Design of Distributed Cyber–Physical Systems for Connected and Automated Vehicles With Implementing Methodologies

Yixiong Feng, Bingtao Hu, He Hao, Yicong Gao, Zhiwu Li, *Fellow, IEEE*, and Jianrong Tan

***Abstract*—With the development of communication and control technology, intelligent transportation systems (ITS) have received increasing attention from both industry and academia. However, plenty of studies providing different formulations for ITS depend on Master Control Center and require a high level of hardware configuration. The systematized technologies for distributed architectures are still not explored in detail. In this paper, we proposed a novel distributed cyber–physical system for connected and automated vehicles, and related methodologies are illustrated. Every vehicle in this system is modeled as a double-integrator and supposed to travel along a desired trajectory for maintaining a rigid formation geometry. The desired trajectory is generated by reference leading vehicles using information from multiple sources, while ordinary following vehicles use velocity and position information from their nearest neighbors and sensor information from on-board sensors to correct their own performance. Information graphs are used to illustrate the interaction topology between connected and automated vehicles. Edge computing technology is used to analyze and process information, such that the risk of privacy leaks can be greatly reduced. The performance scaling laws for the network with a one-dimensional information graph are generalized to networks with *D*-dimensional information graphs, and the results of the experiments show that the performance of the connected and automated vehicles matches very well with analytic predictions. Some design guidelines and open questions are provided for the future study.**

***Index Terms*—Connected and automated vehicle, distributed cyber–physical system (DCPS), double-integrator agent, edge computing (EC), formulation design, performance scaling.**

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Y. Feng, B. Hu, Y. Gao, and J. Tan are with the State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou, Zhejiang 310027, China (e-mail: fyxtv@zju.edu.cn; 11425062@zju.edu.cn; gaoyicong@zju.edu.cn; egi@zju.edu.cn).

H. Hao is with the Pacific Northwest National Laboratory, Seattle, WA 98109, USA (e-mail: He.Hao@pnnl.gov).

Z. Li is with the School of Electro-Mechanical Engineering, Xidian University, Xi'an, Shaanxi 710071, China (e-mail: systemscontrol@gmail.com).

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I. Introduction

Over the past decades, remarkable advances in the field of communication and control technology have revolutionized our way of life. In the upcoming era of Internet of Things (IoT), any object will have a unique way of identification and can be connected [1]. In other words, the barriers between the virtual world and the real world will be eliminated and people can give instructions to physical objects directly. The cyber–physical system (CPS), in which the cyber components (for example, on-board computers and controllers) and the physical components (for example, mechanical equipment and actuators) are highly integrated, is one of the cornerstones of IoT. In the field of intelligent transportation system (ITS), many different formulations based on IoT and CPS are proposed.

ITS are comprehensive systems that combine high technologies with conventional transportation infrastructures, and are believed to have a great potential in transportation management and service [2]. ITS have emerged as an efficient way of avoiding traffic congestion and reducing energy and land consumption. Also, ITS can enhance the driving comfort and security by improving traffic efficiency and providing travelers more choices [3]. Chaturvedi *et al.* proposed a multimodal ITS using limited ITS infrastructure for edge-level speed estimation [4]. Data from cellular network and global positioning system (GPS) probes are also used to compute vehicle flow, space occupancy, and congestion. Xiong *et al.* studied the cyber–physical–social system (CPSS) and realized the stepwise control and management with parallel execution [5]. An embedded system was designed for dedicated short-range communications by Cao, and the results of the function test showed that the system can be a potential mobile compact solution for ITS [6]. Giovanna *et al.* used ITS to support urban evacuation planning process and presented a methodology to calculate risk reduction in transportation system under emergency conditions [7]. It was pointed out by Wu in [8] that the Internet of Vehicle (IoV) can support the development of ITS. They thus established an ITS with a network security mechanism in an IoV environment. The experiment results indicated that the proposed method is rather effective. Dimitrakopoulos *et al.* reported a knowledge-based ITS and used information collected from various sources through vehicular sensor networks to facilitate transportation [9]. To mitigate congestion and enhance mobility of ITS, the traffic-based vehicle control strategies are also well studied [10]. Huang *et al.* presented a new control strategy to alleviate the traffic congestion in [11], and the simulation results through VISSIM showed that the policy is very effective. A predictive trajectory guidance (PTG) framework was presented in [12] to enable the safe operation of autonomous and semiautonomous vehicles. A number of simulation experiments were conducted and the results showed that the scheme performed well in various scenarios with dynamic objects and operating modes. Khelafa *et al.* presented a new control algorithm based on model predictive control and used systematic methodology to reduce computation time and control multimodal traffic lights [13]. The research in [14] focused on typical application scenario between the traffic lights and lorry fleet and formulated a visible light communication (VLC)-based ITS. The result can be used to reduce the potential accidents caused by lorry's frequent acceleration and deceleration.

Although many different ITS formulations and applications have been developed, most studies only focus on one special aspect of ITS, such as architecture design, control algorithm, communication technology, or application in a certain scenario. As a comprehensive system, an ITS consists of a cyber part (such as information collection, communication, control mode, collaborative algorithm, and so on) and a physical part (such as connected and automated vehicles (CAVs), basic infrastructures, different kinds of sensors, on-board computers and controllers, and so on). Hence, CPS are very suitable for ITS to improve safety and mobility. Through CPS, people can directly pass instructions to physical objects in ITS to control them or to collect information while making decisions.

Besselink *et al.* exposed a CPS for road freight transportation and showed how traffic, weather, and other public and private data can be utilized, but the communication method is not considered [15]. Jia *et al.* made a detailed survey on platoon-based vehicular CPS and summarized issues about vehicular networking, traffic dynamics, and coupled mode, but vehicular formulations with high dimensions are not included [16]. It was pointed out in [17] and [18] that the information between stations in ITS may be used to estimate moving preference and cause privacy problems, but a few designers of the CPS for ITS have taken that into consideration. Cloud computing (CC) technologies adopted in CPS requires a high level of hardware configuration. As the amount of data generated by edge devices increases, communication efficiency may be compromised, which leads to security issues. Distributed control of multiagent systems seems to be an effective way to solve this problem since it has been widely used in different fields [19]–[24].

Based on above analysis, a three-layer distributed cyber–physical system (DCPS) is proposed in this paper to describe and analyze the performance of CAVs in ITS. Every vehicle is modeled as a double-integrator agent and is supposed to maintain a constant space between its nearest neighbors. CAVs are labeled into two different types: reference leading vehicles and ordinary following vehicles. The leading vehicles will receive information from ITS infrastructures and generate desired trajectory, while following vehicles only need to receive information from its neighbors and on-board sensors. The collected information of the following vehicles is processed by edge computing (EC) technology such that the following vehicles do not need to receive real-time information feedback from infrastructures. In this way, following vehicles will spend less time making decisions and take less risk of privacy exposure. In addition, the modes of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication are also considered. The main contributions of this research are summarized as follows:

1) This work proposes a layered formulation of DCPS to describe and analyze the performance of CAVs. The related implementing methodologies are also illustrated.
2) We generalize previous work on the performance scaling laws for the network with a one-dimensional (1-D) information graph to networks with *D*-dimensional information graphs;
3) Extensive numerical experiments are conducted to validate the theoretical derivation and the feasibility of the proposed formulation.

