Cluster-Wise Cooperative Eco-Approach and Departure Application along Signalized Arterials

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***Abstract* — In recent years, the Eco-Approach and Departure (EAD) application has been widely studied, which utilizes Signal Phase and Timing (SPaT) information to allow connected and automated vehicles (CAVs) to approach and depart from a signalized intersection in an energy-efficient manner. However, most existing work have studied the EAD application from an ego-vehicle perspective (Ego-EAD), where a single vehicle makes use of Infrastructure-to-Vehicle (I2V) communication, without considering the effect on traffic throughput. To date, relatively limited research about EAD application takes into account cooperation among vehicles at intersections via Vehicle-to-Vehicle (V2V) communication, aiming to benefit not only one vehicle but the entire traffic flow. In this study, we develop a cluster-wise cooperative EAD (Coop-EAD) system to further reduce energy consumption while increasing traffic throughput, compared to existing Ego-EAD applications. Instead of considering CAVs traveling through signalized intersections one at a time, our approach strategically coordinates CAVs' maneuvers to form clusters with the proposed methodologies: initial vehicle clustering, intra-cluster sequence optimization, and cluster formation control. The EAD algorithm is then applied to the cluster leader, and CAVs in the cluster can conduct EAD maneuvers by following the dynamics of the cluster leader. A comprehensive simulation study shows that, compared to an Ego-EAD system, the proposed Coop-EAD system achieves 50% increase on traffic throughput, 11% reduction on energy consumption, and up to 20% reduction on pollutant emissions, respectively.**

Index Terms* — *Eco-Approach and Departure, connected and automated vehicles, cluster, cooperative

I. Introduction and Motivation

In recent years, increased transportation activity has introduced significant impacts on energy consumption and pollutant emissions. In 2015, the transportation sector in the United States consumed approximately 27.71 quadrillion BTUs (British thermal unit) of energy, which consisted of 28.4% of total energy consumption for all sectors nationwide [1]. Transportation-related greenhouse gas (GHG) emissions was the second largest producer of GHG nationwide in 2013, accounting for approximately 27% of total U.S. emissions [2].

These facts increase public awareness of the need to reduce energy consumption and pollutant emissions generated by transportation systems. Among all of the strategies to reduce energy consumption and pollutant emissions of motor vehicles from transportation sector, eco-driving at signalized intersections has garnered significant research interest around the world [3 – 6]. By applying connected vehicle (CV) technology, drivers would effectively reduce the number of full stops and idling, and avoid unnecessary accelerations and decelerations by receiving signal phase and timing (SPaT) information while approaching an intersection [7]. The Eco-Approach and Departure (EAD) application is a typical example, where drivers are guided to approach and depart from signalized intersections in an environmental friendly manner using SPaT and geometric intersection description (GID) information sent from the dedicated short-range communications (DSRC) roadside units (RSU) installed as part of the signalized intersection infrastructure [8 – 9]. In such a manner, CVs can increase their energy efficiency and decrease pollutant emissions by simply following well-designed speed profiles while traveling through the intersection. Results of microscopic simulation models showed a 10-15% reduction on energy consumption and CO_2 emissions by applying the EAD application to fixed-timing signalized intersections [10]. A field test along the El Camino Real corridor in Palo Alto, CA showed 2% to 18% energy and emissions reduction (varied by corridor), by applying the EAD application to actuated signalized intersections in real-world traffic [11]. In terms of congested traffic, the EAD application also worked efficiently in which preceding queues were taken into account by adopting real time vehicle detection and signal information system [12]. Moreover, it was also revealed in previous studies that, drivers' behavior adaptability under actual driving conditions also plays an important role in the effectiveness of the EAD application [13].

Since the recommended speed profile is conveyed to drivers of CVs through driver-vehicle interfaces (DVIs), drivers may not be able to drive by following the recommended speed profile precisely, leading to degraded effectiveness of the EAD application. In this respect, the development of automated vehicle (AV) technology allows vehicles to better follow the recommended speed profiles, thereby ensuring the benefits of the EAD application to be fully realized. An evaluation of the supplementary benefits from vehicle automation in CV applications with the use of the EAD application at signalized intersections are presented in a case study [14].

