ARTICLE INFO
Article ID: 12-06-04-0026

doi:10.4271/12-06-04-0026

Classification of Roadway Infrastructure and Collaborative Automated Driving System

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Abstract

The latest developments in vehicle-to-infrastructure (V2I) and vehicle-to-anything (V2X) technologies enable all the entities in the transportation system to communicate and collaborate to optimize transportation safety, mobility, and equity at the system level. On the other hand, the community of researchers and developers is becoming aware of the critical role of roadway infrastructure in realizing automated driving. In particular, intelligent infrastructure systems, which leverage modern sensors, artificial intelligence, and communication capabilities, can provide critical information and control support to connected and/or automated vehicles to fulfill functions that are infeasible for automated vehicles alone due to technical or cost considerations. However, there is limited research on formulating and standardizing the intelligence levels of road infrastructure to facilitate the development, as the SAE automated driving levels have done for automated vehicles. This article proposes a five-level intelligence definition for intelligent roadway infrastructure, namely, connected and automated highway (CAH). The CAH is a subsystem of the more extensive collaborative automated driving system (CADS), along with the connected automated vehicle (CAV) subsystem. Leveraging the intelligence definition of CAH, the intelligence definition for the CADS is also defined. Examples of how the CAH at different levels operates with the CAV in the CADS are also introduced to demonstrate the dynamic allocation of various automated driving tasks between different entities in the CADS.

History

Received: 28 Sep 2022
Revised: 07 Feb 2023
Accepted: 18 Apr 2023
e-Available: 09 May 2023

Keywords

Roadway infrastructure, Collaborative automated driving system (CADS), Connected automated highway (CAH), Connected automated vehicle (CAV), Intelligence allocation

Citation

Ran, B., Cheng, Y., Li, S., Li, H. et al., "Classification of Roadway Infrastructure and Collaborative Automated Driving System," *SAE Int. J. of CAV* 6(4):2023, doi:10.4271/12-06-04-0026.

ISSN: 2574-0741
e-ISSN: 2574-075X

This article is part of a special issue on Infrastructure Connectivity: Applied Research, Innovative Applications, and Best Practices.

1. Introduction

Automated driving technologies have been developing rapidly to eliminate car crashes, alleviate traffic congestion, and reduce fuel consumption [1, 2, 3]. Most existing efforts are focused on vehicles, installing modern sensors on the vehicles and complex algorithms to make sense of the data collected from sensors and control vehicle movements [4]. All those hardware and software, and millions of mileage needed for training and testing, are not reliable enough in the near term [5, 6]. Tragically, such issues are highlighted by the fatal accidents of the Tesla car with autopilot in 2016 and the Uber self-driving car in 2018, in which the vehicles did not identify the object accurately in time [7].

With the development of modern wireless communication technologies [8], collaborative automated driving systems (CADS) (such as connected and automated highway [CAH] system) have become a more feasible and cost-effective approach to automated driving by enabling cooperation between vehicles and the intelligent roadway infrastructure (such as CAH) [9, 10]. The sensors and processors of the CAH are much less constrained for the power and space they use, unlike their onboard counterparts, which can greatly lower the cost of hardware. In addition, CAH can be deployed on "critical roads" (the most cost-effective location) first, such as intersections, work zones, and other places typically difficult or unreliable for CAVs. Therefore, taking advantage of the sensing, communication, and computing capabilities of the CAH, the CADS establishes an efficient, energy-saving, and safe automatic driving system [11, 12, 13]. However, work on the specific functions of intelligent roadway infrastructure under various circumstances is still limited [14, 15]. Most existing studies focus on the interaction of the target vehicle and its adjacent vehicles, simply using infrastructures as an information relay entity for individual vehicles. Although the SAE J3216 standard lays the foundation of transportation system cooperation and integration by defining the classes of cooperative driving automation, it does not cover the intelligence definition of the road infrastructure [16]. How to develop an automated driving system from a system optimization perspective leveraging the intelligence and connectivity of modern road infrastructure still needs more investigation [5, 17].