The rest of the paper is organized as follows. Section II presents the overall formulation of the DCPS for CAVs. The components and related functions of each layer of the DCSP are described. The implementing methodologies of the above functions for DCPS are illustrated in Section III. In Section IV, several practical and numerical experiments are conducted and the results are compared with theoretical analysis. The paper ends with conclusions and discussions in Section V.

II. Overall Formulation of the DCPS for CAVs

Remarkable advances in communication, sensor, and computing technologies have promoted the development of ITS. ITS can collect information from multiple sources such as GPS, pavement management system (PMS), closed-circuit television (CCTV) of Smart City, and so on, and help enhance the driving comfort and security. Although CC technology has been used to deal with the huge amount of data, the increasing volume of data generated by edge devices can still cause communication delay. To solve this problem, we proposed a three-layer DCPS. The DCPS empowers the CAVs in ITS to make their own decisions under certain rules by means of EC technology. Specifically, the CAVs discussed in this paper are supposed to keep a constant space with their neighbors while traveling along a desired trajectory. The layered formulation of the DCPS is presented in Fig. 1.

In the information layer, the infrastructures will collect information from multiple sources. The collected information will be passed only to leading vehicles through V2I communication to help plan the trajectory. When the leading vehicles start to move, the following vehicles are expected to follow the desired trajectory. The following vehicles do not need to receive real-time information feedback from infrastructures, and thus the communication delay caused by exchanging and processing information will not happen. In this way, the interaction of information between the information layer and the cooperation layer will be compressed to a lower level to protect the privacy

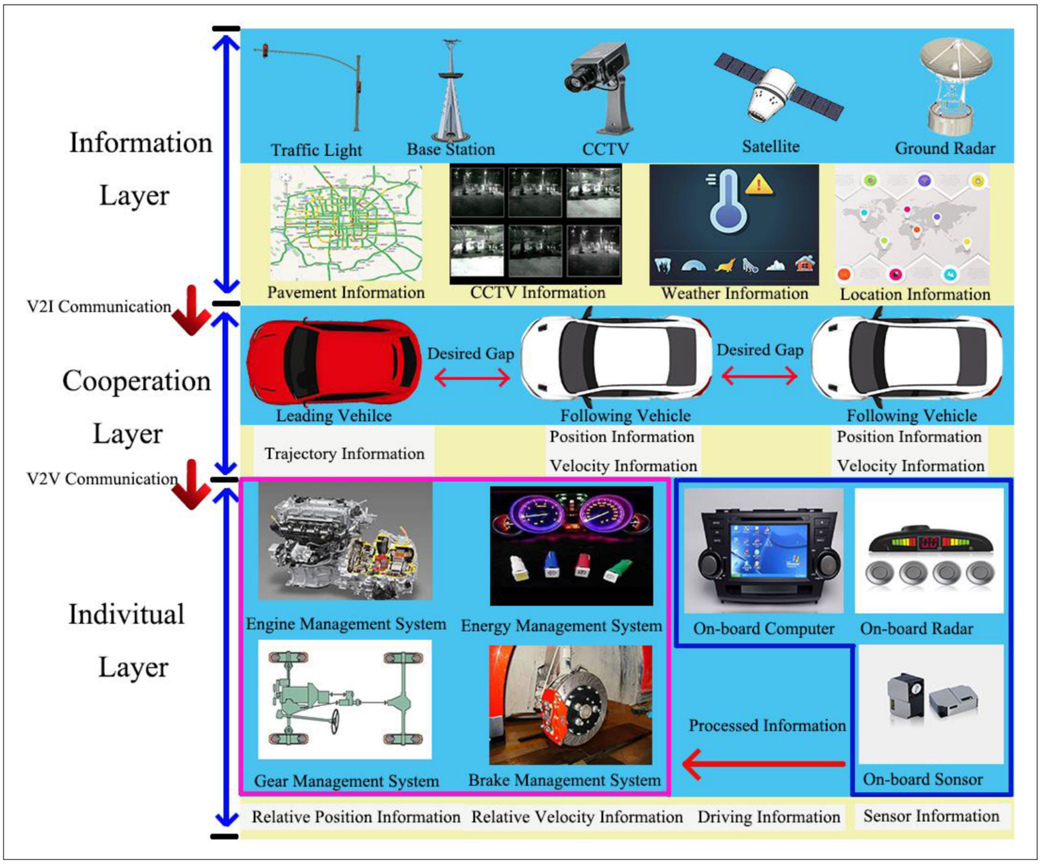

Fig. 1. Formulation of DCPS.

of CAVs compared with the centralized control mode, in which every CAV needs to communicate to the infrastructures. All the physical parts of the DCPS are in the upper portion of each layer and the cyber parts are in the lower portion in Fig. 1.

In the DCPS, CAVs are supposed to maintain a rigid formation while following a desired trajectory. The trajectory is planned by the leading vehicles and is specified by a constant space, i.e., the desired gaps. In the cooperation layer, leading vehicles are assumed to travel in the boundary of the CAV team and perfectly track the desired trajectory. Since the following vehicles will adjust their speed according to the velocity and position information of their nearest neighbors, the real-time information exchange, processing and feedback are not necessary. The velocity and position information can be obtained through an on-board radar. That is, the trajectory information planned by leading vehicles is not passed through direct instructions, but through velocity and position that can be detected.

In the individual layer, each CAV consists of a physical part and a cyber part. In the physical part, the on-board radar will collect velocity and position information from the nearest neighbors and the on-board sensors will collect sensor information such as the surrounding information, the lane information, and the driving information from various systems of the vehicle. In the meantime, the on-board computer will calculate the relative velocity information and the relative position information according to its own velocity and position information. The processed information will be passed to the engine management system, the energy management system, the gear management system, and the brake management system to control the speed for maintaining the desired gap. The information flow of the DCPS is shown in Fig. 2.

In this section, we present the three-layer architecture of the DCPS, and we also elaborate the composition and related functions of each layer. To guarantee the normal operation of the DCPS, the realization of the functions will be discussed in Section III.

III. Implementing Methodologies for DCPS

A. Single CAV Model

Let us consider a network of vehicles moving in Euclidean space. For ease of exposition, we only consider one dimension of the translation motion. The analysis is also applicable to all three dimensions, as long as the dynamics of an agent in each coordinate of the Euclidean space is decoupled [25], [26]. The position of the ith vehicle is denoted by p_i and it is modeled by a double-integrator agent:

$$\ddot{p}_i = u_i + \omega_i,\ i \in \{1, 2, \ldots, N\} \tag{1}$$

where u_i is the control input, ω_i is the external disturbance, and N is the number of agents (excluding the reference agents) in the network. This is a commonly used model for vehicle dynamics in studying vehicular formation, which stems from feedback linearization [27], [28]. For the network of CAVs,

