Intra-Platoon Vehicle Sequence Optimization for Eco-Cooperative Adaptive Cruise Control

Peng Hao, *Member*, *IEEE*, Ziran Wang, *Student Member*, *IEEE*, Guoyuan Wu, *Senior Member*, *IEEE*, Kanok Boriboonsomsin, *Member*, *IEEE*, and Matthew Barth, *Fellow*, *IEEE*

Abstract— **The Cooperative Adaptive Cruise Control (CACC) system has been regarded as an effective solution to increasing the traffic flow efficiency. Today, more and more focus has been concentrated on the environmental sustainability of a CACC system, but very few of them have explored the system-wide strategies to optimize the global environmental sustainability performance of a CACC system, e.g. how to determine the most energy-efficient sequence of vehicles during the lifecycle of a platoon. In this research, we synthetically analyze the platoon-wide impact of the disturbances when vehicles join and leave the Eco-CACC system. A bi-level model is developed to investigate the optimal intra-platoon vehicle sequence (i.e. position in the platoon) when each vehicle joins the platoon to minimize the total of all acceleration, deceleration and cruising maneuvers of the entire platoon. In the lower level, we formulate sub-problems for platoon joining and splitting to figure out minimal energy consumption for gap closing and opening. In the upper level, the set of vehicles' positions when joining the platoon is optimized to determine the most energy-efficient vehicle sequence during the lifecycle of a platoon. Simulation studies of different scenarios are conducted using MATLAB/Simulink. As shown in the numerical results, the optimal solution leads to 51-77% saving on incremental energy consumed from gap opening and closing.**

Index Terms — Sequence Optimization; Cooperative Adaptive Cruise Control; Eco-Cooperative Adaptive Cruise Control (Eco-CACC); Energy consumption; Tabu search

I. Introduction and Motivation

As a promising connected and automated vehicle (CAV) technology, the Cooperative Adaptive Cruise Control (CACC) which leverages the Vehicle-to-Vehicle (V2V) and/or even Infrastructure-to-Vehicle (I2V) communications can significantly improve the system efficiency, by well coordinating the intra-platoon vehicles' longitudinal maneuvers to achieve much shorter headway [1 – 3]. To date, the majority of relevant research has been focused on the development and deployment of protocols such as platoon formation, gap adjustment, gap regulation, and platoon dissolution [4 – 9], and related characteristics such as string stability [10,11] and driver acceptance [12], with less concentration on the energy efficiency in the system design. Alam developed several control strategies for truck platooning and conducted experimental evaluation to explore the fuel-saving potentials [13]. Yang et al. designed a CACC system that receives signal phasing and timing data from downstream signalized intersections and design fuel-optimum vehicle trajectories for the platoon [14].

Very recently, the authors proposed a framework for the development of eco-friendly CACC (Eco-CACC) systems [15], which aims at improving the platoon-wide environmental sustainability. A full spectrum of energy efficient CACC maneuvers was explored and the associated protocols were developed, including gap closing and opening, platoon cruising speed selection, and platoon joining and splitting. Besides, the intra-platoon vehicle sequence (i.e. position in the platoon) was briefly discussed over two heuristic protocols, i.e., "entry-time" based sequencing and "destination" based sequencing. The first protocol determines the order of each vehicle in the platoon based on the time instant when it joins in. The sooner the vehicle joins the platoon, the closer it is to the leading position. The second protocol relies on the distance to destination of each vehicle. The longer the vehicle's distance to destination is, the closer it is to the leading position in the platoon. However, no further effort has been made to obtain an optimal intra-platoon vehicle sequencing protocol in order to minimize the resultant energy consumption and pollutant emissions during the lifecycle of a platoon.