In addition to safety and environmental benefits, the combination of CV and AV technology, i.e., connected and automated vehicle (CAV) technology can also produce traffic throughput benefits. One typical application of the CAV technology is the cooperative adaptive cruise control (CACC) system, which allows CAVs to cooperate with each other to

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978-1-5386-1526-3/17/$31.00 ©2017 IEEE

form vehicle platoons. By sharing information among different CAVs using Vehicle-to-Vehicle (V2V) communication, CAVs can be driven at harmonized speeds with constant distance/time headways between them. A significant amount of effort has been put into the development and assessment of different perspectives of the CACC system [15 – 18], however, relatively little research has focused on the energy perspective, applying the idea of eco-driving to the CACC system. Wang *et al.* proposed a V2V communication based Eco-CACC system, aiming to minimize the platoon-wide energy consumption and pollutant emissions at different stages of the CACC operation [19]. Based on this study, Hao *et al.* developed a bi-level model to synthetically analyze the platoon-wide impact of the disturbances when vehicles join and leave the Eco-CACC system [20]. An Eco-CACC algorithm was developed by Yang *et al.* that computes the fuel-optimum vehicle trajectory through a signalized intersection by ensuring the vehicle arrives at the intersection as soon as the last vehicle in the queue is discharged [21]. Zohdy *et al.* proposed an intersection cooperative adaptive cruise control system (iCACC) to allow intersection controller to receive information from vehicles and advise each vehicle on the optimum course of action ensuring crash-free and meanwhile minimize the intersection delay [22].

Since most of the existing EAD system are designed from an ego-vehicle perspective (Ego-EAD), considering the interaction with other traffic in a passive manner. This may result in negative impacts, e.g., queue spillback, on the upstream traffic along a corridor with short blocks due to the "pushing-back" effects of Ego-EAD algorithms. To overcome this issue while preserving the benefits from EAD, we combine the ideas of EAD and CACC to propose a cluster-wise cooperative Eco-Approach and Departure (Coop-EAD) application, enabling CAVs to cooperate with each other to form clusters and travel through the signalized intersection with smaller time headways in an energy efficient manner. The proposed system not only reduces energy consumption and pollutant emissions, but also improves system efficiency (e.g. traffic throughput) and safety.

The remainder of this paper is organized as follows: Section II demonstrates mathematical preliminaries and system specifications of this study. Section III proposes the methodology for this Coop-EAD system, including four different parts: initial vehicle clustering, intra-cluster sequence optimization, cluster formation control, and cooperative eco-approach and departure. A preliminary evaluation of the proposed system by MATLAB/Simulink and MOVES is conducted, and its results are analyzed in Section IV. Section V concludes this paper together with further discussion on future work.

II. Mathematical Preliminaries and System Specifications

In this study, if we consider every vehicle as a node of a network, then the information flow topology of this CAV cluster network can be represented by using a directed graph (digraph) $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{1, 2, \dots, n\}$ is a finite nonempty node set and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is an edge set of ordered pairs of nodes, called edges. The edge $(i, j) \in \mathcal{E}$ denotes that vehicle j can obtain information from vehicle i. However, it is not necessarily true in reverse. The neighbors of vehicle i are denoted by $\mathcal{N}_i = \{j \in \mathcal{V}: (i, j) \in \mathcal{E}\}$. A sequence $1, 2, \dots, l$ of distinct nodes is a directed path if $(i, i-1) \in \mathcal{E}$, $i = 2, 3, \dots, l$. The topology of the graph is associated with an adjacency matrix $\mathcal{A} = [a_{ij}] \in \mathbb{R}$, which is defined such that $a_{ij} = 1$ if edge $(j, i) \in \mathcal{E}$, $a_{ij} = 0$ if edge $(j, i) \notin \mathcal{E}$, and $a_{ii} = 0$. $\mathcal{L} = [\ell_{ij}] \in \mathbb{R}$ (i.e., $\ell_{ij} = -a_{ij}$, $i \neq j$, $\ell_{ii} = \sum_{j=1, j\neq i}^{n} a_{ij}$) is the nonsymmetrical Laplacian matrix associated with $\mathcal{G}$. A directed tree is a digraph in which every node has exactly one parent node except for the root, which has no parent and has a directed path to every other node in the digraph. A directed spanning tree is a directed tree formed by graph edges that connects all the nodes of the graph.