In this article, we consider the road infrastructure as the materials and information facilities that provide transportation services, which ensure the normal operations of transportation activities [18, 19]. The road infrastructure generally includes Highway structures (such as the road base, pavement, bridges, and tunnels); Traffic engineering and ancillary facilities (such as road signs and marking); Energy systems; Communication systems; Information platforms (such as monitoring systems, sensor systems, toll systems, special communication and information networks for facilities, traffic control, navigation, roadside systems, and other modern equipment systems) [20].

The focus areas of the roadway infrastructure system can be characterized as informatization, intelligence, and automation [9]. The informatization of the roadway infrastructure system (including digitalization and connectivity) refers to the storage of traffic information in the database leveraging detection, communication, networking, and other technologies, in which the information is shared among drivers, vehicles, and traffic management agencies for decision-making and traffic operations [8, 21, 22, 23]. The intelligence of the roadway infrastructure system refers that the roadway infrastructure is able to actively or proactively meet the needs of driving tasks and make partial decisions and control while being supported by technologies such as informatization and artificial intelligence [17, 24]. The automation of the roadway infrastructure system implies that the roadway infrastructure can achieve the desired driving goals through collaborative sensing, prediction, decision-making, and control, not requiring human intervention.

This article proposes novel definitions for the intelligence levels of roadway infrastructure (CAH) and CADS from the perspective of collaborative automated driving. Different from the earlier research that is mainly from the vehicle perspective to develop an automated driving system, this article introduces the definition, classification, and architecture of CADS from the whole transportation system perspective: in a CADS, the system intelligence and tasks for automated driving are dynamically distributed among CAH and CAVs based on actual circumstances. Therefore, the CADS can realize safe and reliable automated driving and transportation management through the optimal cooperation of CAH and CAV subsystems; in other words, CAH and CAV do the most suitable tasks they do and standby as each other's backup.

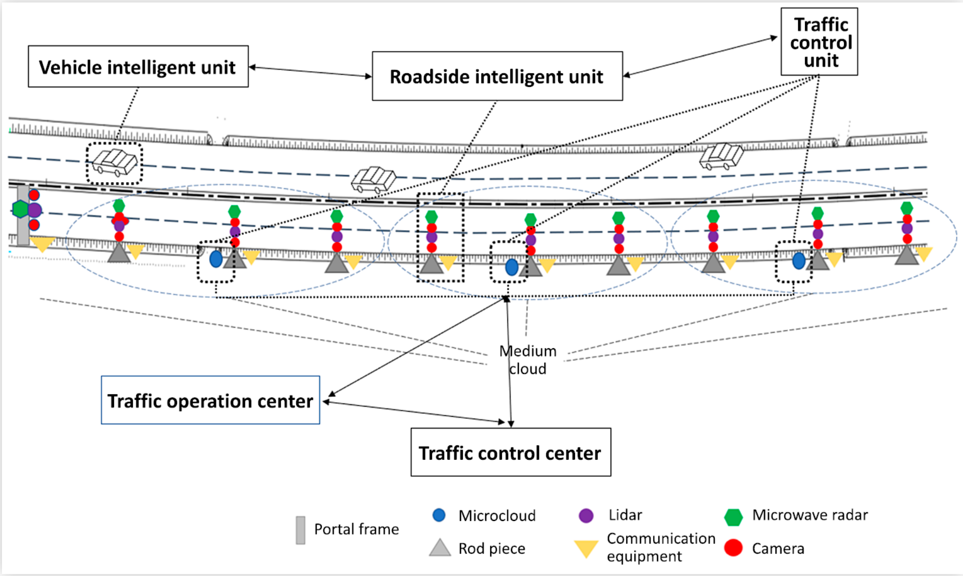
2. Classification of Roadway Infrastructure

Roadway infrastructure (I) refers to the materials and information facilities that provide transportation services. It is a public service system that ensures the normal operations of transportation activities [20]. It generally includes Highway structures (such as the road base, pavement, bridges, and tunnels); Traffic engineering and ancillary facilities (such as road signs and marking); Energy systems; Communication systems; Information platforms (such as monitoring systems, sensor systems, toll system, special communication and information networks for facilities, traffic control, navigation, roadside systems, and other modern equipment systems), as shown in Figure 1. Table 1 summarizes the roadway infrastructure (I) levels, which are elaborated in the following texts.