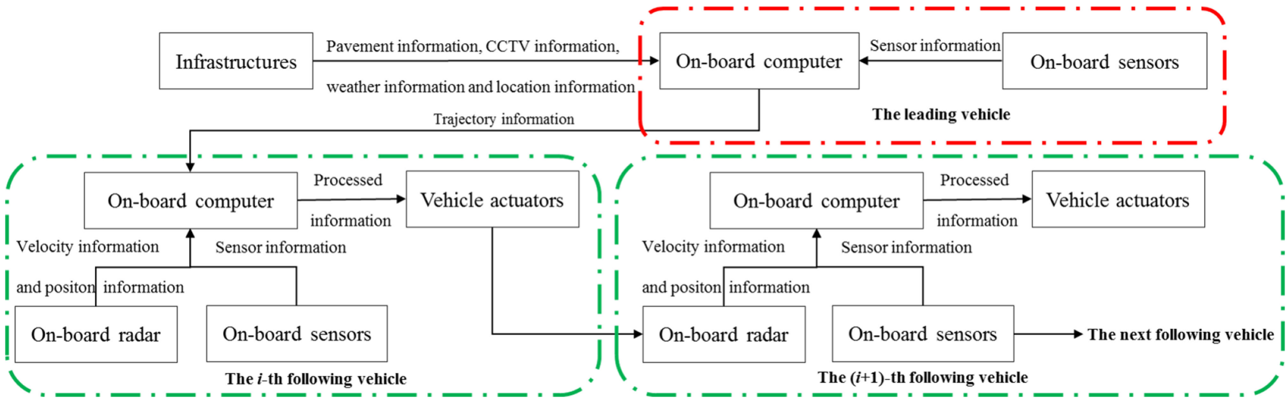

Fig. 2. Information flow of the DCPS.

the control objective is to make the CAVs maintain a rigid formation geometry by following a desired trajectory. The desired geometry of the formation is specified by the desired gaps $\Delta_{(i,j)}$ for $i, j \in \{1, 2, \ldots, N\}$, where $\Delta_{(i,j)}$ is the desired value of $p_i(t) - p_j(t)$. The desired intervehicle gaps $\Delta_{(i,j)}$s are constants and they have to be specified in a mutually consistent fashion, i.e., $\Delta_{(i,k)} = \Delta_{(i,j)} + \Delta_{(j,k)}$ for every triple (i, j, k). As stated above, the desired trajectory of the formation is planned by leading vehicles. The trajectory of the leading vehicles indexed by 0 is denoted by $p_0^*(t)$ and its dynamics is independent of the other agents. The desired trajectory of the ith agent $p_i^*(t)$ is then given by

$$p_i^*\ (t) = p_0^*\ (t) - \Delta_{(0,i)}. \tag{2}$$

In this paper, we consider the following distributed linear control law, where the control action u_i of an agent only depends on the relative position and relative velocity information from its neighbors, i.e.,

$$u_i = -\sum_{j\in\mathcal{N}_i} \left(k\left(p_i - p_j + \Delta_{(j,i)}\right) + b\left(\dot{p}_i - \dot{p}_j\right)\right) \tag{3}$$

where k and b are positive constants. The relative velocity and relative position information can be obtained by the on-board radar (see Fig. 3). For a network of agents that is desired to travel at a constant speed, we assume the reference trajectory is of a constant velocity type, i.e., $p_0^*(t) = v_0\, t + c_0$ for some constants v_0 and c_0. To facilitate analysis, we define the following position tracking error:

$$\tilde{p}_i := p_i - p_i^* \tag{4}$$

where p_i^* is given in (2). The closed-loop dynamics of the network can now be expressed by the following coupled-ODE:

$$\ddot{\tilde{p}}_i = -\sum_{j\in\mathcal{N}_i} \left(k\left(\tilde{p}_i - \tilde{p}_j\right) + b\left(\dot{\tilde{p}}_i - \dot{\tilde{p}}_j\right)\right) + \omega_i \tag{5}$$

where $i \in \{1, 2, \ldots, N\}$. Note that $\tilde{p}_0 = \dot{\tilde{p}}_0 \equiv 0$, since the reference agent perfectly tracks its desired trajectory. The closed-loop system can also be written in the following state space form:

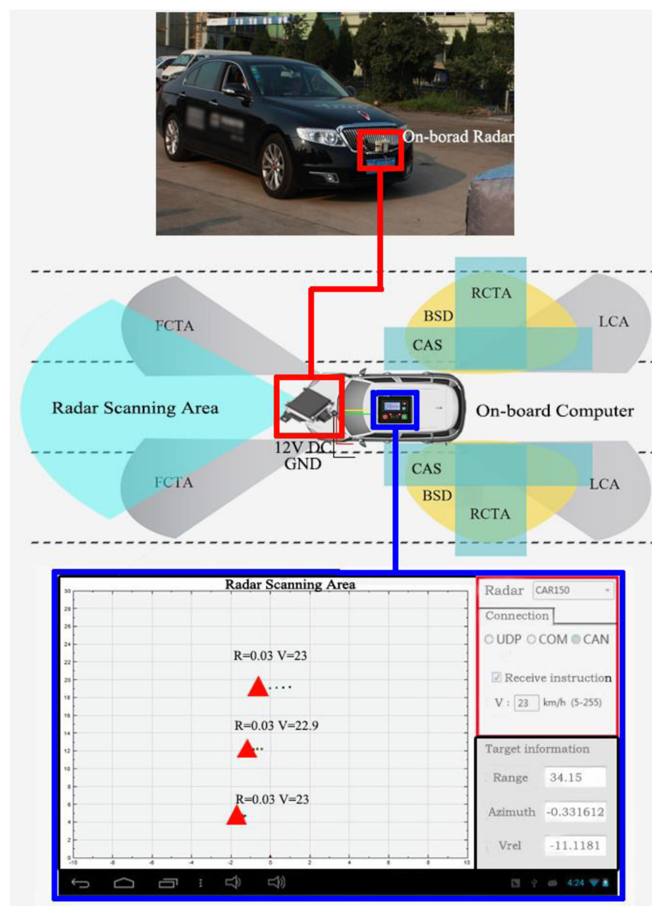

Fig. 3. CAVs loaded with radar can get the velocity and position information from nearest neighbors. (FCTA: Front cross traffic alert system; RCTA: Rear cross traffic alert system; BSD: Blind spot detection; CAS: Collision alert system; LCA: Lane-change assistant system.)

$$\begin{aligned} \dot{x} &= Ax + B\omega \\ y &= Cx \end{aligned} \tag{6}$$

where the state, output, and disturbance vectors are defined as $x := [\tilde{p}_1, \dot{\tilde{p}}_1, \ldots, \tilde{p}_N, \dot{\tilde{p}}_N]^T$, $y := [\tilde{p}_1, \ldots, \tilde{p}_N]^T$, and $\omega := [\omega_1, \ldots, \omega_N]^T$, and A, B, C are the state, input, and output

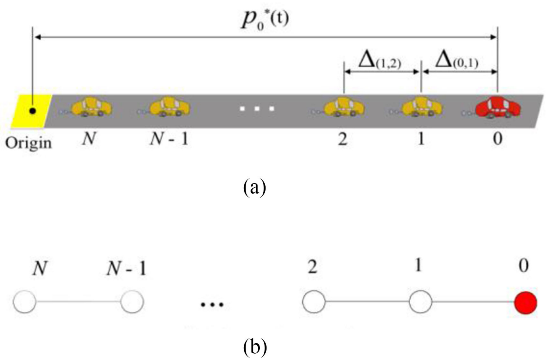

Fig. 4. Desired formation and its information graph of a vehicular platoon with and 1 leading vehicle and N ordinary following vehicles. (a) Vehicular platoon. (b) Information graph.

matrices, respectively. ω contains random disturbances and information collected by on-board sensors of the driver assistance systems (see Fig. 3). The transfer function from disturbance ω to position tracking error y is given by

$$G(s) = C(sI_{2N} - A)^{-1}B \tag{7}$$

where s is the Laplace variable, and I_{2N} is the $2N \times 2N$ identity matrix.