It shall be noted that since our study mainly focus on designing V2V communication topology and control protocol of the system, some reasonable specifications are made as follow while modelling the system to enable the theoretical analysis:

1) All vehicles in this study are CAVs with the ability to share information with each other.
2) All vehicles in this study are equipped with appropriate sensors, such as inertial measurement unit (IMU), on-board diagnostic system, and high-precision GPS, to measure their instantaneous speed and absolute position.
3) All measurements in this study are precise without noise. Communication delay exists in this system, but there is no vehicle actuator delay.
4) Vehicle may be heterogeneous in type, with known vehicle length, location of GPS antenna on vehicle, and braking performance.
5) Actual vehicle dynamics are neglected, such as steering dynamics, traction control dynamics, etc.

III. Methodology

The proposed approach can be divided into four steps: 1) Assign each vehicle into the associate potential cluster initially; 2) Adjust the sequence of vehicles inside each potential cluster in order to maximize the throughput. In some cases, some of the vehicles need to be re-clustered due to infeasibility; 3) Identify the leader of each cluster and apply a consensus-based algorithm to cluster formation; 4) Apply the EAD algorithm to the cluster leader in consideration of the passage of entire cluster.

A. Initial Vehicle Clustering

Assume N CAVs are approaching to a signalized intersection from one approach (could be multi-lanes) with a predefined set of green windows, $\Gamma = \{G_1, G_2, \cdots, G_p, G_{p+1}, \cdots\}$, where G_p represents the pth green window with respect to some reference time point, i.e., $G_p \triangleq [g_p^s, g_p^e]$, where g_p^s and g_p^e represent the start and end of the pth green phase for the designated approach.

To initialize the clustering of vehicles, we first estimate the earliest departure time, $T_i^e(t)$ of the ith vehicle at time t, without considering the intervention from other vehicles. In this case, we assume vehicles can accelerate from the instantaneous speed to roadway speed limit, with the maximum acceleration. Therefore, $T_i^e(t)$ can be written as a function of distance to intersection, $s(t)$ and instantaneous speed, $v(t)$, given the internal and external constraints, such as the maximum acceleration a_i^{max}, and roadway speed limit v^{limit}, i.e.,

$$T_i^e(t) = f(s(t), v(t)|a_i^{max}, v^{limit}) \tag{1}$$

If $T_i^e(t) \in G_p$ and $T_j^e(t) \in G_p$, then vehicle *i* and vehicle *j* are assumed to be in the same initial cluster. However, if interactions among vehicles as well as the maximum discharge rate are considered, then it might not be feasible to let all the vehicles whose $T_i^e(t) \in G_p$ travel through the intersection within G_p. In such cases, sequence optimization (as described in Section III. *B*) can be applied in order to identify the first *n* (*n* < *N*) vehicles that can safely travel through the intersection (by keeping a certain time headway) in the same green window.

B. Intra-Cluster Sequence Optimization

To figure out the best sequence of vehicles in a cluster to achieve the maximum throughput, we formulate the problem as a job scheduling on identical parallel machines with minimum total completion time and classify it as $P||\sum C_i$, by following the scheme presented by Graham *et al*. [23]. More specifically, if we define

$$x_{i,j,k} = \begin{cases} 1, & \text{vehicle } i \text{ is the } k\text{th vehicle on lane } j \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

then,

$$\min \textstyle\sum_i T_i^a \tag{3}$$

subjects to

$$\textstyle\sum_j \sum_k x_{i,j,k} = 1 \qquad \forall i \tag{4}$$

$$\textstyle\sum_i x_{i,j,k} \leq 1 \qquad \forall j,k \tag{5}$$

$$t_{j,k} \geq t_{j,k-1} + t_{min}^h \qquad \forall j,k \tag{6}$$

$$t_{j,k} \geq \textstyle\sum_i T_i^e \cdot x_{i,j,k} \qquad \forall j,k \tag{7}$$

