semsar-Kazerooni et al., 2016]). Dey et al. presented an overall review of CACC system-related performance evaluation. In addition to a forward-looking radar used to prevent potential conflicts, it was concluded that the CACC application also has the significant 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 [Dey et al., 2016].

Safety Benefits

The Forward Collision Warning application is a relatively mature application, 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 (see, e.g., [Kusano and Gabler, 2012]). Kusano and 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. Similarly, Szczurek et al. presented an Emergency Electronic Brake Light application-related algorithm, showing safety benefits represented by the lower average number of collisions [Szczurek et al., 2012]. In this work, only the potential safety benefits were analyzed; the potential mobility and environmental impacts gains/losses were not addressed in both [Kusano and Gabler, 2012] and [Szczurek et al., 2012]. However, the safety benefits that are described might be 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 pedestrian warning systems, where stop-and-go activity will likely increase.

Safely changing lanes is one of the highest concerns for many drivers; as such, lane-change warning systems and lane-change assist systems have been attracting increasing 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 called Carai [Schubert et al., 2010]. However, detailed quantitative effectiveness evaluation regarding traffic safety was not evaluated in this reference. In addition, Dang et al. take into account the drivers' reaction delay and brake time and proposed a real-time minimum safe distance model [Dang et al., 2014]. 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.

Environmental Impacts & Safety Co-Benefits

Some co-benefits in terms of safety aspects can be well achieved by fine tuning system parameters of environmental impacts-oriented CAV applications. In this direction, an Android system based ecodriving 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 [Orfila et al., 2015]. Even though one of the objectives was to improve the safety performance, potential safety effectiveness was not evaluated, only the 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) (see [Li et al., 2012]), 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. showed 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 also investigated in this paper.

Environmental Impact Benefits

As for the environmental impacts-focused CAV applications, eco-routing systems are very 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 [Boriboonsomsin et al., 2012]. The trade-off between mobility and environmental impacts of the proposed system is described in this paper. The authors concluded that significant fuel savings can be well achieved from eco-routes compared to the fastest route, leading to travel time increases. The tradeoff between travel time and fuel consumption can be seen in many environmentally-focused CAV applications.

Environmental Impacts and Mobility Co-Benefits

Some mobility-oriented CAV applications are focused on 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 [Winter et al., 2016]. 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 [Zargayouna et al., 2016]. The urban parking management is expected to reduce fuel consumption by decreasing parking spots search time.

Mobility Benefits

There are very few CAV applications purely focusing on mobility improvements to date. A freeway work zone harmonizer has been proposed, which was mainly designed to control shockwave propagation and to reduce travel time delay [Ramezani and Benekohal, 2015]. 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 [Tian et al., 2016], which was proposed to estimate lane-level traffic state and to advise the driver to change to a faster lane, targeting improved travel times. The average speed of equipped vehicles and unequipped vehicles were compared, and the fuel consumption and potential conflict frequencies are also investigated in [Tian et al., 2016]. 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).

Table 3. Vehicle-centric CAV Applications

Categories	Platform	Project/Application name & Ref	MOE focus S	MOE focus M	MOE focus E	Contributions
Vehicle-centric	Non-EV	MINECO/FEDER Project [16]	•↑	○	○	A stochastic model as the surrogate measure for accidents evaluation of cooperative chain collision warning applications
		FP7 European project ecoDriver [45]	◑↑	◐↓	•↑	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
		EU 7th Seventh Framework Programme research project SOCIONICAL [13]	◑↑	•↑	○	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
		Automatic Lane-Change [50]	◑↑	○	○	A situation awareness-based automatic lane-change scheme based on image processing, Kalman filtering and Bayesian networks approaches
		Emergency Electronic Brake Light [51]	•↑	○↓	○↓	A machine learning approach-based emergency brake warnings relevance-decision estimation for safety applications
		Lane Change Warning [9]	◑↑	○	○	A V2V-based lane change warning system by analyzing safe distance between ego-vehicle and surrounding vehicles in the original lane and the target lane
		Cooperative Adaptive Cruise Control [53]	◑↑	◑↑	○	An analysis on gap closing and collision avoidance functionality of the Cooperative Adaptive Cruise Control system
		Advanced Forward Collision Warning [27]	•↑	○↓	○↓	A pre-collision system integrating forward collision warning, pre-crash brake assist and autonomous pre-crash brake to reduce severe highway crashes
		Eco-routing navigation system [3]	○	◐↓	•↑	An eco-routing navigation system accommodating origin-destination inputs through user interfaces to assist the driver to find the most eco-friendly route
		Cooperative Adaptive Cruise Control [10]	◑↑	◑↑	○	A review of Cooperative Adaptive Cruise Control systems which have the potential to improve traffic throughput by increasing the roadway capacity and to harmonize speed of the moving vehicles platoon in the safe manner
		Urban parking management [66]	○	◑↑	◑↑	Online localized cooperative resource allocation models for urban parking management to decrease available parking spots search time
		Connected Vehicles Harmonizer [48]	○↑	•↑	○↑	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 [56]	◐↓	•↑	◐↓	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 [33]	◑↑	○	•↑	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 [62]	○	◐↑	•↑	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