B. Interaction Topology Between CAVs

In this paper, we use information graphs to model the interaction topology between agents. An information graph is a graph $G = (V, E)$ with node set V and edge set E. The set of edges $E \subseteq V \times V$ specifies the information flow between neighboring agents. An edge (i, j) exits if node *i* has information exchange with node j. The set of neighbors of node *i* is defined as $\mathcal{N}_i := \{j \in V : (i, j) \in E\}$. In addition, the information graph is assumed to be undirected, which means $i \in \mathcal{N}_j$ if and only if $j \in \mathcal{N}_i$. A graph is said to be connected if there is a path between every pair of nodes. The graph Laplacian L is defined by $L_{ij} = -1$ if $(i, j) \in E$ and $L_{ii} = -\sum_k L_{ik}$. The grounded graph Laplacian L_g of an information graph is obtained by removing from L the rows and columns corresponding to the grounded (reference) nodes.

To facilitate the analysis, we restrict our attention to a specific class of information graph, namely a finite rectangular lattice. A lattice, denoted by $Z_{n_1 \times n_2 \times \cdots \times n_D}$, is a D-dimensional graph. The numbers of its nodes on each dimension are denoted by $n_1, n_2, \ldots, n_D$, respectively. A lattice is drawn in $\mathbb{R}^D$ with a Cartesian reference frame whose axes are denoted by $x_1, x_2, \ldots, x_D$. We define $N_d (d = 1, \ldots, D)$ as the number of nodes in the x_d-direction excluding the reference node. We thus have $N_1 N_2, \ldots, N_D = N$ and $n_1 n_2, \ldots, n_D = N + N_r$, where N_r is the number of nodes that represent the leading vehicles in the graph, i.e., reference nodes. For the 1-D lattice, it is indeed the information graph for a vehicular platoon (see Fig. 4). Regarding a 2-D lattice, it can represent information for formations, as shown in Fig. 5.

In this paper, we assume that there is at least one boundary (an outermost edge) on which every node is a reference node.

Fig. 5. Aircraft formation that can be represented by 2-D lattice.

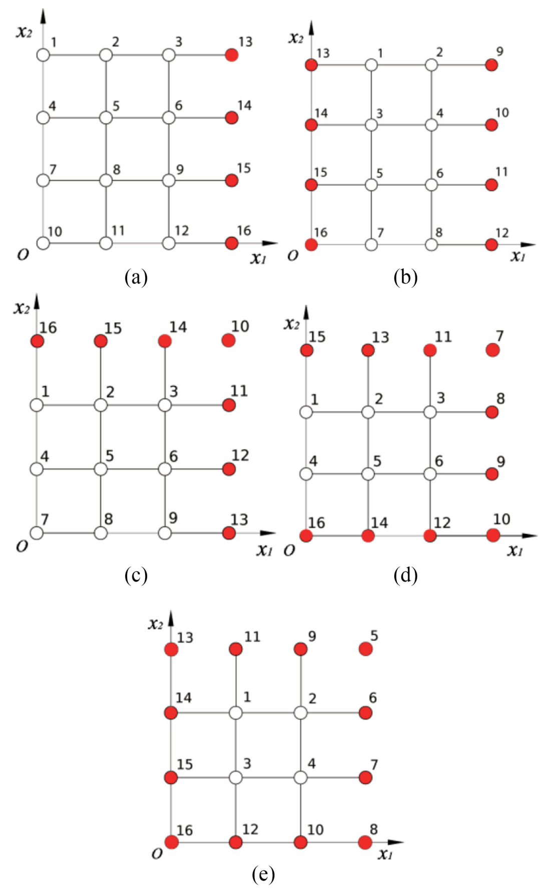

Fig. 6. 2-D lattice graphs with different boundary conditions.

Reference nodes are only placed on the boundaries because leading vehicles typically are the outermost vehicles in a formation. We call such a boundary a Dirichlet boundary. Without loss of generality, we assume the first D_0 axes in the information graph have Dirichlet boundaries. Fig. 4 shows the desired formation and its information graph of a vehicular platoon. The leading vehicle is in the front of the platoon and indexed by 0, and the following vehicles are indexed from 1 to N. Fig. 6 depicts several 2-D lattice graphs with different boundary conditions.

To understand the scalability of large-scale multiagent systems, several important works have investigated the performance scaling with respect to the network size. The authors in [26], [29], and [51] studied the scaling of the stability margin in large vehicular formations and proposed a mistuning-based controller design method to improve it. In our previous work [30], two performance metrics have been defined to study the scalability of a large network of double-integrator agents.

Definition 1: The convergence rate of the network is defined as the absolute value of the real part of the least stable eigenvalue of the state matrix A, i.e.,

$$R := \left|\Re\left(E_\lambda^{\text{ls}}\left(A\right)\right)\right| \tag{8}$$

where $E_\lambda^{\text{ls}}(A)$ denotes the least stable eigenvalue of matrix A, in which the least stable eigenvalue is the one with the largest real part.

Definition 2: The sensitivity to disturbance of the network is defined as the H_∞ norm of the transfer function $G(s)$

$$S := \max_\omega \sigma_{\max}\ \left(G\left(j\omega\right)\right) = \sigma_{\max}\ \left(G\left(j\omega_p\right)\right) \tag{9}$$

where the maximum is assumed to be achieved and $\omega_p := \arg\max_\omega \sigma_{\max}(G(j\omega)$, in which $\sigma_{\max}$ denotes the maximum singular value.

For a network of double-integrator agents whose dynamics is described by (5), it is straightforward to show that its state matrix A can be expressed in the following form:

$$A = I_N \otimes A_1 + L_g \otimes A_2 \tag{10}$$

where $\otimes$ denotes the Kronecker product, and A_1, A_2 are given as below:

$$A_1 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix},\ A_1 = \begin{bmatrix} 0 & 0 \\ -k & -b \end{bmatrix}. \tag{11}$$

In addition, some analytic expressions have been derived in our previous works [31], [32] as follows.

Theorem 1: Given a network of double-integrator agents, whose state matrix A is given in (10), if its information graph is connected, then the convergence rate of the system is given by

$$R = \begin{cases} \dfrac{b\lambda_{\min}}{2}, & \text{if } \lambda_{\max} \leq \dfrac{4k}{b^2} \\ \dfrac{2k}{b+\sqrt{b^2-4k/\lambda_{\max}}}, & \text{if } \lambda_{\min} \geq \dfrac{4k}{b^2} \\ \min\left\{\dfrac{b\lambda_{\min}}{2}, \dfrac{2k}{b+\sqrt{b^2-4k/\lambda_{\max}}}\right\}, & \text{otherwise} \end{cases} \tag{12}$$

where $\lambda_{\min}$ and $\lambda_{\max}$ are the minimum and maximum eigenvalues of the grounded graph Laplacian L_g, respectively.