$$T_i^a = \textstyle\sum_j \sum_k t_{j,k} \cdot x_{i,j,k} \qquad \forall i \tag{8}$$

where $t_{j,k}$ is the departure time for the *k*th vehicle on lane *j*; and T_i^a represents the actual departure time for vehicle *i* (may be already sorted by the earliest departure time). Constraint (4) ensures that each vehicle is assigned to only one position in the sequence for some particular lane. Constraint (5) guarantees that not more than one vehicle is assigned to any position in the sequence along any lane. Constraint (6) restricts any vehicle on the *k*th position in the sequence along lane *j* from departure until a minimum headway, t_{min}^h elapses after the vehicle on the (*k*-1)th position departs from the same lane. Constraint (7) prevents any vehicle on the *k*th position in the sequence along lane *j* from departure earlier than its earliest departure time. Constraint (8) defines the actual departure time for vehicle i, T_i^a.

According to [24], the problem above can be solved in an efficient way, i.e., in O($nlogn$) time, where $n = N \times J$ (*N* is the number of vehicles in the cluster and *J* is the number of lanes in the approach), by using the *shortest processing time* (SPT) rule.

Without loss of generality, if we further define

$$T_1^a \geq g_p^s \tag{9}$$

then we may identify the last vehicle (e.g., vehicle *l*) that can travel through the intersection within the *p*th green phase by solving the aforementioned sequence optimization problem, where

$$T_l^a \leq g_p^e \text{ but } T_{l+1}^a > g_p^e \tag{10}$$

Therefore, we can finalize the vehicle cluster and its intra-cluster sequence based on the initialization in Section III. *A*.

C. Cluster Formation Control

Once the intra-cluster sequence of the cluster is determined, the vehicle with the smallest $T_i^e(t)$ in a cluster is selected as the cluster leader, and vehicles ranked first on different lanes are selected as platoon leaders. When vehicles' desired intra-cluster sequences are on different lanes from the ones they are originally on, they will firstly conduct lane change maneuvers to get to the desired lanes. Then they will adjust their speeds and longitudinal positions to form clusters based on the proposed longitudinal control protocol.

In this work, since actual vehicle dynamics are neglected, and the main influence factor of fuel consumption and pollutant emissions is longitudinal speed trajectories, the specific lateral control protocol is ignored. Vehicles are assumed to be capable of changing lanes by a predefined lateral control protocol. It needs to be noted that while vehicle i is conducting a lane change maneuver, it maintains a constant speed on the longitudinal direction, i.e., $\dot{x}_i(t) = 0$.

After the potential lane change maneuver of vehicle i is completed, the cluster longitudinal control protocol is applied to vehicle i to reach its desired intra-cluster sequence. Towards this end, if vehicle i is a follower in a platoon, then it adjusts its longitudinal speed and relative longitudinal position with respect to its predecessor. Likewise, if vehicle i is a platoon leader, then it adjusts its longitudinal speed and relative longitudinal position with respect to the cluster leader. Based on the distributed consensus algorithm [25 - 26], the longitudinal control algorithm for the cluster can be proposed as

$$\begin{aligned} \ddot{x}_i(t) = &-a_{ij}[x_i(t) - x_j\left(t - \tau_{ij}(t)\right) + l_{if} + l_{jr} \\ &+\dot{x}_j\left(t - \tau_{ij}(t)\right)\left(t_{ij}^g + \tau_{ij}(t)\right)b_i] \\ &- \gamma a_{ij}\left[\dot{x}_i(t) - \dot{x}_j\left(t - \tau_{ij}(t)\right)\right], i,j \in V \end{aligned} \tag{11}$$

where $\ddot{x}_i(t)$ is the longitudinal acceleration of vehicle i at time t; a_{ij} is the (i,j)th entry of the adjacency matrix; $x_i(t)$ is the longitudinal position of the GPS antenna on vehicle i at time t; $\tau_{ij}(t)$ is the time-varying communication delay when information is transmitted from vehicle *j* to vehicle *i* at time t; l_{if} is the length between the GPS antenna to the front bumper of vehicle i; l_{jr} is the length between the GPS antenna to the rear bumper of vehicle j; t_{ij}^g is the desired inter-vehicle time gap between vehicle i and vehicle j, and therefore time headway $t_{ij}^{h} = t_{ij}^{g} + \frac{l_{if}+l_{jr}}{\dot{x}_j\left(t-\tau_{ij}(t)\right)}$; b_i is the braking factor of vehicle i; γ is the tuning parameter; $\dot{x}_i(t)$ is the longitudinal speed of vehicle i at time t.