NCST

Infrastructure-Centric CAV Applications

Infrastructure-centric CAV applications are typically targeted at traffic performance improvements (i.e., mobility) and is well studied in the literature. These infrastructure-centric applications can be further divided into two groups based on the control strategy implemented: a decentralized approach (controlled by local infrastructure) and a centralized approach (controlled by a centralized traffic management center).

Safety & Mobility Co-Benefits

The fundamental task of localized infrastructure in decentralized infrastructure-centric CAV applications is to collect and relay the vehicles information within a certain range. A number of studies have explored decentralized control strategies. Yang and Monterola proposed a self-organized approach where each individual vehicle approaching a signalized 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 [Yang and Monterola, 2016]. 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 [Yang and Monterola, 2016], where the proposed control scheme's positive effects to the intersection capacity were illustrated. Direct tests on safety, environmental impacts and other mobility-related indicators were not investigated in this study. However, based on our parameters tuning strategy analysis (next section), it is expected that the fuel consumption likely decreases since there are smoother traffic flows in the intersections and more efficient braking operations.

There are many lane merging control schemes that operate in a decentralized manner; for example, Milanés et al. proposed an on-ramp merging system consisting 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 [Milanés et al., 2011]. 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 a similar direction, Pei and Dai presented an intelligent lane-merge control system for freeway work zones [Pei and Dai, 2007]. Pei and Dai used a traffic-information collection system to comprehensively identify traffic states (e.g., traffic volume, velocity and occupancy) and implemented 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.

Safety Benefits

As described earlier, most reported infrastructure-centric applications also focus on safety benefits in terms of collision mitigation. As a safety-oriented application based on vehicle-infrastructure-driver interaction, an advanced curve warning system was proposed in [Glaser et al., 2007] as a speed limitation/harmonization scheme on curvy roadways. The proposed system was tested in Matlab/Simulink, integrating the upcoming road geometry feature and a safe speed implementation module. Similar to [Fullerton et al., 2007], a queue-end warning system was presented in [Khan, 2007] 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 application has been presented in [Schendzielorz et al., 2013], where a safety-critical situations awareness warning system based on lane occupying probability estimation algorithm via vehicle-to-infrastructure communication was proposed with the purpose of improving on-road-users' safety at intersections.

There are many examples of centralized traffic management center-based CAV applications benefiting safety. As reported in [Tak et al. 2016], 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 measure. Using a cloud center tactic, the system efficiency could 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 [Tak et al. 2016]. 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 explicitly measured in [Tak et al., 2016]. Another typical example of safety-focused CAV application is the danger-notification-dissemination scheme. 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 curves) to disseminate warnings to app-enabled vehicles in the vicinity of hazards [Haupt et al., 2013]. 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 [Haupt et al., 2013].

Environmental Impact Benefits

To achieve vehicle emissions reduction from transportation systems, Wu et al. proposed an eco-speed harmonization scheme for reducing the overall fuel consumption on freeways using mutual vehicle-to-infrastructure communication [Wu et al., 2015]. 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.