As the follow-up effort, therefore, the authors propose in this study to develop a protocol for intra-platoon vehicle sequence optimization (VSO). A bi-level integer programing model is developed to investigate the most energy-efficient intra-platoon position when each vehicle joins the platoon to minimize the total of all acceleration, deceleration and cruising maneuvers from gap opening and closing. The rest of this paper is organized as follows: Section II details the problem formulation of VSO and the methodology to solve it, along with a discussion on the extension of VSO model, Section III presents the setup and results of numerical experiments in Matlab/Simulink [16] for validation. The last section concludes this paper with discussion of future direction.

Peng Hao is with the Center for Environmental Research and Technology, University of California at Riverside, Riverside, CA 92507, USA (e-mail: haop@cert.ucr.edu).

Ziran Wang is with the Center for Environmental Research and Technology, University of California at Riverside, Riverside, CA 92507, USA (e-mail: zwang050@ucr.edu).

Guoyuan Wu is with the Center for Environmental Research and Technology, University of California at Riverside, Riverside, CA 92507, USA (e-mail: gywu@cert.ucr.edu).

Kanok Boriboonsomsin is with the Center for Environmental Research and Technology, University of California at Riverside, Riverside, CA 92507, USA (e-mail: kanok@cert.ucr.edu).

Matthew Barth is with the Center for Environmental Research and Technology, University of California at Riverside, Riverside, CA 92507, USA (e-mail: barth@ece.ucr.edu).

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II. METHODOLOGY

A. Vehicle Sequence Optimization

In this paper we develop a model to synthetically consider the impact of the disturbances when each single vehicle joins and splits from the platoon and optimize the energy consumption. We assume the time order of the event when each vehicle joins or leaves the platoon is pre-determined before the platoon is formulated, i.e. all vehicles shares their origins and destinations information before they join the platoon. For an Eco-CACC system associated with M vehicles, there are $2M$ platoon joining and splitting events in total. For vehicle i, the event IDs of the joining event and leaving event are defined as A_i and B_i respectively ($A_i<B_i$). Accordingly, for event k, the corresponding vehicle ID is defined as V_k and the event type is defined as an integer variable S_k, where S_k is 1 for joining event and -1 for leaving event. Then N_k, the number of vehicles in the platoon (or platoon length) right after event k is calculated as

$$N_k = \sum_{l=1}^{k} S_l \tag{1}$$

As the time order of joining and leaving events are pre-determined, the variables stated above, i.e. A_i, B_i, V_k, S_k, N_k, can be considered as constants for a certain Eco-CACC system.

In the proposed optimization problem, we aim to find the optimal sequence (i.e. position in the platoon) when each vehicle joins the platoon to minimize the total energy consumption of all acceleration and deceleration maneuvers of the entire platoon. For vehicle i, we define the position when joining and leaving the platoon as x_i ($1 \le x_i \le N_{A_i}$) and y_i ($1 \le y_i \le N_{B_i} + 1$) respectively. Note that N_{B_i} is the platoon length right after event B_i and y_i is the vehicle position before event B_i, so y_i may be equal to $N_{B_i} + 1$ if the i[th] vehicle is at the end of the platoon. For the joining maneuver, a gap is created to allow vehicle i to join a platoon of size N_{Ai} at position x_i. This can be accomplished either by following vehicles after a deceleration-cruising-acceleration gap opening process, or by leading vehicles after an acceleration-cruising-deceleration process. Corresponding to the most energy-efficient way to open a gap, the minimum incremental energy consumption for vehicle i to join the platoon at position x_i is defined as $F(x_i)$. Similarly, the minimum incremental energy consumption for vehicle i at position y_i to leave a platoon is defined as $G(y_i)$. The objective of the optimal sequence problem is then formulated as follows:

$$\min_{\{x_i\},\{y_i\}} z = \sum_{i=1}^{M} F(x_i) + \sum_{i=1}^{M} G(y_i) \tag{2}$$

In (2), $\{y_i\}$ can be considered as a function of $\{x_i\}$. To prove that, we define the position of vehicle i right after event k ($A_i \le k < B_i$) as $R_i(k)$, which is calculated and updated iteratively as follows:

1. Right after event A_i, $R_i(A_i)$ is initialized as x_i,

2.1. Right after event k ($A_i< k< B_i$), if S_k=1, vehicle V_k joins the platoon at position x_{V_k}.

$$R_i(k) = \begin{cases} R_i(k-1)+1 & if\, x_{V_k} \le R_i(k-1) \\ R_i(k-1) & otherwise \end{cases} \tag{3}$$

2.2. Right after event k ($A_i< k< B_i$), if S_k =-1, vehicle V_k at position y_{V_k} leaves the platoon.

$$R_i(k) = \begin{cases} R_i(k-1)-1 & if\, y_{V_k} \le R_i(k-1) \\ R_i(k-1) & otherwise \end{cases} \tag{4}$$

3. Right after event B_i, vehicle i leaves the platoon. The final position right before splitting is $y_i = R_i(B_i-1)$. Therefore y_i is determined by x_i after above iterations.

Therefore y_i, the position of vehicle i when leaving is formulated as follows

$$y_i = x_i + \sum_{k=A_i}^{B_i-1} \xi_k^i S_k, \tag{5}$$

where ξ_k is a binary parameter that describes whether the event vehicle V_k is in front of vehicle I in event k.

Based on (2) and (5), we can formulate the complete form of the optimal sequence problem:

$$\min_{\{x_i\},\{y_i\}} z = \sum_{i=1}^{M} F(x_i) + \sum_{i=1}^{M} G(y_i) \tag{6.1}$$

$$\text{s.t. } 1 \le x_i \le N_{A_i}, i = 1,2,3 \dots M \tag{6.2}$$

$$1 \le y_i \le N_{B_i} + 1,\ i = 1,2,3 \dots M \tag{6.3}$$

$$y_i = x_i + \sum_{k=A_i}^{B_i-1} \xi_k^i S_k\, , i = 1,2,3 \dots M \tag{6.4}$$

The optimal sequence problem (6) is a bi-level optimization problem. Variable sets $\{x_i\}$ and $\{y_i\}$ are first applied to the sub-problems for platoon joining and splitting to figure out minimal incremental gap opening/closing energy consumption $F(x_i)$ and $G(y_i)$. Then we calculate the objective values according to each variable set pair $\{x_i\}$ and $\{y_i\}$ and search for the optimal solution that to minimize the total energy consumption of all acceleration and deceleration maneuvers of the entire Eco-CACC system.

B. Gap Closing and Opening Strategies

The optimization goal of the integer programing problem (6) is to minimize the incremental energy consumption of all gap closing and opening maneuvers due to the joining and leaving of vehicles. Thus we need to identify $F(x_i)$ and $G(y_i)$ in (6), the minimum incremental energy consumption per gap opening/closing.

There are two approaches to create a gap. If vehicle i plans to join the platoon at position x_i, following vehicles (from the x_i^{th} vehicle to the NAi^{th} vehicle in the existing platoon) can open a gap after a deceleration-cruising-acceleration process. The incremental energy consumption during this process is computed as $\sum_{j=x_i}^{N_{A_i}} (E_j^D - E_j^C)$, where E_j^D is the energy consumption for vehicle j to make a designed deceleration-cruising-acceleration trajectory and E_j^C is the energy consumption for vehicle j if it keeps the current speed during the same time period. Symmetrically, leading vehicles (from the 1[st] vehicle to $(x_i-1)^{\text{th}}$ vehicle in the existing platoon) may also make an acceleration-cruising-deceleration maneuvers to create the gap. The incremental energy consumption during this process is $\sum_{j=1}^{x_i-1} (E_j^A - E_j^C)$, where

E_j^A is the energy consumption for vehicle j to make a designed acceleration-cruising-deceleration trajectory.