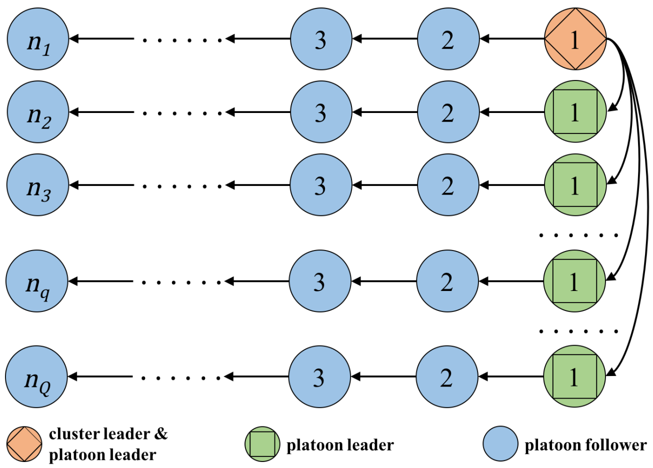


Fig. 1. Information flow topology.

The information flow topology of this cluster network can be illustrated as Fig. 1, which shows that the number of platoons and the number of vehicles in one platoon are both not constrained by the topology. In the cluster network, the cluster leader also works as a platoon leader. It not only needs to send information to the other platoon leaders as a cluster leader, but also sends information to its platoon follower as a platoon leader. Eq. (11) is applied to all vehicles in the cluster except for the cluster leader, since the cluster leader does not have a predecessor to follow. For each platoon follower, it adjusts its longitudinal speed and relative longitudinal position with respect to its predecessor by Eq. (11). For each platoon leader (cluster leader excluded), it adjusts its longitudinal speed and relative longitudinal position with respect to the cluster leader, which works as a "predecessor" for all these platoon leaders. Since each platoon leader is on a different lane from the one the cluster leader is on, the relative longitudinal position between a platoon leader and the cluster leader might be zero (but not necessarily), i.e., they are driven parallel to each other on adjacent lanes.

D. Cooperative Eco-Approach and Departure

This step happens simultaneously with step *C*, which means that as the cluster longitudinal control protocol starts to work, where each vehicle already finishes lane change maneuver if needed, the cluster leader also starts to conduct EAD maneuver towards the intersection. Upon receiving the SPaT information from the intersection, the EAD algorithm is applied to the cluster leader by analyzing different parameters (e.g., current vehicle speed, current distance to intersection, speed limit, etc.), allowing the cluster leader to approach and depart from the intersection with an optimized speed profile that minimizes energy consumption and pollutant emissions. Then, platoon leaders can follow the dynamics of the cluster leader, and the other vehicles in different platoons of the cluster can follow the dynamics of their preceding vehicles, both by V2V communication, to conduct EAD maneuvers towards the intersection. The details of the EAD algorithm can be referred to [27].

IV. Preliminary Evaluation and Results

MATLAB/Simulink is used to conduct numerical simulation of the proposed Coop-EAD system, and the U.S. Environmental Protection Agency's MOtor Vehicle Emission Simulator (MOVES) is adopted to perform analysis on the environmental impacts of the proposed system [28 – 29]. The results are also compared to the Ego-EAD system along urban signalized arterials.

The general parameters of this simulation are set in TABLE I. To get a more explicit result, we assume all vehicles in this simulation to be identical, i.e., they have the same vehicle length, GPS antenna location on the vehicle, and braking factor.

The starting time of this simulation is 0 s, and the order of the signal phase is set to be red-green-yellow-red-green-yellow. These 16 vehicles are distributed on these two lanes (*a* and *b*) with different initial speeds and initial distances to the intersection, as listed in TABLE II.