Similarly, a popular environmentally-focused application is the eco-approach and departure system as signalized intersections. As an example, this application is highlighted in [Xia et al., 2013], 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 consumption savings produced by the Comprehensive Modal Emissions Model (CMEM) was compared, and results show that there is higher fuel savings as the penetration rate of equipped vehicles increases. The mobility and safety performance measures were not estimated in [Xia et al., 2013]. Nevertheless, the individual vehicle's speed is often smoothed 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 [Yang et al., 2016]. The proposed system used a queue-length-prediction algorithm and 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. speed and acceleration advice). There is a minimum penetration rate value required for overall intersection fuel efficiency improvement for the multi-lane 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 [Jin et al., 2016], 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 [Guan and Frey, 2016; Santos, 2016].

Table 4. Infrastructure-Centric CAV Applications

Categories		Project/Application name & Ref	MOE focus			Contributions
			S	M	E	
Infrastructure-centric	Decentralized	A*STAR SERC "Complex Systems" [64]	◐↑	●↑	○↑	An self-organized intersection control algorithm to smoothen intersection traffic flow and to increase the intersection capacity in urban area with safe and efficient operations on individual vehicle dynamics control
		AUTOPIA [40]	◐↑	◐↑	○↑	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
		REM 2030 [19]	○	○	●↑	A model predictive energy efficiency minimization system implemented on the electric vehicle
		SAFESPOT [52]	◐↑	○	○	An intersection safety-critical situation awareness application based on lane occupying estimation via vehicle-to-infrastructure communication
		AERIS [61]	○↑	○	●↑	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 [63]	○↑	○↑	●↑	An eco-approach departure application which utilizes SPaT and preceding vehicles information to guide drivers to pass through intersections smoothly
		The 11th Five National Science and Technology Research Item [46]	●↑	●↑	○↑	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
		Queue-end warning [28]	◐↑	○	○	A queue-end location prediction algorithm using artificial neural network together with sensors and on-road message signs to reduce rear-end collision in highway work zones
		Eco-CACC-Q [65]	○↑	○↑	●↑	An eco-cruise control system using shockwave prediction by SPaT messages and V2I information to refer the driver fuel-optimum trajectory at the signalized intersections
		Connected Eco-Driving [24]	◐↑	○	●↑	A vehicle's longitudinal control system considering inner driving operation and outer on-road factors to increase energy efficiency in the safe manner
		Curve warning system [18]	◐↑	○	○	A speed limitation algorithm that integrates the upcoming road geometry and a safe speed decision scheme to achieve safe driving in sharp curves
		Platoon-based MAS-IMA [26]	○↑	●↑	●↓	A multi-agent intersection management system based on platoon formation to increase mobility performance
		Optimal lane selection [25]	◐↑	●↑	●↑	An optimal lane change selection algorithm using on-road and desired speed of individual vehicles to regulate traffic flow and reduce negative impacts induced by uncoordinated lane changes
		MA based Freight Signal Priority [30]	○↑	●↑	●↑	A regulation scheme of signal timing for freight vehicles priority in order to increase travel time and reduce fuel consumption
	Centralized	ADIS/ATMC Applications [39]	○	●↑	○	A dynamic traffic assignment model seeking optimal assignment of vehicles to the network for route guidance
		Hybrid collision warning system [55]	●↑	○↓	○↓	A hybrid collision warning system with integration of NGSIM loop detectors data, vehicle-to-vehicle smartphones information and cloud center to offer the driver potential collision warnings and to decrease collision risks
		Local Danger Warning System [21]	◐↑	○	○	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

Environmental Impact and Mobility Co-Benefits

A Multi-agent systems (MAS) approach to traffic operation turns out to be another frequently used method to regulate traffic flow and to save fuel consumption (see, e.g., [Jin et al., 2013; Jin et al., 2014; Kari et al., 2014]). A platoon-based intersection management system was proposed in [Jin et al., 2013], aiming at improving mobility and environmental sustainability by forming vehicles platoons using connected vehicles technologies. The intersection capacity is increased due to the platooning vehicles, 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 platoon formation as well, however, slightly higher fuel consumption is introduced (validated). MAS can be applied to not only longitudinal maneuvers but also lateral maneuvers. Jin et al. also 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 [Jin et al., 2014]. 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 freight signal priority based on 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 [Kari et al., 2014]. Besides the freight-vehicle-priority algorithm, there were some studies done in order to lead to a safe and smooth traffic society by using signal preemption systems for emergency vehicles (see, e.g., [Miyawaki et al., 1999] and [Kang et al., 2014]). Table 4 lists some of the infrastructure-centric CAV applications from the angle of co-benefits and tradeoffs among different MOEs.