The optimal strategy to open a gap is then the one with less incremental energy consumption, so the minimum incremental energy consumption for vehicle i to join the platoon at position x_i is

$$F(x_i) = \min\left\{\sum_{j=x_i}^{N_{A_i}}(E_j^D - E_j^C), \sum_{j=1}^{x_i-1}(E_j^A - E_j^C)\right\} \quad (7)$$

For gap closing process, after vehicle i at position y_i leaves the platoon, there are also two approaches - an acceleration-cruising-deceleration gap closing process acted by following vehicles, or a deceleration-cruising-acceleration process acted by leading vehicles. Then the incremental energy consumption for each approach is $\sum_{j=y_i}^{N_{B_i}-1}(E_j^A - E_j^C)$ and $\sum_{j=1}^{y_i-1}(E_j^D - E_j^C)$, respectively. The minimum incremental energy consumption for vehicle i at position y_i leave the platoon is

$$G(y_i) = \min\left\{\sum_{j=y_i}^{N_{B_i}-1}(E_j^A - E_j^C), \sum_{j=1}^{y_i-1}(E_j^D - E_j^C)\right\} \quad (8)$$

In this paper, we estimate energy consumption E_j^A, E_j^D and E_j^C using MOtor Vehicle Emission Simulator (MOVES) model developed by U.S. Environmental Protection Agency [17]. In MOVES, the vehicle operating modes (OpMode) are grouped into 23 categories with vehicle-specific power (VSP) as its primary metric. As VSP is a function of speed, acceleration, mass, road grade, and vehicle-specific coefficients, the energy consumption is mainly decided by planed trajectory and type (e.g. light-duty or heavy duty) of each vehicle in the platoon. As the sequence optimization is conducted before the actual gap opening or closing maneuvers are performed, it is reasonable to assume each vehicle follows a well-calibrated standard deceleration-cruising-acceleration or acceleration-cruising-deceleration trajectory during the process. For certain vehicle type n, we use Δ_n^D to represent the incremental energy consumption for deceleration-cruising-acceleration, and Δ_n^A to represent that for acceleration-cruising-deceleration process. Then (4) and (5) could be reformulated as

$$F(x_i) = \min\left\{\sum_{j=x_i}^{N_{A_i}}\Delta_{n(j)}^D, \sum_{j=1}^{x_i-1}\Delta_{n(j)}^A\right\}, \text{and} \quad (9.1)$$

$$G(x_i) = \min\left\{\sum_{j=y_i}^{N_{B_i}-1}\Delta_{n(j)}^A), \sum_{j=1}^{y_i-1}\Delta_{n(j)}^D\right\}, \quad (9.2)$$

where $n(j)$ denotes the vehicle type of vehicle j. In particular, if all vehicles in the platoon are under the same vehicle type (say n^*), the objective function (6.1) is reduced into the following form.

$$\min_{\{x_i\},\{y_i\}} z = \sum_{i=1}^{M}(\min\{x_i\Delta_{n^*}^A, (N_{A_i} - x_i + 1)\Delta_{n^*}^D\} + \min\{y_i\Delta_{n^*}^D, (N_{B_i} - y_i)\Delta_{n^*}^A\}) \quad (10)$$

C. Solution Method

The integer programing problem (6) is difficult to be solved exactly if the size of the platoon is large. Since each vehicle have N_{A_i} candidate position when joining the platoon, it is computational expensive if all possible combinations ($\prod_{i=1}^{M} N_{A_i}$ in total) are enumerated. The complexity of the problem grows explosively as the number of vehicles increases, e.g. consider a platoon with 20 vehicles, there are $20! = 2.43 \times 10^{18}$ possible combination outcomes. To avoid enumerating all possible outcomes, the problem is solved using a global optimization algorithm called tabu search. Tabu search applies local search procedure to move from one potential solution to another enhanced solution. A memory structure named tabu list is introduced to avoid poor-scoring areas that may trap conventional local search methods. The solution procedure is briefly summarized in Fig. 1. For more theoretical discussion of the tabu search method, one can refer to [18, 19].

