UCR College of Engineering- Center for Environmental Research & Technology

Developing a Distributed Cooperative Eco-Approach and Departure System at Signalized Intersections Using V2X Communication

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Introduction

Recently, 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. Most existing work have studied the EAD application from an egoistic perspective (Ego-EAD), without considering the effect on traffic flow throughput. However, relatively limited research aims to benefit not only one vehicle but the whole system.

In this study, we develop a cluster-wise cooperative EAD (Coop-EAD) system to further reduce energy consumption while increasing traffic flow throughput, on top of the existing Ego-EAD system. Instead of considering CAVs traveling through signalized intersections one at a time, we strategically coordinate CAVs' maneuvers to form clusters by the proposed methodologies of initial vehicle clustering, intra-cluster sequence optimization, and cluster formation control. Then the EAD algorithm is applied to the cluster leader, and CAVs in the cluster can conduct EAD maneuvers by following the dynamics of the cluster leader.

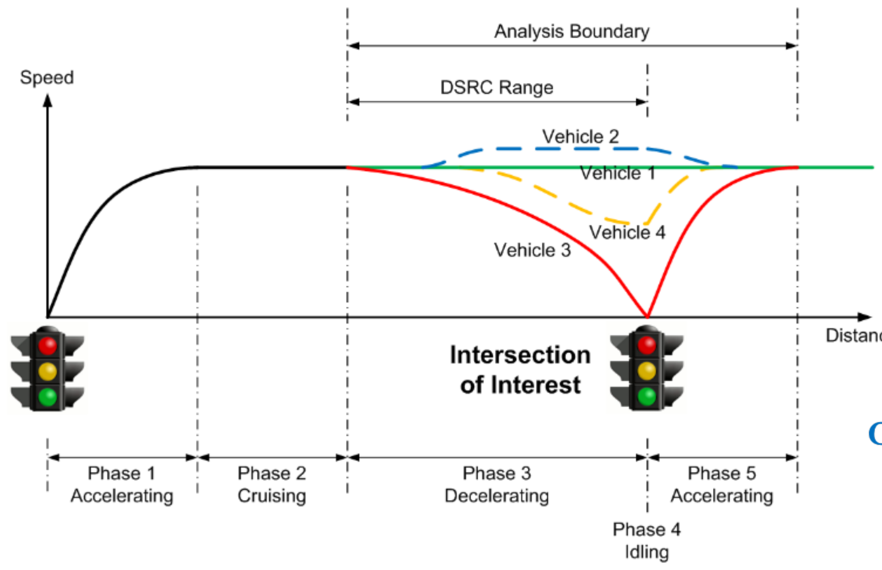

Figure 1. Different Vehicle Trajectories Approaching an Intersection

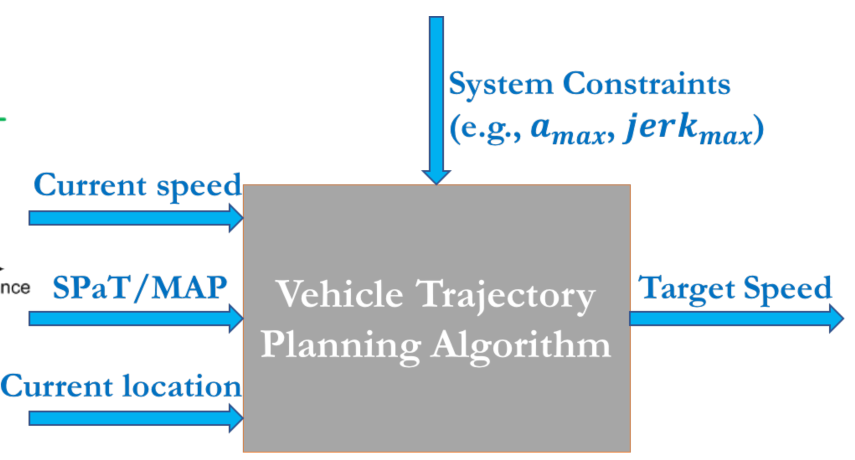

Figure 2. Vehicle Trajectory Planning Algorithm of EAD

Methodology

- **Initial Vehicle Clustering**
  - ✓ Assign each vehicle in the associate potential cluster
- **Intra-Cluster Sequence Optimization**
  - ✓ Adjust the sequence of vehicles inside each potential cluster to maximize the traffic flow throughput
- **Cluster Formation Control**
  - ✓ Identify the leader of each cluster and apply the lateral and longitudinal control protocol to cluster formation
- **Cooperative Eco-Approach and Departure**
  - ✓ Apply the EAD protocol to the cluster leader to allow the whole cluster pass the intersection in an energy-efficient manner

Initial Vehicle Clustering

- 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., $G_p \triangleq [g_p^s, g_p^e]$.
- Estimate the earliest departure time of the ith vehicle at time t:

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

where $s(t)$ is the distance to intersection, $v(t)$ is the instantaneous speed, a_i^{max} is the maximum acceleration, and v^{limit} is the roadway speed limit.

- 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.
- If N vehicles whose $T_{(i)}^e(t) \in G_p$ cannot travel through the intersection within G_p, then intra-cluster sequence optimization can be applied to identify the first n ($n < N$) vehicles to travel through by keeping certain time headways

Intra-Cluster Sequence Optimization

Define

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

then,

$$\min \textstyle\sum_i T_i^a \quad (3)$$

subjects to

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

$$\textstyle\sum_i x_{i,j,k} \le 1 \qquad \forall j,k \quad (5)$$

$$t_{j,k} \ge t_{j,k-1} + t_{min}^h \qquad \forall j,k \quad (6)$$

$$t_{j,k} \ge \textstyle\sum_i T_i^e \cdot x_{i,j,k} \qquad \forall j,k \quad (7)$$

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

where $t_{j,k}$ is the departure time for the kth vehicle on lane j, T_i^a is the actual departure time for vehicle i, and t_{min}^h is the minimum headway.

The problem above can be solved in $O(n \log n)$ 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