Traveler-Centric CAV Applications

Safety Benefits

Pedestrian protection is one of the urgent challenges needed to be solved 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 vehicle and infrastructure, and collision avoidance based on collision prediction with pedestrian dynamics and behavior analysis [Gandhi and Trivedi, 2007]. In addition to computer-vision-based pedestrian detection techniques, there are also a few studies on pedestrian protection through V2X communications (see, e.g., [Andreone et al. 2007]; [Anaya et al., 2014]; [Dhondge et al., 2014]; [Greene et al., 2011]). An approach to avoiding accidents by making use of sensors and communication technologies is described in [Andreone et al., 2007]. 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 include V2ProVu and WiFiHonk, described in [Anaya et al. 2014] and [Dhondge et al., 2014]. These projects utilized a communication device NexCom (installed with the IEEE 802.11g and a conventional GPS chip) and a smartphone-based beacon with a Wi-Fi based Vehicle-to-Pedestrian (V2P) communication system, respectively. In [Dhondge et al., 2014], the probability of collision was defined as the ratio between the required time to stop and the time available to stop, which was tested and compared with a conventional Wi-Fi communication method.

Mobility Benefits

In addition to the safety applications described above, multimodal traveler information based traffic situation awareness systems have been developed in order to detect users travel mode and to provide further proper routing suggestion. Zhang et al. proposed an iPhone/Android-enabled Path2Go application which is supposed to improve the mobility of equipped users, fusing the GPS data from both transit vehicles and smart phones, detecting mobile users' activity, differentiating the user's proper travel mode and supplying proper routing advice (including mode choices) to users [Zhang et al., 2011]. 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 5 lists some of the traveler-centric applications from the different MOEs benefits perspective.

Table 5. Traveler-based CAV Applications

Categories	Project/Application name & Ref	MOE focus			Contributions
		S	M	E	
Traveler-based	WATCH-OVER [1]	◑ ↑	○	○	A cooperative system framework integrating sensors and V2X communications to prevent road accidents that involve vulnerable active road users
	V2ProVu [2]	◑ ↑	○	○	A pedestrian protection application using Wi-Fi based NexCom devices for V2P communication for vehicle presence informing and/or hazard alarming
	Path2Go [67]	○	◑ ↑	○	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 [8]	●↑	○	○	A collision estimation algorithm between providing issue warnings using the beacon stuffed Wi-Fi communication
	[37]	○	○	◑ ↑	A dynamic inductive power transfer lane designed for electric bikes

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

Parameter Tuning Strategies

As seen in the literature described above, a number of traffic-related network-wide parameters can have an impact on performance of various CAV applications. Some system parameters are not readily controllable; for example, the penetration rate of CAV application-equipped vehicles and traffic volume. However, other system-wide parameters exist that are controllable, for example vehicle dynamics-related parameters (e.g., car-following parameters), infrastructure-related (e.g., ramp meter timing), and powertrain-related parameters (e.g., gear selection). To be more specific, vehicle dynamics-related parameters include trajectory planning and other vehicle maneuvers; Infrastructure-related parameters consist of signal phase and timing such as the red/green time ratio; Powertrain-related parameters comprise regenerative braking and A/C power usage.

Rather than set the controllable parameters at fixed values, it is possible to "tune" an application with different benefits in terms of safety, mobility and environmental impacts. The ultimate goal of future CAV applications is to achieve performance improvement across all aspects of safety, mobility and environment/energy. By tuning the controllable system-wide parameters of a single application, positive synergistic effects may be achieved, in terms of improvement of all MOEs (see Figure 4).