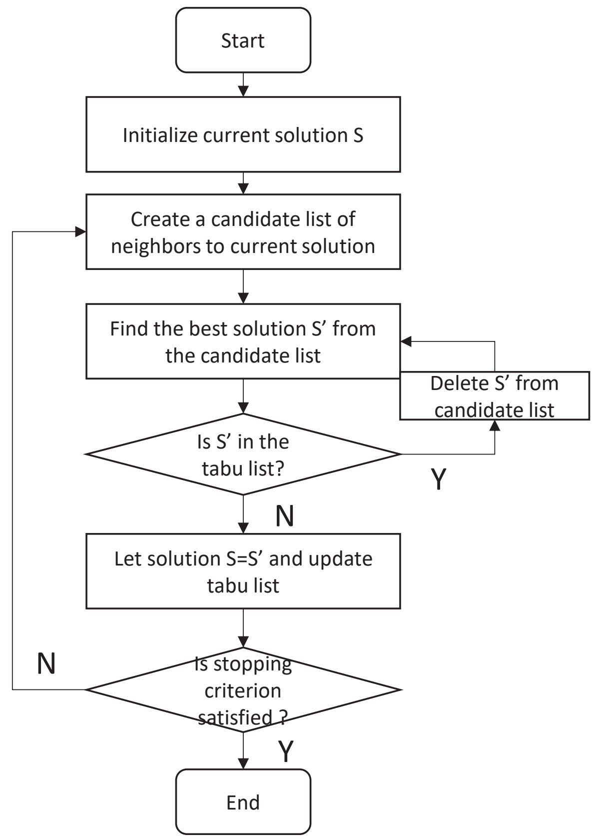

Figure 1. Flowchart of tabu search algorithm

D. Model extension

The proposed model can be extended to the scenarios that multiple vehicles would make cooperative plan to join or leave the platoon simultaneously. In this situation, in an Eco-CACC system associated with M vehicles, $2M$ events are grouped into M_c event clusters. Each cluster consists of joining/leaving events that are planned to be acted cooperatively at the same time. For the n^{th} cluster, we define the position set of all joining vehicles as $\{x_i^n\}$ and the position set of all leaving vehicles as $\{y_i^n\}$. Then a bi-level optimization problem can be formulated to estimate the optimal $\{x_i^n\}$ and $\{y_i^n\}$ at each event cluster. Similar as the basic model in (6), in the lower-level, we investigate the most energy-efficient approach to open and close multiple gaps for a certain set of $\{x_i^n\}$ and $\{y_i^n\}$ at each event cluster. For example, if two vehicles plan to join an Eco-CACC platoon at the 2nd and the 9th position respectively as shown in Fig. 2, the existing platoon have three strategies to make two gaps to accommodate the newcomers: (1) the 1st vehicle makes an acceleration-cruising-deceleration maneuver to move two gaps forward in relative to its presumed location under operation speed, and the 2nd ~ 6th vehicle in the existing platoon move one gap forward; (2) the 1st vehicle moves one gap forward and the 7th ~ 8th vehicles move one gap backward; and (3) the 7th ~ 8th vehicles move one gap backward, and the 2nd ~ 6th vehicle move one gap backward. The MOVES based energy consumption estimation method is then applied to identify the optimal strategy corresponding to certain pair of $\{x_i^n\}$ and $\{y_i^n\}$.

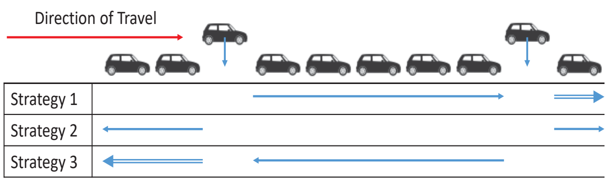

Figure 2. An example of event cluster when two vehicles join the platoon simultaneously

In the upper-level of the event cluster based optimization problem, we explore the optimal combination of M_c event clusters that minimize the incremental energy consumption from all gap opening and closing behaviors. A tabu search method can be developed to solve this problem efficiently.