$$T_1^a \ge g_p^s \quad (9)$$

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

$$T_l^a \le g_p^e \text{ but } T_{l+1}^a > g_p^e \quad (10)$$

Cluster Formation Control

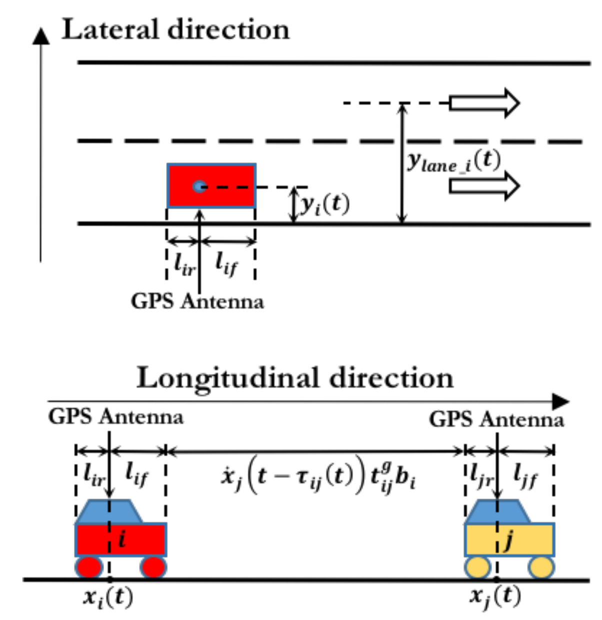

Figure 3. Illustration of Variables

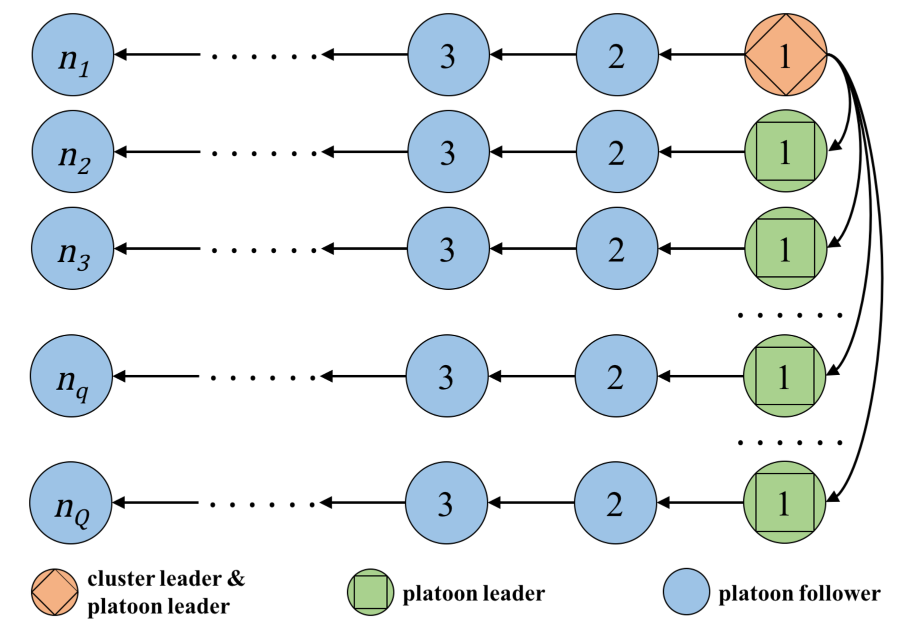

Figure 4. Information Flow Topology

1) Lateral Control Protocol

$$\dot{y}_i(t) = -\lambda(y_i(t) - y_{lane\_i}(t)), i \in V \quad (11)$$

2) Longitudinal Control Protocol

$$\ddot{x}_i(t) = -a_{ij}[x_i(t) - x_j\left(t - \tau_{ij}(t)\right) + l_{if} + l_{jr} + \dot{x}_j\left(t - \tau_{ij}(t)\right)\left(t_{ij}^g + \tau_{ij}(t)\right) b_i] - \gamma a_{ij}\left[\dot{x}_i(t) - \dot{x}_j\left(t - \tau_{ij}(t)\right)\right], i,j \in V \quad (12)$$

Table 1. List of Variables

$x_i(t)$	**Longitudinal position of vehicle i at time t**	V	**Finite nonempty node set**
$y_i(t)$	**Lateral position of vehicle i at time t**	t_{ij}^g	**Inter-vehicle time gap**
$\dot{x}_i(t)$	**Longitudinal speed of vehicle i at time t**	l_{if}	**Length between GPS antenna to front bumper**
$\dot{y}_i(t)$	**Lateral speed of vehicle i at time t**	l_{jr}	**Length between GPS antenna to rear bumper**
$\ddot{x}_i(t)$	**Longitudinal acceleration of vehicle i at time t**	b_i	**Braking factor of vehicle i**