As an example, if a vehicle's trajectory is designed for safety purposes, it may also be smoothed for mobility and environmental impact reduction. Further, a vehicle's path may be better planned out, or the vehicle's maneuvers may be adjusted (such as forming platoons), in order to improve safety-focused CAV applications with improvements in mobility, due to a net traffic network's capacity increase. Vehicle maneuvers using steady speeds and smooth accelerations/deceleration may be embedded into the safety-oriented CAV applications as well to obtain fuel consumption savings. Further, we can achieve energy savings as well, by adjusting endogenous operations (e.g., engine dynamics and transmission, regenerative braking and A/C power usage), and by integrating exogenous information (e.g., signal phase and timing). On the other hand, synergistic safety benefits of mobility-focused and environmental impacts-oriented applications can be achieved through add-on conservative automated maneuvers, front/rear radars and increased spacing, for example. Some typical CAV applications were analyzed from the perspective of possible system parameters tuning and potential MOEs co-benefits.

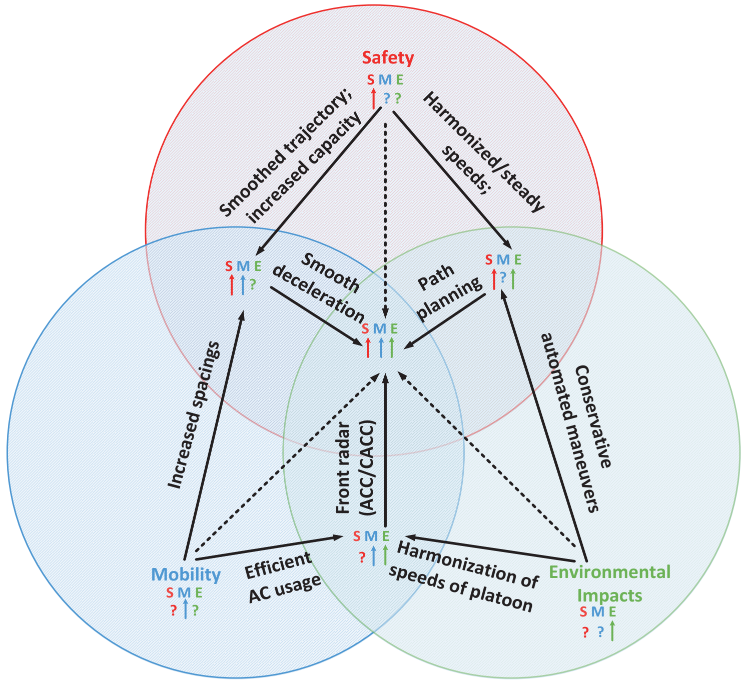


Figure 4. Parameters tuning strategy diagram in terms of Measures of Effectiveness (MOEs)

Specific Case Studies

To complete our study, we selected three CAV applications that were recently in the literature for a more in-depth analysis. The CAV applications include High Speed Differential Warning (HSDW, vehicle-centric), Lane Speed Monitoring (LSM, vehicle-centric), and Eco-Speed Harmonization (ESH, infrastructure-centric). In these applications, it is assumed that information (such as instantaneous speed and location) can be obtained via V2V communication in the form of Basic Safety Messages (BSM) [Kenney, 2011]. By exchanging such information within a specific communication range, the vehicle-centric HSDW application can identify different scenarios where high-speed differentials exist between the ego or host vehicle and the surrounding remote vehicles on the current lane or adjacent lanes. The application can then provide the driver with guidance on deceleration operation, aiming to reduce the risk of collision through timely deceleration [Li et al., 2016].

The LSM application was mainly designed to achieve mobility benefits in terms of average speed (or 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. The LSM application belongs to the mobility-focused vehicle-centric application category, however, safety and environmental impacts were not taken into consideration when this application was initially designed. We set up a simulation of the operation, such that the driver-vehicle-units equipped with the LSM function would choose to change to a target (more advantageous) lane after estimating and comparing the downstream traffic state. This lane-change advice often leads to more frequent lane change operations than usual. Other than mobility impacts, the other two MOEs of the LSM application were expected to deteriorate due to aggressive driver behavior (e.g., higher speeds and frequent lane change operations), which is viewed as a tradeoff between mobility and safety/environmental impacts.