Another extension to (6) is to include the incremental energy that the new vehicle consumed when catching up the platoon and join it. To achieve the designed optimal sequence, the new joining vehicle may spend additional energy cost to find the pre-determined location and merge into the platoon. In this paper, we assume the single vehicle is well coordinated and synchronized with the platoon so that it can meet the platoon at the pre-determined location from the optimal solution at beginning. However, if the relative location information is provided and the energy consumption of the new joining vehicle before merging is calibrated, a new energy consumption term can be included to the objective function (6.1) to address the energy consumption of the new vehicles when they join the platoon.

III. Numerical Experiments

A. Model Calibration

In order to calibrate the sequence optimization model, sample vehicle trajectories for gap opening and closing are required as the input of energy consumption estimation in (7) and (8). As shown in Fig. 3, we collect vehicle speed profile data from the simulated gap opening and closing maneuvers in a proposed distributed consensus algorithm based CACC system from MATLAB/Simulink simulation [4]. As discussed in Section II, the acceleration-cruising-deceleration profile (represented by solid curve) corresponds to the typical behavior of following vehicles in gap closing and that of leading vehicles in gap opening. The deceleration-cruising-acceleration profile (represented by dashed curve) corresponds to the typical behavior of leading vehicles in gap closing and following vehicles in gap opening.

Based on the sample vehicle trajectories, the second-by-second VSP are calculated using following equation,

$$VSP = v\left[a(1+\varepsilon_i) + g\phi + \frac{9.80665}{W}(A + Bv + Cv^2)\right], \quad (10)$$

where v is the velocity (m/s), a is the acceleration rate (m/s^2), g is the acceleration of gravity (m/s^2), and W is the vehicle test weight (kg). Parameters A, B, C are dynamometer road load coefficients, and ε_i, the "mass factor", is the equivalent translational mass of the rotating components (wheels, gears, shafts, etc.) of the powertrain. Based on VSP, speed, acceleration and vehicle type information, we can identify the OpMode for specific vehicle at each time step, and calculate the incremental energy consumption for both maneuvers using MOVES [17]. In the following part of the numerical experiment sections, we assume all vehicles that associate with the Eco-CACC system are under passenger truck category, i.e. Category 31, so the incremental energy consumption is 172 kJ for the acceleration-cruising-deceleration process and 373 kJ for the deceleration-cruising-acceleration process.

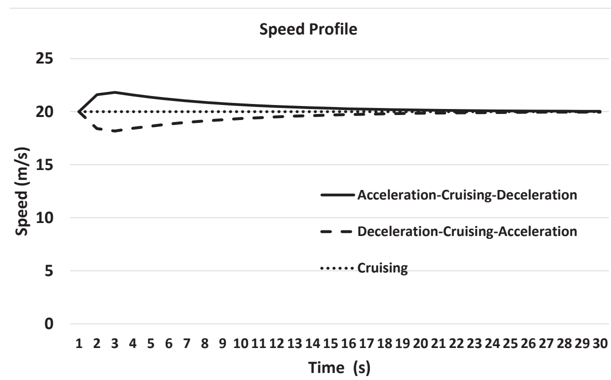

Figure 3. Sample vehicle traejctories during gap opening and closing

TABLE I. Results of Numerical Simulation

Platoon Size	Mean Incremental Energy (KJ)			Saving (%)
	To front	To back	Optimal	
8	738	748	196	73.8
9	942	965	229	76.3
10	1269	1220	339	72.2
11	1472	1488	442	70.3
12	2054	2077	716	65.5
13	2384	2362	838	64.5
14	2886	2830	1084	61.7
15	3287	3182	1314	58.7
16	3666	3779	1591	57.9
17	4432	4358	1921	55.9
18	5006	5059	2214	56.2
19	5623	5652	2786	50.7
20	6171	6322	3053	51.7