I0: Non-informatization/Non-intelligence/Non-automation

It is the traditional roadway and traffic management, in which there is no information interaction between the roadway infrastructure and vehicles.

FIGURE 1 General roadway infrastructure framework with CAVs.



I1: Preliminary Digitization/ Preliminary Intelligence/ Preliminary Automation

The roadway infrastructure has microscopic sensing and basic prediction capabilities which can support low spatial and temporal resolution traffic information services, traffic management, and driver assistance.

I2: Partial Connectivity/Partial Intelligence/Partial Automation

The roadway infrastructure has complex sensing and deep prediction capabilities; through infrastructure and vehicle communication (including I2X); the roadway infrastructure can realize automated driving assistance and traffic management in a higher spatial and temporal resolution.

I3: Conditional Automated Driving Based on Traffic Infrastructure/Highly Networked

The highly interconnected roadway infrastructure provides dynamic information about the surrounding vehicles and control commands for a single automated vehicle (automation level of 1.5 and above) in milliseconds and achieves conditional automated driving on major roads, including dedicated lanes. In special circumstances, the vehicle requires the intervention of the human driver.

I4: Highly Automated Driving Based on Roadway Infrastructure

The roadway infrastructure provides detailed driving instructions for automated vehicles (automation levels of 1.5 and

TABLE 1 Roadway infrastructure (I) level definition.

Level	Informatization (digitization and connection)	Intelligence	Automation	Client	Scenarios	Take-over
I0	None	None	None	Operator	N/A	Operator
I1	Preliminary	Preliminary	Preliminary	Operator/vehicle	Most	Operator
I2	Partial	Partial	Partial	Operator/vehicle	Partial	Operator
I3	Highly	Conditional	Conditional	Operator/vehicle	Dedicated lane	Operator
I4	Fully	Highly	Highly	Vehicle	Specific	Roadway infrastructure system
I5	Fully	Fully	Fully	Vehicle	All	Roadway infrastructure system

above), achieving highly automated driving in specific scenarios/areas (e.g., preset time and space). In special circumstances, the vehicle can be controlled by the roadway infrastructure system, not requiring the intervention of the human driver.

I5: Fully Automated Driving Based on Roadway Infrastructure

The roadway infrastructure can realize the complete sensing, prediction, decision-making, control, communication, and other functions of automated vehicles (automation level of 1.5 and above) and achieve fully automated driving in all scenarios, and optimize the services of the entire roadway infrastructure network. Any subsystems required to complete the automated driving do not require deploying any backup systems on the automated vehicles. The roadway infrastructure can also provide full active safety measures. In special circumstances, the vehicle is controlled by the roadway infrastructure system, not requiring the intervention of the human driver.

3. Definition and Classification of CADS

CADS is a new generation of intelligent transportation systems built on four pillars: informatization, intelligence, collaboration, and integration (Table 2). The system utilizes advanced sensing technology, network technology, computational control technology, and artificial intelligence technology to collaborate with vehicles and roads to efficiently execute sensing, prediction, decision-making, and control functions [25, 26, 27]. It takes the connected and automated vehicle highway technology as the core of this new traffic system that can integrate, coordinate, control, manage, and optimize all vehicles, information services, facilities and equipment, intelligent traffic management, etc. [9, 28].

S0: Non-informatization/Non-intelligence/Non-collaboration/Non-integration

It is the traditional transportation system in which there is no information interaction between the roadway infrastructure and vehicles. No automated driving can be realized by the collaboration of vehicles and the infrastructure.