Theorem 2: Given a network of double-integrator agents whose closed-loop dynamics is described by (2), its sensitivity S to disturbance and peak frequency ω_p are, respectively,

$$S = \begin{cases} \dfrac{2}{\lambda_{\min}^{3/2} b\sqrt{4k-\lambda_{\min}b^2}}, & \text{if } \lambda_{\min} \leq 2k/b^2 \\ \dfrac{1}{\lambda_{\min}k}, & \text{otherwise} \end{cases} \tag{13}$$

$$\omega_p = \begin{cases} \dfrac{\sqrt{4\lambda_{\min}k - 2\lambda_{\min}^2 b^2}}{2}, & \text{if } \lambda_{\min} \leq 2k/b^2 \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

where $\lambda_{\min}$ is the smallest eigenvalue of the grounded graph Laplacian L_g.

For a network of DCPS where the interaction topology of CAVs is described by information graphs, it is very challenging to obtain an analytic formula for the eigenvalues of the grounded Laplacian of an arbitrary information graph. Since we focus on the special class of information graph, i.e., lattice, we are able to obtain the exact formulae for the smallest eigenvalue of its grounded graph Laplacian.

The next result whose proof is given in the Appendix gives an explicit formula for the convergence rate of a large-scale network with lattice information graphs.

Corollary 1: Consider a network of double-integrator agents with a D-dimensional lattice information graph. If $\min_{d=1,\ldots,D_0} N_d \gg 1$, the convergence rate of the network satisfies

$$R = \frac{\lambda_{\min} b}{2} \approx d = 1 \sum^{D_0} \left(\frac{I_1\left(x_d\right)}{4} + I_2\left(x_d\right)\right) \frac{\pi^2 b}{2N_d^2} \tag{15}$$

where the indicator function $I_j(x_d)(j = 1, 2)$ is defined as

$$I_j\left(x_d\right) = \begin{cases} 1, & \text{if there are } j \text{ Drichlet} \\ & \text{boundaries on the } x_d \text{ axis} \\ 0, & \text{otherwise.} \end{cases} \tag{16}$$

For example, there is only one Dirichlet boundary on the x_1-axis in Fig. 6(a), and thus we have $I_1\ (x_1) = 1, I_2\ (x_1) = 0$. In Fig. 6(e), there are two Drichlet boundaries on both x_1 and x_2 axes, and thus we have $I_1\ (x_1) = I_1\ \ (x_2) = 0$ and $I_2\ (x_1) = I_2\ \ (x_2) = 1$. Corollary 1 gives an explicit formula for the convergence rate of a large-scale network with lattice information graphs.

In particular, for the 1-D vehicular platoon depicted in Fig. 4, we obtain from Corollary 1 that its convergence rate is given by

$$R \approx \frac{b\pi^2}{8N^2}$$

when the number of vehicles in the platoon is large. This shows that the convergence rate of the vehicular platoon decays to 0 with a scaling law of $O(1/N^2)$ as N tends to ∞.

The next corollary whose proof is given in the Appendix gives an explicit formula for the scaling laws of the sensitivity for disturbance for large-scale networks with lattice information graphs.

Corollary 2: In a network of double-integrator agents with a D-dimensional lattice information graph, its sensitivity to disturbance and the corresponding peak frequency satisfy

$$S \approx \frac{8}{\sqrt{k}b\pi^3\left(\sum_{d=1}^{D_0}\left(I_1\left(x_d\right)+4I_2\left(x_d\right)\right)\frac{1}{N_d^2}\right)^{3/2}} \tag{17}$$

$$\omega_p \approx \frac{\sqrt{k}\pi}{2}\left(\sum_{d=0}^{D_0}\left(I_2\left(x_d\right)+4I_2\left(x_d\right)\right)\frac{1}{N_d^2}\right)^{1/2} \tag{18}$$

when $\min_{d=1,\ldots,D_0} N_d \gg D_0 \geq 1$.

In particular, for the 1-D vehicular platoon depicted in Fig. 4, when the number of vehicles is large, i.e., $N \gg 1$, we obtain from Corollary 2 that its sensitivity to disturbance and peak frequency are given by

$$S \approx \frac{8N^3}{\sqrt{k}b\pi^3},\ \omega_p \approx \frac{\sqrt{k}\pi}{2N}.$$

This implies that the sensitivity to disturbance of the vehicular platoon grows to $+\infty$ with a scaling law of $O(N^3)$, and its peak frequency decays to 0 on the order of $O(\frac{1}{N})$.

C. V2X Communication Technologies

Although the single model and the interaction topology have been described in detail, the V2X communication technologies (including V2I and V2V communication) to guarantee the normal operation of the DCPS is still lacking. In this paper, CAVs use controller area network (CAN)-based vehicle ad hoc networks (VANETs) to communicate with each other. The existing works on VANET mainly focus on three aspects. Some studies [34], [37], [41] are concerned with the spatial and transmission capacity, some involve the design of protocols and approaches [36]–[40], and others deal with the privacy-preserving [35], [36].

In this paper, we focus on the privacy protection of CAVs since we only use VANET as a tool for V2X communication and the experiment is conducted in a relatively simple environment. The VANET is an effective way in ITS to broadcast traffic information all over the system [43], but the misuse of the information can lead to deliberate attacks. In [18], the authors have demonstrated that the privacy information such as location data can be used to analyze the drivers' moving preference and then to perform reidentification attacks. Shokri *et al.* [42] tried to use the hidden Markov model to represent the user profiles, but the research in [33] showed that even if the data was set to be anonymous, the user can still be identified as long as the individual CAV has a unique pattern. Therefore, we put forward the following three guidelines that should be considered when designing an ITS:

1) in an ITS, there should not be a data center that collects all user-related information;
2) the information collected from an individual CAV should be as less as possible; and
3) the number of CAVs that exchange information with a specific CAV should be as small as possible.

Based on the above consideration, we designed the proposed DCPS formulation. First, the data sources in the information layer are different, and only the necessary and limited data will be provided to leading vehicles to plan the trajectory. The control centers that receive all the information can be avoided in this way. Second, the only privacy information of an individual CAV that can be collected is velocity and position information. Note that the position information here is different from the GPS information, and is expressed by angle and straight-line distance. Third, the velocity and position information of an individual CAV is only provided to the nearest neighbors such that the information exchange can be limited to a very small range. The velocity and position information is only used to calculate the relative velocity and relative position to correct the CAVs' trajectory. Besides, the trajectory planning of a following vehicle is also affected by the data from the on-board sensors, which partly reduces the impact of maliciously or incorrectly transmitted information.

D. Information Processing Using EC

CAVs are expected to carry more on-board sensing and computing facilities to support and promote the ITS. Hence, vehicular networking is starting to emerge as an effective way to help manage vehicular platoons. Vehicular cloud computing (VCC) is one of the most popular solutions that were proposed to enable vehicular networking technologies. VCC can provide different types of services such as Network as a Service (NaaS), Storage as a Service (StaaS), Cooperation as Service (CaaS), and so on [44], but there are still several drawbacks:

1) the linear growth of centralized cloud computing capacity cannot match the explosive growth of massive edge data;
2) the transmission of data from edge devices to cloud centers causes a dramatic increase in the bandwidth of the network, which will result in longer communication delay;
3) the privacy data transmitted to cloud centers from edge devices may cause security issues; and
4) the data transmission consumes too much energy for an edge device whose power is limited.

Therefore, investigations about datacenter [45], [46], fog computing [47], and cloudlet [48] have been introduced to the community because CC is not always an efficient way to process data, especially when the data is produced at the edge of the network.