B. Validation in Numerical Simulation

We then evaluate the performance of the proposed model using numerical simulation in MATLAB. Two baseline strategies are introduced for comparison. For "To front" strategy, each new vehicle becomes the first vehicle of the platoon. For "To back" strategy, each new vehicle is attached to the end of platoon. For different sizes of platoon (i.e. number of vehicles that associates with the CACC system), we make 100 runs with random event sequences. The numerical results are summarized in Table I. As listed in the table, the incremental energy consumption from gap opening/closing are reduced significantly by implementing the optimal strategy. The percentage improvement of the optimal solution in relative to the "To back" strategy decreases from 74% to 52% when the platoon size increases from 8 to 20. That means, more than 50% of gap opening/closing related acceleration and deceleration maneuvers can be reduced by smartly organize the in-platoon vehicle sequence during the lifecycle of platoon.

B. Simulation with MATLAB/Simulink model

To further validate the proposed VSO algorithms, MATLAB/Simulink is adopted to conduct a simulation on a CACC system of 10 vehicles [16]. All vehicles in the platoon are assumed to be capable to send and receive velocity and position information among them. We further assume they adopt distributed consensus based CACC algorithm to conduct gap opening and closing maneuvers [4]. This double-integrator distributed consensus algorithm can be stated as

$$\ddot{x}_i(t) = -\left[x_i(t) - x_j\left(t - \tau_{ij}(t)\right) + c_j + \dot{x}_j\left(t - \tau_{ij}(t)\right) t_{ij}^g b_i\right] \\ -\gamma\left[\dot{x}_i(t) - \dot{x}_j\left(t - \tau_{ij}(t)\right)\right], i = 2, \ldots, n, j = i - 1 \qquad (11)$$

where the acceleration of vehicle i at time t is based on the absolute position difference and the velocity difference between itself and its preceding vehicle j. This algorithm takes into account the length c_j and braking ability b_i of different vehicles, and also the communication delay $\tau_{ij}(t)$ between two vehicles.

MATLAB/Simulink simulation is then conducted to evaluate three different join strategies: "To front", "To back", and optimal. The parameters of the simulation are listed in Table II and the vehicle speed trajectory results of the three strategies are shown in Fig. 4.

TABLE II. PARAMETERS OF MATLAB/SIMULINK SIMULATION

Parameters	Value
Number of Vehicles	10
Length of Each Vehicle	5 m
Initial Velocity of Vehicles	20 m/s
Desired Velocity of Vehicles	20 m/s
Final Inter-Vehicle Gap Between Vehicles in the Platoon	10 m