The ESH application belongs in the infrastructure-centric application category and was primarily designed to reduce fuel consumption to protect the environment. A speed harmonization scheme was used to smooth the speeds of vehicles equipped with the ESH function. In the simulation, the driver-vehicle-units with the ESH function were advised to travel at a proper velocity, helping regulate traffic flow based on downstream traffic conditions. The purpose of the speed harmonization strategy is to reduce unnecessary stop-and-go behavior and to encourage smooth driving at energy-efficient speeds for the entire traffic flow. Since hard braking behavior is weakened by the ESH application, the potential conflict risks were expected to be mitigated as well, which is viewed as a co-benefit between environmental impacts and safety. For more details of the three applications please refer to [Li et al., 2016]; [Tian et al., 2016]; and [Wu et al., 2015].

Performance Indicators

In this section, we examine these three applications in detail, illustrating the tradeoffs and co-benefits of several major MOEs, i.e., safety, mobility and environmental sustainability. Three performance indicators were used to represent these three MOEs. For safety, we consider average conflict number (the probability of a crash). For mobility, we use average travel time. And for environmental impacts, we use average fuel consumption. The performance measure results (average speed, travel time, and average fuel consumption) are generated from the microscopic traffic simulation software PARAMICS, which was developed to model the individual vehicles dynamics behavior, and to connect control schemes and on-road users through an Application Programming Interface (API) [Paramics, 2015]. A Paramics API calculates the aggregated travel time results, vehicle-miles-travelled and vehicle-hours-travelled. The United States Environmental Protection Agency (USEPA) MOVES model (USEPA, 2015) was embedded in the API and the tailpipe emissions were calculated in the API as well. As for the conflict number calculation, PARAMICS produces a massive vehicle trajectory file, which is then used as input in to the Surrogate Safety Assessment Model (SSAM). SSAM then post processes the data and generates a potential conflict number associated with vehicle IDs [Federal Highway Administration, 2015].

Simulation Model and Scenario

Regarding the simulation scenario location, California freeway SR-91E 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 [Barth et al., 2006]. 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 [TRB, 2010].

The HSDW application, the LSM application and the ESH application were evaluated under different scenarios. The penetration rate of application-equipped vehicles is an important dimension when evaluating the traffic flow impacts and overall performance measure. In this study, two penetration rates of the application-equipped vehicles were selected, i.e., 20% and 80%, to generally observe the tradeoffs/co-benefits of the three MOEs, regarding the three selected applications.

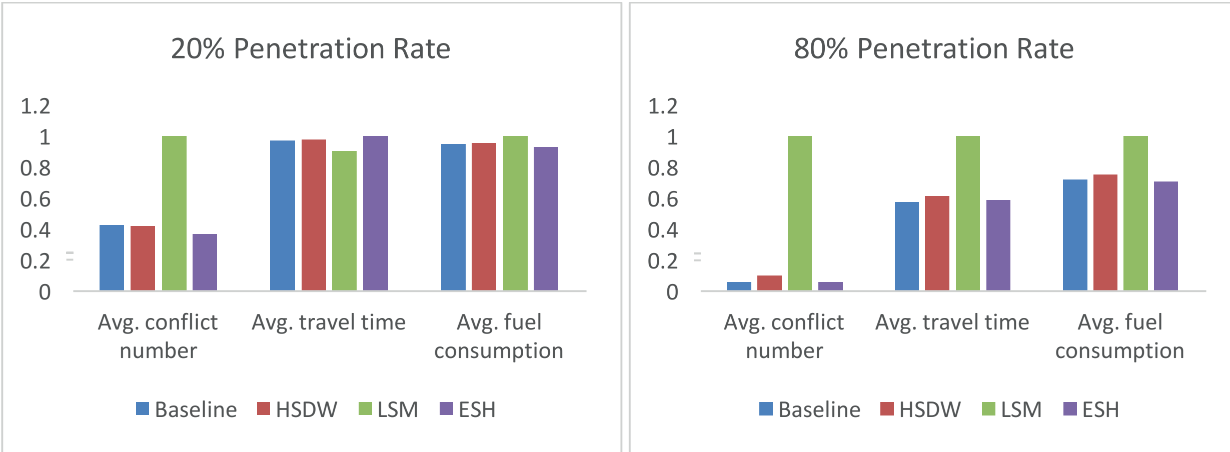
Numerical Results and Tradeoff/Co-Benefit Analysis