In the CC-based distributed formulation of CAVs, every vehicle needs to send the information to a cloud center, and then the cloud center sends a decision back after analyzing and processing the related data. However, the data generated by CAVs can be one Gigabyte every second [49], and the speed of data transmission is becoming the bottleneck such that the real-time decision making becomes very difficult or costs too much time to respond. With the development of manufacturing and the computer technologies, the on-board micro data center loaded in CAVs is already capable of processing the information collected by the CAV itself, based on which EC has emerged as a typical technology. EC refers to the enabling technologies that happen at the proximity of data sources and allow computation to be performed at the edge of the network [50].

For an individual CAV in the DCPS, EC indicates the whole process from receiving information to making decisions. For a leading vehicle, it will receive the information from the information layer and the information from its on-board sensors. The on-board central information processor will analyze all the information to generate a reasonable trajectory. For a following vehicle, it will receive the velocity and position information, and calculate the relative velocity and relative position accordingly. Together with the data collected by on-board sensors, the on-board central information processor will decide how to perform to travel along the desired trajectory. The data are heterogeneous from different sources (for example, the speed information is a numerical value, while the camera information is an image) and

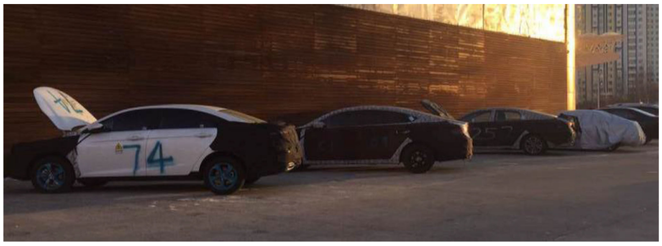

Fig. 7. CAVs loaded with radar for practical experiment.

contains redundant information (for example, the leaves on the road generally do not affect the normal driving of the vehicle). EC is expected to first decouple heterogeneous data and get rid of invalid information, and then analyze and make a decision. Compared with CC, EC do not need to upload and download data so that it will cost less time and less energy to respond, which is important for a real-time process. Moreover, the omission the data transmission can also reduce the disclosure of privacy data.

IV. Experiments and Results

To verify the validity of the proposed DCPS, several practical and numerical experiments are conducted in this section. We examined the feasibility of CAVs receiving the velocity and position information from the nearest neighbors (see Fig. 7). The CAVs are loaded with some certain types of millimeter-wave on-board radar. The radar emits fan-shaped millimeter waves forward and backward, and calculates the relative velocity and relative position of the nearest vehicles by measuring the Doppler effect of the echo. The resolution of the radar reached 1 cm and the distance measuring range is 30 m, while it consumes very little power (0.8 W) with a small size ($95 \times 68 \times 20$ mm^3). The refresh rate of the on-board central information processor is 20–50 Hz, and the visualized image of the lower part of Fig. 3 shows that results can meet the needs of the DCPS with a test velocity ranging from 20 to 30 km/h.

We compare the numerically computed convergence rate with our analytic prediction provided by Corollary 1. The numerically computed convergence rate is obtained from MATLAB by calculating the absolute value of the real part of the least stable eigenvalue of the state matrix A. In all calculations, the control gains used are $k = 1$ and $b = 0.5$. Fig. 8 plots the convergence rates in log scale as a function of the number of agents in the system for a 1-D vehicular platoon. We observe that our theoretical predictions match the numerically computed values very well, especially when the number of vehicles in the platoon is large. In addition, we compare the convergence rates for large networks with 2-D lattice information graphs. In particular, we set $N_2 = 3\ N_1 = 3n$ in the lattice, and let n increase progressively. We observe from Fig. 9 that although there are small prediction errors when n is small, our analytic formula provides a very good prediction for the convergence rate when the network size is large. The same observations (not reported in this paper due to space limitation) are obtained for networks with 2-D lattice information graphs of different aspect ratios. In conclusion,

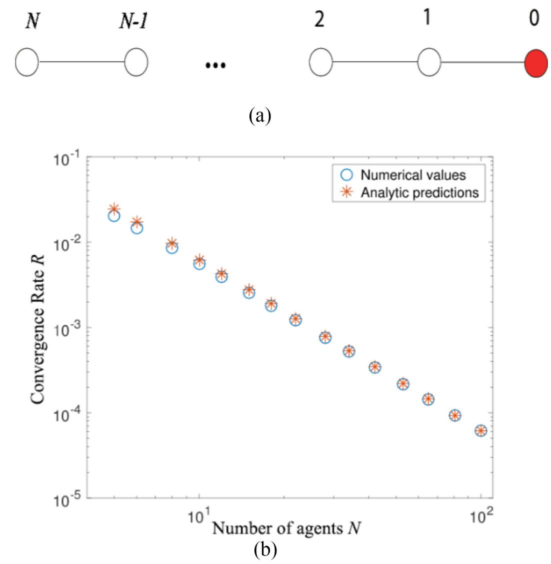

Fig. 8. Comparison of the convergence rates between numerically computed values and analytic predictions by Corollary 2 for a 1-D *N*-vehicle platoon. (a) 1-D lattice graph. (b) Scaling of convergence rate.

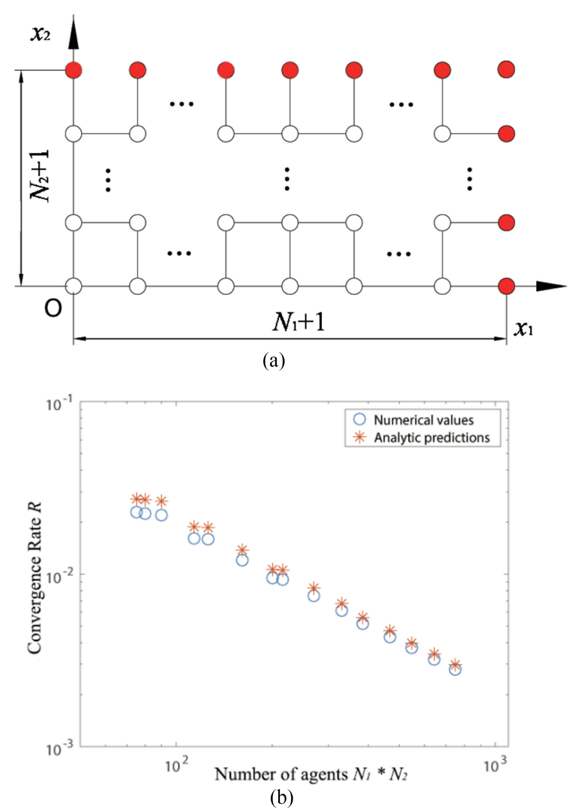

Fig. 9. Comparison of the convergence rates between numerically computed values and analytic predictions by Corollary 2 for a network with 2-D lattice graph. (a) 2-D lattice graph. (b) Scaling of convergence rate.

we show that our theoretic analysis provides an accurate analytic prediction of the network's convergence rate when the number of agents is large.