For the Ego-EAD system, based on the desired time headway and the signal phase and timing information, these 16 vehicles can be assigned into two clusters stated in TABLE III. Furthermore, for the Coop-EAD system, by applying the proposed methodologies in Section III. *A* and *B*, vehicles can be assigned into two clusters with adjusted sequences inside each cluster, which is demonstrated in TABLE IV.

Then we can apply the Ego-EAD algorithm to vehicles in the Ego-EAD system, and apply the proposed methodologies in Section III. C and D to vehicles in the Coop-EAD system, respectively. For the sake of brevity, in this simulation we only consider the time and energy consumed by vehicles to control longitudinal positions, without considering the effect of lateral control. The trajectories of all vehicles on lane a and lane b of both systems are illustrated in Fig. 2 and Fig. 3.

As shown in Fig. 2 and Fig. 3, in the Ego-EAD system, only 5 vehicles on lane a and 5 vehicles on lane b can travel through the intersection during the first green window, respectively. However, in the Coop-EAD system, all vehicles but vehicle 16 on lane a and all vehicles on lane b travels through the intersection during the first green window, respectively. Specifically, vehicle 16 on lane a cannot catch up with the cluster due to the roadway speed limit, i.e., even if it travels with the speed v^{limit}, it cannot shorten the time headway to 1 s with its preceding vehicle. Compared to the Ego-EAD system, the results show a 50% increase on traffic throughput of the Coop-EAD system. After the MOVES model has been adopted to analyze the environmental impacts of these two systems, a comparison result of the average of energy consumption and pollutant emissions per vehicle per trip are shown in TABLE V.

TABLE I. VALUES OF SIMULATION PARAMETERS

Parameter	*Value*
Number of Cars (N)	16
Number of Lanes (J)	2
Simulation Time Step	0.1 s
Communication Delay (τ_{ij})	60 ms
Roadway Speed Limit (v^{limit})	17.88 m/s
Maximum Acceleration (a_i^{max})	3.5 m/s^2
GPS Antenna to Front Bumper (l_{if})	3 m
GPS Antenna to Rear Bumper (l_{jr})	2 m
Braking Factor (b_i)	1
Desired Time Headway (t_{ij}^h) for Ego-EAD	2 s
Desired Time Headway (t_{ij}^h) for Coop-EAD	1 s
Red Window (not allowed to travel through)	27 s
Green Window (allowed to travel through)	8 s
Yellow Window (not allowed to travel through)	2 s

TABLE II. VALUES OF VEHICLE PARAMETERS

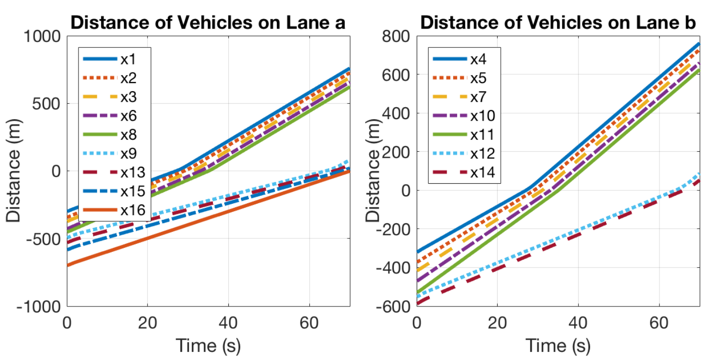
Vehicle Index	*Lane/Sequence Index*	*Initial Speed*	*Initial Distance to Intersection*
1	*a*/1	13.41 m/s^2	300 m
2	*a*/2	14.32 m/s^2	344 m
3	*a*/3	14.42 m/s^2	374 m
4	*b*/1	14.10 m/s^2	321 m
5	*b*/2	12.39 m/s^2	372 m
6	*a*/4	13.09 m/s^2	428 m
7	*b*/3	13.12 m/s^2	417 m
8	*a*/5	12.44 m/s^2	452 m
9	*a*/6	12.77 m/s^2	494 m
10	*b*/4	13.88 m/s^2	470 m
11	*b*/5	13.29 m/s^2	529 m
12	*b*/6	12.67 m/s^2	552 m
13	*a*/7	12.64 m/s^2	530 m
14	*b*/7	13.08 m/s^2	588 m
15	*a*/8	13.22 m/s^2	584 m
16	*a*/9	13.30 m/s^2	700 m