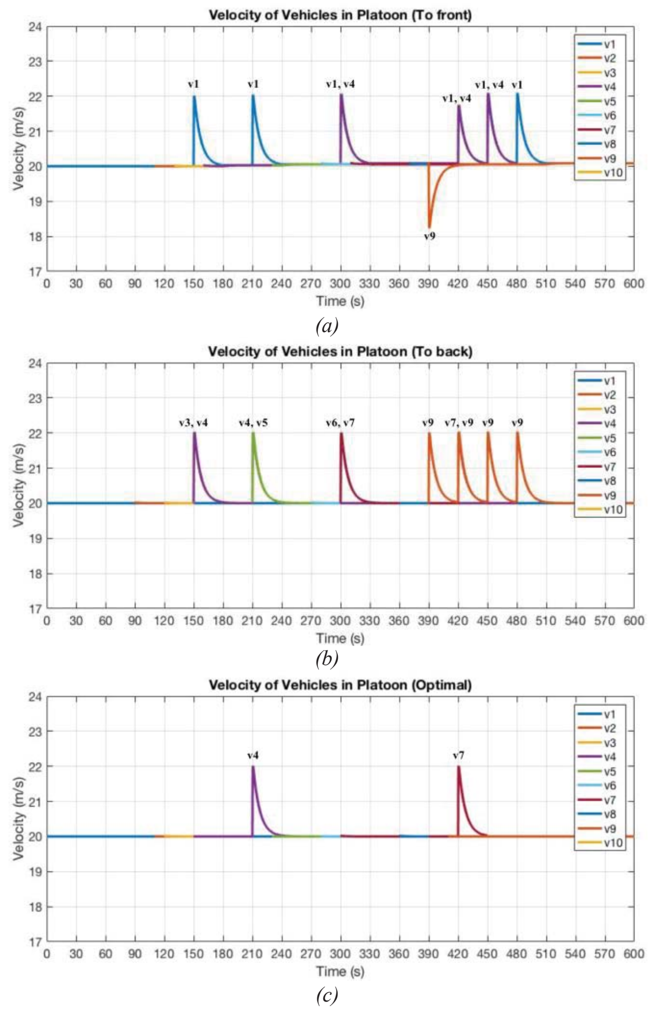

Figure 4. Vehicle traejctories under *(a)* "To front", *(b)* "To back", and *(c)* Optimal Strategies

Since we only analyze the gap opening and closing maneuvers of the platoon, we filter out the free vehicle catching-up process, which is the first 30-second trajectory of each vehicle. As can be seen from the Fig. 4(a), "To front" strategy has nine acceleration-cruising-deceleration profiles (six of them are overlapped in pairs) and one deceleration-cruising-acceleration profile, "To back" strategy also has nine acceleration-cruising-deceleration profiles (six of them are overlapped in pairs). In Fig 4(c), the optimal strategy only has two acceleration-cruising-deceleration profiles, which shows the ability of the proposed vehicle sequence optimization methodology to reach higher energy-efficiency during the lifecycle of a platoon.

We further analyze the emissions and energy consumption of three strategies, and results are shown in Table III. For the entire trips which include all CACC cruising and merging/splitting processes, the proposed optimal solution have the best performance in emissions and energy consumption, saving 1.6% energy from the "To back" strategies and 1.6%~23.8% air pollutant emissions. If we concentrate on the incremental emissions and energy consumption made from gap opening and closing, the advantage is more explicit – about 74% saving on emissions and energy consumption.

TABLE III. Results from MATLAB/Simulink Simulation

Total Emissions and Energy Consumption						
Strategy	HC (g/s)	CO (g/s)	NOx (g/s)	CO2 (g/s)	Energy (KJ/s)	PM2.5 (g/s)
Optimal	1.11	28.36	4.71	5067	70462	0.074
To front	1.32	40.09	6.17	5989	83280	0.109
To back	1.14	30.94	4.83	5149	71601	0.097
Saving(%)	3.2	8.3	2.6	1.6	1.6	23.8
Incremental Emissions and Energy Consumption						
Strategy	HC (g/s)	CO (g/s)	NOx (g/s)	CO2 (g/s)	Energy (KJ/s)	PM2.5 (g/s)
Optimal	-0.03	0.98	-0.02	28	396	0.074
To front	0.18	12.71	1.45	950	13214	0.109
To back	0.002	3.56	0.11	110	1534	0.097
Saving(%)	-	73	-	74	74	24

IV. Conclusions and Future Work

In this research, a platoon-wide vehicle sequence optimization problem is formulated to address the impact of the disturbances when a free vehicle joins and splits from the platoon in a CACC system. We construct a bi-level integer programing model to minimize the total of all acceleration, deceleration and cruising maneuvers from gap opening and closing. We formulate sub-problems for platoon joining and splitting to figure out minimal platoon-wide energy consumption for gap closing and opening, and optimize the in-platoon vehicle sequence to determine the most energy-efficient vehicle sequence during the lifecycle of a platoon. Simulation studies are conducted using MATLAB/Simulink, showing 74% saving on incremental energy consumption made from gap opening and closing.

In the future, we will extend the proposed model to an on-line robust sequence determination system in which the origin and destination information of upcoming vehicles may be inaccurate or missing. We will also conduct micro-simulation or field test to validate the basic version of VSO and its variation for multiple vehicle types and event clusters. New solution algorithms that are more reliable and computational efficient will be also explored in the future studies.

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