We also present comparison results between the numerically computed sensitivity to disturbance and its analytic predictions

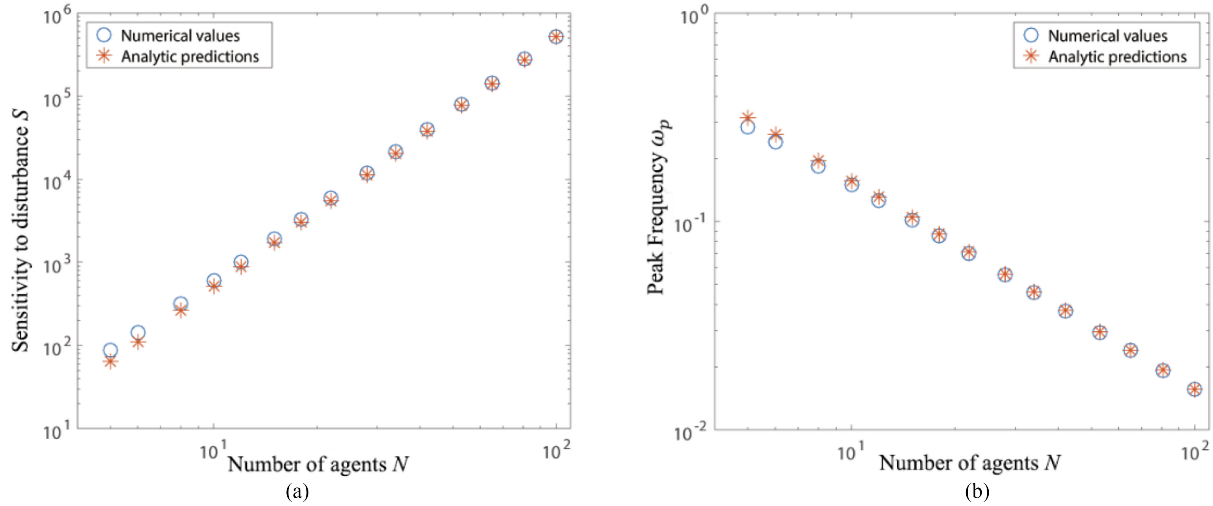

Fig. 10. Comparison of the sensitivities to disturbance and the peak frequencies between the numerically computed values from MATLAB and the analytic predictions by Corollary 2 for a 1-D *N*-vehicle platoon. (a) Sensitivity to disturbance. (b) Peak frequency.

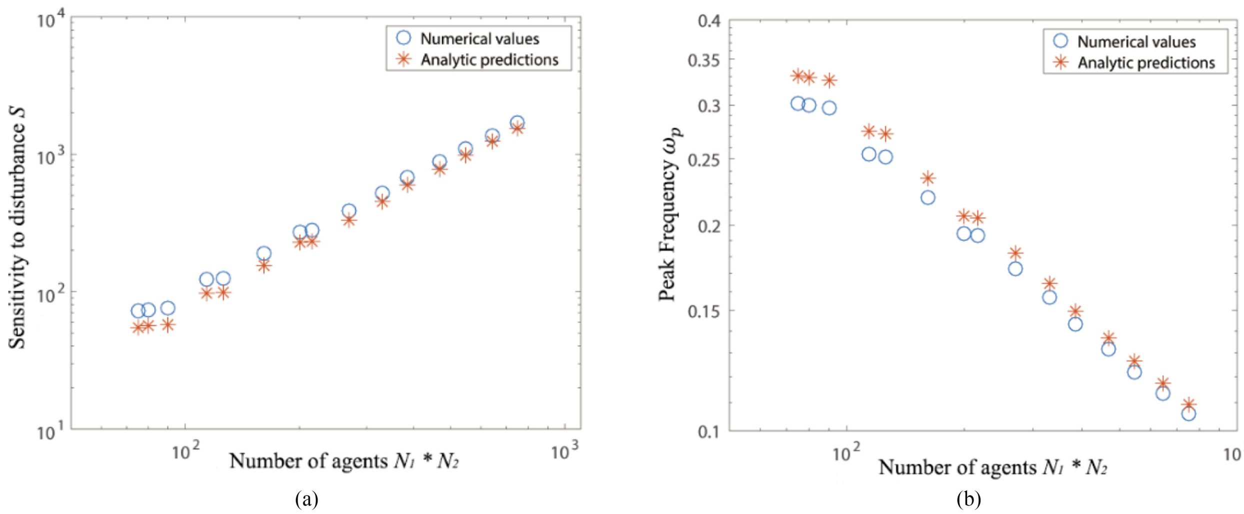

Fig. 11. Comparison of the sensitivities to disturbance and the peak frequencies between the numerically computed values from MATLAB and the analytic predictions by Corollary 2 for a network with 2-D lattice information graphs. (a) Sensitivity to disturbance. (b) Peak frequency.

provided by Corollary 2. The numerically computed sensitivity to disturbance is obtained by calculating the H_∞ norm of the transfer function $G(s)$ using MATLAB. In all calculations, the control gains used are $k = 1$ and $b = 0.5$. Fig. 10 shows the sensitivity to disturbance and the peak frequencies in log scale as a function of N for a 1-D N-vehicle platoon. We observe that the analytic formulae derived in Corollary 2 gives accurate predictions for the H_∞ norm and the peak frequency. We also compare the sensitivities to disturbance and the peak frequencies for a network of double-integrator agents with 2-D lattice information graphs. Fig. 11 shows that the proposed theoretic predictions well match the numerically computed values, especially when the size of the network is large.

V. Conclusion and Future Work

To reduce the privacy leak and communication delay of the CAVs in ITS, this paper proposed a DCPS formulation and elaborated its implementing methodologies. In the DCPS, leading vehicles will communicate with infrastructures and plan a trajectory accordingly, while following vehicles, modeled as double-integrator agents, only need to interact with their nearest neighbors. A CAN-based VANET is used for intra- and inter-vehicle communication to collect necessary information. We recommend that there should be no data center that collects all user-related information in ITS because the fewer infrastructures have access to user information, the better the privacy can be protected. The application of VANET and EC enables an individual CAV to process information and make its own decisions so that the risk of exposing privacy data is greatly reduced.

To study the performance of the networked system, we use information graph to describe the interaction topology between CAVs, and two performance matrices, the convergence rate and sensitivity to disturbance, were introduced to study the performance scaling. Based on our previous work, several analytic expressions were derived with respect to the smallest eigenvalue of the grounded graph Laplacian. In particular, for the most common N-vehicle platoon whose information graph is a 1-D lattice, its convergence rate decayed to 0 as $O(1/N^2)$, and its sensitivity to disturbance grew to $+\infty$ as $O(N^3)$. The numerical experiments show that the performance of the CAVs matches very well with our analytic predictions.

Although the work in this paper can improve the performance of control and driving for CAVs, we agree to the point that there are still some deep gaps between design and application. For example, our road test experiments were conducted in a relatively simple environment, and the emergencies in driving were not considered. We assumed that the dynamics of all the CAVs is homogeneous, but the problem will be more complicated for real world and some more realistic models have been proposed [52], [53]. We will model the CAVs more realistically and conduct the experiments under more complex road conditions for future research.