$y_{lane\_i}(t)$	**Lateral position of vehicle i's desired lane at time t**	λ	**Tuning parameter**
$\tau_{ij}(t)$	**Communication delay at time t**	γ	**Tuning parameter**

Simulation Study

- **MATLAB Simulink is used to conduct numerical simulation**
- **USEPA's MOtor Vehicle Emission Simulator (MOVES) is adopted to perform analysis on the environmental impacts**
- **The proposed Coop-EAD system is compared with the existing Ego-EAD system**

Table 2. Values of Simulation Parameters

Parameter	*Value*
Number of Cars (N)	16
Number of Lanes (J)	2
Travel Downstream Distance to Intersection	100 m
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/s²
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 3. Values of Vehicle Parameters

Vehicle Index	*Lane/Sequence Index*	*Initial Speed*	*Initial Distance to Intersection*
1	a/1	13.41 m/s²	300 m
2	a/2	14.32 m/s²	344 m
3	a/3	14.42 m/s²	374 m
4	b/1	14.10 m/s²	321 m
5	b/2	12.39 m/s²	372 m
6	a/4	13.09 m/s²	428 m
7	b/3	13.12 m/s²	417 m
8	a/5	12.44 m/s²	452 m
9	a/6	12.77 m/s²	494 m
10	b/4	13.88 m/s²	470 m
11	b/5	13.29 m/s²	529 m
12	b/6	12.67 m/s²	552 m
13	a/7	12.64 m/s²	530 m
14	b/7	13.08 m/s²	588 m
15	a/8	13.22 m/s²	584 m
16	a/9	13.30 m/s²	700 m