TABLE III. EGO-EAD VEHICLE CLUSTERS AND SEQUENCES

Sequence	*Lane a*	*Lane b*	*Cluster*
1	Vehicle 1	Vehicle 4	Cluster 1: Travel through the intersection in the first green window (27 s – 35 s)
2	Vehicle 2	Vehicle 5	
3	Vehicle 3	Vehicle 7	
4	Vehicle 6	Vehicle 10	
5	Vehicle 8	Vehicle 11	
6	Vehicle 9	Vehicle 12	Cluster 2: Travel through the intersection in the second green window (64 s – 72 s)
7	Vehicle 13	Vehicle 14	
8	Vehicle 15		
9	Vehicle 16		

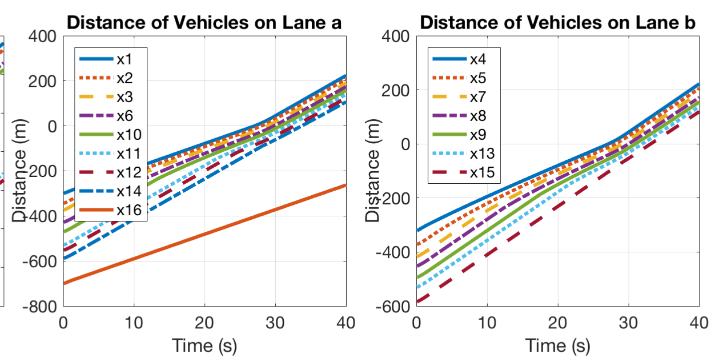
TABLE IV. COOP-EAD VEHICLE CLUSTERS AND SEQUENCES

Sequence	*Lane a*	*Lane b*	*Cluster*
1	Vehicle 1	Vehicle 4	Cluster 1: Travel through the intersection in the first green window (27 s – 35 s)
2	Vehicle 2	Vehicle 5	
3	Vehicle 3	Vehicle 7	
4	Vehicle 6	Vehicle 8	
5	Vehicle 10	Vehicle 9	
6	Vehicle 11	Vehicle 13	
7	Vehicle 12	Vehicle 15	
8	Vehicle 14		
9	Vehicle 16		Cluster 2: Travel through the intersection in the second green window (64 s – 72 s)



(a) (b)

Fig. 2. Vehicle trajectories of Ego-EAD.



(a) (b)

Fig. 3. Vehicle trajectories of Coop-EAD.

TABLE V. COMPARISON OF ENERGY CONSUMPTION AND POLLUTANT EMISSIONS OF EGO-EAD AND COOP-EAD

	HC (g)	*CO (g)*	*NO_X (g)*	*CO_2 (g)*	*PM2.5 (g)*	*Energy (KJ)*
Ego-EAD	0.041	1.161	0.144	159.852	0.011	2222.938
Coop-EAD	0.037	1.398	0.141	142.253	0.009	1978.150
Reduction%	10.23	13.25	2.29	11.01	19.91	11.01

V. Conclusions and Future Work

In this study, we have proposed a cluster-wise Coop-EAD system, aiming to increase traffic throughput, and further reduce energy consumption and pollutant emissions, when compared to the existing Ego-EAD system. A set of methodologies have been developed for different stages of the system, including initial vehicle clustering, intra-cluster sequence optimization, cluster formation control, and cooperative eco-approach and departure. A comprehensive simulation study has been conducted by using MATLAB/Simulink and MOVES, showing the proposed Coop-EAD system can achieve not only 50% increase on traffic throughput, but also 11% reduction on energy consumption, and up to 20% reduction on pollutant emissions, respectively, when compared to the Ego-EAD.

Since this study only focused on the system-level of CAV, where the actual vehicle dynamics have been neglected, the development of the physical model of CAV might be one extension of this study. Furthermore, it could be expected that many realistic issues might occur during the future field implementation, which have not been addressed in this study yet. Specifically, how to deal with a traffic system when the CAV penetration rate is not 100% might lead to another research direction.

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