Appendix

A. Proof of Corollary 1

For a D-dimensional lattice graph, we obtain from [30] that the smallest eigenvalue of its grounded graph Laplacian is given by the following formula:

$$\lambda_{\min} := 2D_0 - 2\sum_{d=1}^{D_0}\left[I_1(x_d)\cos\frac{\pi}{2N_d+1} + I_2(x_d)\cos\frac{\pi}{N_d+1}\right].$$

Since $N_d \gg 1$ for each d in the summation, we use $\cos x = 1 - x^2/2 + O(x^4)$ when $|x| \ll 1$ to obtain

$$\cos\frac{\pi}{2N_d+1} = 1 - \frac{\pi^2}{8N_d^2} + O\left(\frac{1}{N_d^4}\right)$$
$$\cos\frac{\pi}{N_d+1} = 1 - \frac{\pi^2}{N_d^2} + O\left(\frac{1}{N_d^4}\right).$$

Hence, we have

$$\lambda_{\min} \approx \sum_{d=1}^{D_0}\left(\frac{I_1(x_d)}{4} + I_2(x_d)\right)\frac{\pi^2}{N_d^2}.$$

In addition, when $\min_{d=1,\ldots,D_0} N_d \gg 1$, we obtain from (12) that

$$\mathrm{R} = \frac{\lambda_{\min} b}{2} \approx \sum_{d=1}^{D_0}\left(\frac{I_1(x_d)}{4} + I_2(x_d)\right)\frac{\pi^2 b}{2N_d^2}.$$

B. Proof of Corollary 2

It follows from the proof of Corollary 1 that the smallest eigenvalue of the grounded graph Laplacian L_g is approximately

$$\lambda_{\min} \approx \sum_{d=1}^{D_0}\left(\frac{I_1(x_d)}{4} + I_2(x_d)\right)\frac{\pi^2}{N_d^2}$$

when $\min_{d=1,\ldots,D_0} N_d \gg 1$.

By (13), $\lambda_{\min} \le 2k/b^2$ holds if $\forall d \in \{1,\ldots,D_0\}, N_d \gg 1$. Thus, the sensitivity to external disturbance is given by

$$S \approx \frac{8}{\sqrt{k} b \pi^3 \left(\sum_{d=1}^{D_0}(I_1(x_d) + 4I_2(x_d))\frac{1}{N_d^2}\right)^{3/2}}.$$

Similarly, the peak frequency follows

$$\omega_p \approx \frac{\sqrt{k}\pi}{2}\left(\sum_{d=1}^{D_0}(I_1(x_d) + 4I_2(x_d))\frac{1}{N_d^2}\right)^{1/2}.$$

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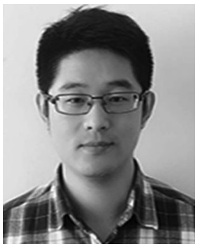
Yixiong Feng received the B.S. and M.S. degrees in mechanical engineering from Yanshan University, Qinhuangdao, China, and the Ph.D. degree in mechanical engineering from Zhejiang University, Hangzhou, Zhejiang, China, in 1997, 2000, and 2004, respectively.

He is currently a Professor with the Department of Mechanical Engineering, Zhejiang University, China, and a Member of the State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University. He has published more than 100 journal and conference proceedings papers. He has been the Principal Investigator of four projects supported by the National Natural Science Foundation of China and one project supported by the National High-tech R&D Program of China (863 Program). His research interests include mechanical product design theory, intelligent automation, and advanced manufacturing technology.

Dr. Feng is the recipient of the Zhejiang Province Outstanding Youth Fund and the National Outstanding Youth Fund.

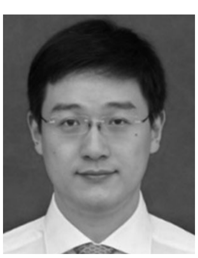


Bingtao Hu received the B.S. degree in mechanical engineering from Zhejiang University, Hangzhou, Zhejiang, China, in 2014, where he is currently working toward the Ph.D. degree.

He is a Member of the State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, China. His research interests include intelligent transportation, mechanical product design theory, and advanced manufacturing technology.

He Hao received the B.S. degree in mechanical engineering and automation from Northeastern University, Shenyang, China, the M.S. degree in mechanical engineering from Zhejiang University, Hangzhou, China, and the Ph.D. degree in mechanical engineering from the University of Florida, Gainesville, FL, USA, in 2006, 2008, and 2012, respectively.

He was a Postdoctoral Fellow with the Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA, USA. He is currently a Lead Data Scientist with Centrica, Windsor, U.K. Before joining Centrica, he was a Senior Research Scientist with the Electricity Infrastructure and Buildings Division, Pacific Northwest National Laboratory. His research interests include machine learning and optimization and controls with applications to smart grid, demand response, smart buildings, and power and energy systems.



Yicong Gao received the B.S. degree in mechanical engineering from East China University of Science and Technology, Shanghai, China, and the Ph.D. degree in mechanical engineering from the Department of Mechanical Engineering, Zhejiang University, Hangzhou, China, in 2005 and 2011, respectively.

He is currently an Assistant Research Fellow with the State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, China. His research interests include mechanical design methodology, product green design, and advanced manufacturing technology.

Zhiwu Li (M'06–SM'07–F'16) received the B.S. degree in mechanical engineering, the M.S. degree in automatic control, and the Ph.D. degree in manufacturing engineering from Xidian University, Xian, China, in 1989, 1992, and 1995, respectively.

In 1992, he joined Xidian University. Over the past decade, he was a Visiting Professor with the University of Toronto, the Technion – Israel Institute of Technology, the Martin Luther University of Halle-Wittenburg, the Conservatoire National des Arts et Métiers, and Meliksah University. He is currently working with the Institute of Systems Engineering, Macau University of Science and Technology, Taipa, Macau. His research interests include Petri net theory and application, supervisory control of discrete event systems, workflow modeling and analysis, system reconfiguration, game theory, and data and process mining.

Dr. Li is a Member of the Discrete Event Systems Technical Committee, the IEEE Systems, Man, and Cybernetics Society, and the IFAC Technical Committee on Discrete Event and Hybrid Systems from 2011 to 2014. He received the Alexander von Humboldt Research Grant, Alexander von Humboldt Foundation, Germany. He serves as a frequent reviewer for more than 50 international journals, including the *Automatica* and several IEEE Transactions and many international conferences. He is listed in *Marquis Who's Who in the World*, 27th ed., 2010. He is the Founding Chair of Xian Chapter of the IEEE Systems, Man, and Cybernetics Society.

Jianrong Tan received the B.S. degree in mechanical engineer, and electronic engineering from The Open University of China, Beijing, China, the M.S. degree in engineering from the Huazhong University of Science and Technology, Wuhan, China, and the Ph.D. degree in mathematics from Zhejiang University, Hangzhou, China, in 1982, 1985, and 1987, respectively.

He is currently a specially appointed Professor with Zhejiang University, a Doctorial Supervisor and an Academician of the Chinese Academy of Science, the Dean of Mechanical Engineering, the Associate Supervisor of the CAD&CG State Key Laboratory, the Head of the Institute of Engineering & Computer Graphics, Zhejiang University, and the Chief Supervisor of Engineering Graphics State Fundamental Courses. He has authored 8 monographs or compiled 142 papers, which have been searched by SCI/EI and been cited 1600 times. He has 15 years of working experience in manufacturing and its theory in science, and proposed the technique in combination of batch and customization, which is used for multitudinous customization, the status in engineering transition, the fuzzy status, the technology simulation of random status modeling and digitalized prototype integration, the combination of figures and geometry in multicomponent correlation in intricate equipment, the analysis of multilevel disposing, and multiparameter matching. He put his technology into the software and obtained 12 copyrights of computer software, which are used by many manufacturing enterprises. His research interests include mechanical designing and theory, and digitalized designing and manufactory.

Dr. Tan received the National Pride four times, which includes the Second Prize in National Technology Progress twice, the First Prize in National Excellent Education Achievement, and the First Prize in provincial-level technology progress six times.