Table 3. 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		

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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)

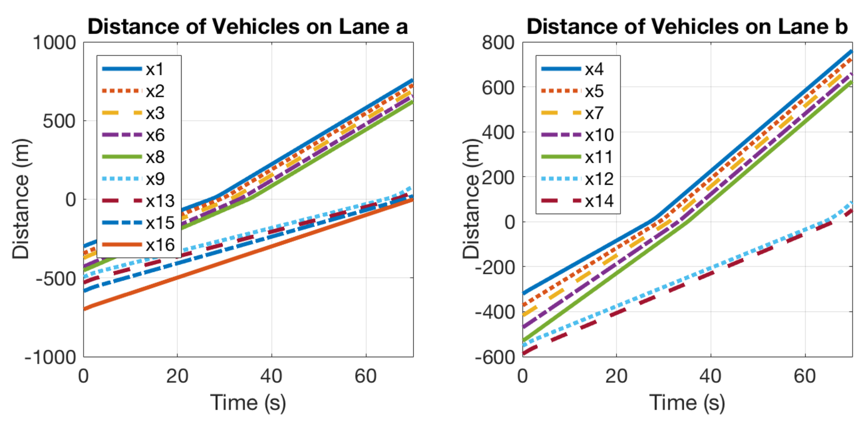

Figure 5. Vehicle Trajectories of Ego-EAD

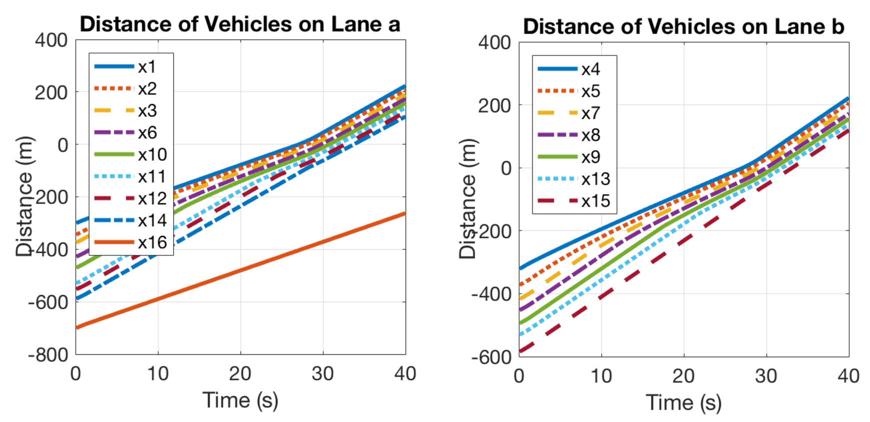

Figure 6. Vehicle Trajectories of Coop-EAD

Table 5. Comparison Results of Ego-EAD and Coop-EAD

	HC (g/s)	*CO (g/s)*	*NO_X (g/s)*	*CO_2 (g/s)*	*PM2.5 (g/s)*	*Energy (KJ/s)*	*Average Travel Time (s)*
Ego-EAD	0.041	1.161	0.144	159.852	0.011	2222.938	51
Coop-EAD	0.037	1.398	0.141	142.253	0.009	1978.150	39
Reduction%	10.23	13.25	2.29	11.01	19.91	11.01	23.62

Conclusions and Future Work

- **A set of methodologies have been developed for different stages of the Coop-EAD system**
- **A comprehensive simulation has been conducted to show the proposed system can achieve 50% increase on traffic flow throughput, 11% reduction on energy consumption, and up to 20% reduction on pollutant emissions, respectively**
- **Further research should consider the actual vehicle dynamics model (feature of nonlinearity), and take into account the penetration rate of CAVs in the system**