S1: Preliminary Informatization/Preliminary Intelligence/Preliminary Collaboration/Preliminary Integration

The CADS has preliminary informatization, intelligence, collaboration, and integration. The system can provide driving assistance for the CAV. The CAV is dominant in the realization of the collaboration of the CADS. The system has the sensing collaborative sensing abilities. When the condition that the system cannot handle happens, the users can take over the vehicle.

S2: Partial Informatization/Partial Intelligence/Partial Collaboration/Partial Integration

The CADS has partial informatization, intelligence, collaboration, and integration. The system has collaborative sensing

TABLE 2 CADS level definition.

		System characteristics				System collaboration		
Level	Level	Informatization	Intelligence	Collaboration	Integration	dominance	Take-over	Scenarios
S0	Manual driving	None	None	None	None	CAV	Users	N/A
S1	Driver assistance	Preliminary	Preliminary	Preliminary	Preliminary	CAV	Users	Partial
S2	Partial driving automation	Partial	Partial	Partial	Partial	CAV/CAH	Users	Partial
S3	Conditional driving automation	Highly	Highly	Highly	Conditional	CAV/CAH	Users	Partial
S4	High driving automation	Fully	Fully	Fully	Highly	CAV/CAH	Roadway infrastructure system	Partial
S5	Full driving automation	Fully	Fully	Fully	Fully	CAV/CAH	Roadway infrastructure system	All

and decision-making abilities. The system can provide partial driving automation for the CAV. CAV or CAH is dominant in the realization of the collaboration of the CADS. When the condition that the system cannot handle happens, the users can take over the vehicle.

S3: High Informatization/High Intelligence/High Collaboration/Conditional Integration

The CADS has high informatization, intelligence, and collaboration. The system has the abilities of collaborative sensing, prediction, decision-making, and control. The system has conditional integration. The system can provide conditional driving automation for the CAV. CAV or CAH is dominant in the realization of the collaboration of the CADS. When the condition that the system cannot handle happens, the users can take over the vehicle.

S4: Full Informatization/Full Intelligence/Full Collaboration/High Integration

The CADS has full informatization, intelligence, collaboration, and high system integration. The system can provide high driving automation for the CAVs. CAV or CAH is dominant in the realization of the collaboration of the CADS. When the condition that the system cannot handle happens, the system can take over the vehicle.

S5: Full Informatization/Full Intelligence/Full Collaboration/Full Integration

The CADS has full informatization, intelligence, collaboration, and integration. The system can provide full driving automation for the CAV. CAV or CAH is dominant in the realization of the collaboration of the CADS. When the condition that the system cannot handle happens, the system can take over the vehicle.

4. Dynamic Allocation of Driving Intelligence within CADS

Driving a vehicle safely from the origin to the destination involves essential activities or “driving tasks,” which can be categorized as Control, Guidance, and Navigation [29, 30]. In a CADS, the driving tasks, instead of relying solely on the vehicle capabilities, are redistributed among the CAVs and CAH, depending on the intelligence levels of the two, and dynamically adjusted.

In other words, the system intelligence is dependent on the vehicle and infrastructure intelligence, e.g., as represented by the following equation (S = system intelligence; V = vehicle intelligence; and I = infrastructure intelligence):

$$S = f(V, I)$$

A typical way of operations is that the CAH and CAV subsystems jointly cover all the driving tasks among the three categories; the two subsystems both have sensing and telecommunication capabilities to facilitate those driving tasks, and the two subsystems are highly integrated to work together through the two types of capabilities. The integration and collaboration of the CAV and CAH subsystems also serve as the backup for each other, which increases the overall system safety and reliability.

5. System Analysis and Case Description

As mentioned above, there are many different combination methods to achieve a certain system intelligence level. This section mainly shows three ways to achieve S3 and S4, which use different intelligent levels of vehicle subsystem and infrastructure subsystem.