The results of the HSDW, the LSM and the ESH performance in terms of three performance indicators are listed in Table 6. The corresponding bar plots are shown in Figure 5, where each performance measurement is normalized for comparison purposes. To be specific, the results in Figure 5 represent normalized values, which are obtained by choosing the largest value of the certain group data in Table 6 as one, and the others in that group are calculated in accordance with the relative proportions. The baseline case is 0% penetration rate of application-equipped vehicles. The performance measure results of the other scenarios in Table 6 are for application-equipped vehicles.

Table 6. Numerical results of the case studies

	Baseline	HSDW		LSM		ESH	
Penetration rate	0%	20%	80%	20%	80%	20%	80%
Avg. conflict number/ veh	0.1673	0.1646	0.287	0.3922	2.8443	0.1455	0.1711
Avg. speed (mph /veh)	60.6	60.5	56.7	65.5	34.8	59	59.0
Avg. fuel consumption (KJ/mile/veh)	4275.3	4300.9	4464.5	4502.1	5917.2	4191.2	4195.2

Table 6 and Figure 5 illustrates the tradeoffs/co-benefits of travel time, conflict number and fuel consumption and show:



(a) (b)

Figure 5. Bar plots of three MOEs (normalized) for the three selected applications

Penetration Rate of 20%: Compared to the baseline, the HSDW application achieves slightly lower conflict frequency, but is subject to slightly lower travel time and higher fuel consumption due to increased braking behavior aiming to obtain safety benefits. The LSM application provides lower travel time due to faster-lane change behavior, but is exposed to higher potential conflicts and requires higher fuel consumption due to the encouragement of more aggressive driving behaviors (e.g., frequent lane changes and higher speed). Whereas the ESH application is the opposite case, lower fuel consumption is achieved as it is an environmental protection-oriented application. Simultaneously, lower conflict number are achieved as a co-benefit due to the steady speed and smooth driving behavior. However, compared to the baseline, the environmental impacts and safety are improved due to harmonized but slower traffic flow, at the cost of longer travel time.

P*enetration Rate of 80%*: As the penetration rate of application-equipped vehicles increases, more frequent braking operation of the HSDW application causes not only slow speeds, high fuel consumption, but also higher conflict frequency even though this application is initially designed to reduce overall traffic conflict risk. On the other hand, all the performance of the LSM deteriorates compared to either the baseline or the ESH application due to majority of equipped vehicles were trying to execute lane changes, which leads to more chaos on the roadway. However, the ESH application performance trend does not change significantly, reducing both the fuel consumption and conflict number at the cost of the decrease of average speed.

Conclusions and Future Work

This whitepaper provides an in-depth literature review on CAV applications related research, analyzing 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 was concluded that a trend exists that a portion of those CAV applications are being designed to improve more than one MOE (usually two), however, very few CAV applications improve all the three major MOEs (i.e., safety, mobility and environmental impacts). Based on a fundamental MOEs framework, we propose a tuning approach or strategy, where some key system-wide parameters be optimized, thereby helping achieve positive synergistic effects with the ultimate goal of improving all the key MOEs.

In combination with co-benefits analysis of some typical CAV applications, we identified the key influential parameters on system performance (benefits), such as trajectory planning, increased spacing, capacity increase, speeds/deceleration smoothing, regenerative braking, vehicle's dynamics and exogenous signal phase and timing adjustment, etc. The in-depth investigation of the High Speed Differential Warning, the Lane Speed Monitoring and the Eco-Speed Harmonization show that there exists tradeoffs between the key MOEs for a single-MOE-focused application (e.g., the HSDW application case and the LSM application case). On the other hand, some CAV applications may have co-benefits in the sense that they can improve a combination of safety, mobility and environmental sustainability by better designing or tuning system parameters (e.g., the ESH application case).

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 growing trend toward mixed traffic within the next decade. Other parameters considered as macroscopic influential factors on system performance include but not limit to traffic demand, truck percentage and even communication transmission range.

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