S3: I3 + V1.5

In this S3 system, the I3 system continuously tracks the automated driving tasks online in full time and provides the vehicle with all the information needed to complete the automated driving tasks such as sensing, decision-making, and control. The vehicle achieves driving tasks based on the received information. In an emergency, the CAH system will take over the vehicle to complete functions such as automated driving or pulling over. At this time, the vehicle intelligence level only needs to be 1.5 and above to make the CADS reach the S3 level and above. Under a certain intelligence level of the CAH system, the intelligence level upgrade of the system comes from the upgrade of the vehicle intelligence level. The following will elaborate on the functions that can be achieved under the S3 system level:

1. **Cooperative sensing:** The CADS can achieve information transmission between the CAH system and the CAVs. The CAH system mainly takes the sensing function of the CADS; similar sensors and processing algorithms that are used on CAVs can be used for CAH, although necessary calibration and adjustment are needed. While vehicles traveling at a certain speed have a small amount of time to detect, process, and identify objects, the roadside CAH has

the luxury of time to track an object within the detection range. In addition, the CAH sensors, when possible, are mounted high on the roadside to reduce sight obstructions. The dynamic information of the vehicle driving environment is mainly detected and provided by the equipment of the CAH system. The system and the CAVs can communicate in real time at the millisecond level, and the system can provide dynamic information about the surrounding vehicles and the environment of the vehicle. The CAV has partial sensing functions which can detect and provide the basic status of the vehicle [31].

2. **Cooperative prediction:** The CADS predicts short-term traffic conditions from a macro perspective based on the vehicle and traffic information in the local network. Based on the prediction, it implements lane-level traffic management strategies and conveys the prediction results to CAVs.
3. **Cooperative decision-making:** The CADS mainly relies on the CAH system. The CAVs in the autonomous driving state automatically follow the planning and decision-making instructions of the CAH system. The system can determine strategies for traffic control and vehicle guidance from the perspective of global optimization based on the fused road traffic network perception and prediction information. It includes lane-level traffic control, such as lane management, and variable speed limit control, as well as providing optimized path planning for vehicles with intelligence of V1.5 and above.
4. **Cooperative control:** The CAH system participates in vehicle control. For vehicles in an autonomous driving state, the CAH system takes over the vehicle subsystem and sends control instructions to the CAVs, and the CAVs execute the control instructions. When there is a conflict decision, the CAVs will adopt the instruction provided by the infrastructure. The system reports and stores the conflict events and provides early warnings to the traffic control center and surrounding vehicles.

S3: I2 + V3

In this S3 system, the CAH system reaches the I2 level, and the vehicle intelligence reaches the V3 level. The I2 level CAH system continuously monitors and updates static data such as infrastructure, dynamic data such as local weather, and other related information in time and space. It provides the CAVs with the necessary information to complete automated driving tasks such as sensing, decision-making, and control. The CAV senses itself and the surrounding environment according to the driving task and obtains other required information from the CAH system. In an emergency, the CAVs can complete functions such as automated driving or parking alone or in cooperation with the infrastructure. The following will elaborate on the functions that can be achieved under the S3 system level:

1. **Cooperative sensing:** The CAH system is mainly responsible for the sensing traffic information of the infrastructure, weather, and road segment. The CAVs perceive dynamic information about the driving environment and surrounding vehicles [32]. The CADS can communicate with the CAH system and CAVs in real time, perform fusion calculations on sensing data, and provide dynamic information about the vehicles and the environment to the CAH system and CAVs.
2. **Cooperative prediction:** The CADS predicts traffic conditions from a macro perspective based on the vehicle travel demand and traffic information in the local network and sends relevant information to the CAVs. Based on the prediction information sent by the roadside infrastructure, the vehicle predicts its motion state in the next control time step and sends the prediction result to the CADS.
3. **Coordinated decision-making:** The CADS will track system tasks at all times and spaces based on the prediction information of the CAH system and CAVs, formulate traffic control strategies, and send them to the roadside infrastructure and CAVs. Based on the prediction results of the own motion state and the received traffic control information, the vehicle coordinates the control decisions, formulates driving path planning, and sends relevant results to the CADS for backup.
4. **Cooperative control:** Based on the planning and decision-making information, the CAVs formulate control instructions such as the acceleration, speed, and steering angle of the vehicle and send it to the CADS for backup. The CAH system detects and reports the execution result of the CAVs according to the control information transmitted by the CAVs; when the vehicle is in an abnormal state, the CAH system will promptly warn the vehicle and surrounding vehicles and report the CADS.

S4: I4 + V3

In this S4 system, the I4 system not only continuously tracks the automated driving tasks online in full time and provides the vehicle with all the information needed to complete the automated driving tasks such as sensing, decision-making, and control but also makes better deployment of vehicles in the covered road network to achieve better global optimization. The vehicle achieves driving tasks based on the received information. In an emergency, the CAH system will take over the vehicle to complete functions such as automated driving or pulling over. The following part will elaborate on the functions that can be achieved under the S3 level, and the vehicle level is V3:

1. **Collaborative sensing:** The CAH system mainly takes the sensing function of the CADS. The dynamic information of the vehicle driving environment is mainly detected and provided by the equipment of the CAH system. The roadside system under the I4 level can provide CAVs with the dynamic information of the road network and longitudinal and lateral

control instructions for the surrounding vehicles within a few milliseconds. The CAV under the V3 level has partial basic sensing functions, which can detect the basic status and acceleration of the vehicle, and is capable of communicating with the CAH system to achieve autonomous driving functions.

2. **Collaborative prediction:** The CADS effectively predicts traffic conditions based on the vehicle and traffic information in the local network and overall traffic network to realize the road network-level traffic management strategy and ease road congestion.
3. **Collaborative decision-making:** The CADS mainly relies on the CAH system. The CAVs in the autonomous driving state automatically follow the planning and decision-making instructions of the CAH system. The system can provide an optimized path planning scheme for CAVs from the perspective of macro path planning based on the fused road traffic network perception and prediction information. The system can make more optimal deployment of vehicles in the covered road network to achieve better global optimization; it has the ability to provide optimized path planning solutions for vehicles in the autonomous driving state above the V3 level.
4. **Collaborative control:** Under special circumstances, vehicles are controlled by the CAH system without the driver taking over. For vehicles in an autonomous driving state, the CAH system takes over the vehicle subsystem, and the CAVs automatically execute the control instructions. When there is a conflict decision, the CAVs will adopt the instruction provided by the infrastructure. The system reports and stores the conflict events and provides early warning to the traffic control center and surrounding vehicles, and the system participates in the reasonable control of surrounding vehicles in order to alleviate the impact of the conflict.

6. Concluding Remarks

It has become increasingly clear that intelligent road infrastructure with sensing, communication, and computing capabilities can play a key role in addressing the difficulties in automated driving. The proposed systematic approach, a CADS, built upon the collaboration of CAV and CAH as subsystems, can greatly reduce the threshold for achieving automatic driving by building an intelligent roadside system with perception, integration, planning, control, and communication. In a CADS, CAVs with low-cost onboard equipment can achieve a higher level of automated driving than relying on the vehicle itself. In addition, the system reliability and safety can be improved since the CAV and CAH can work as backups of each other. Therefore, such a CADS is a more reliable and cost-effective way to achieve automated driving than either the pure road-based approach or the pure vehicle-based approach.

This article proposes the intelligence definition for the CAH and the CADS. Leveraging the intelligence definitions, methods for the CAH and CAVs at different levels to collaborate and share the sensing and computing resources optimized in the CADS can be developed, for example, the dynamic allocation of various automated driving tasks between different entities in the CADS. It is worth noting that the deployment of a CAH system involves more stakeholders, such as road infrastructure owner operators (IOOs), roadside device manufacturers, and vehicle manufacturers; much more effort is needed for collaboration across several industries before the CAH system can be deployed. Therefore, this approach can promote a whole ecosystem for automated driving systems industries of vehicle manufacturers, communication service providers, and IOOs.

Funding Statement

Yang Cheng was partially supported by the National Science Foundation through Award Number 2222541.

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