Gap Opening Control to Facilitate Human-Driven Vehicle Overtaking of Connected and Automated Vehicle Platoons on Two-Lane Highways

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***Abstract*—Connected and automated vehicle (CAV) platooning enhances fuel efficiency and operational performance but poses safety challenges when interacting with human-driven vehicles (HDVs) attempting to overtake on two-lane undivided highways. The close spacing within platoons limits overtaking opportunities, increasing collision risks of passing vehicles with oncoming traffic. This paper proposes a CAV platoon control strategy of gap opening for guided single HDV overtaking scenarios, which consists of algorithms that determine optimal gap location, gap opening complete time, and gap opening start time, to balance the trade-off between gap prediction accuracy, controller performance, and platoon string stability. The control strategy is evaluated with a simulation, demonstrating its capability to dynamically adapt to real-time traffic conditions and achieve the goals of control accuracy and reliability. The results highlight the feasibility of implementing the control strategy in CAV platooning systems for safe handling of interactions with HDVs in the two-lane highway overtaking scenarios.**

***Index Terms*—Connected and automated vehicle, overtaking maneuver, platoon gap control, traffic safety in mixed traffic**

I. Introduction

Connected and automated vehicle (CAV) platooning has emerged as a transformative innovation. By linking multiple vehicles electronically and maintaining a minimal gap between them through Cooperative Adaptive Cruise Control (CACC) and Vehicle-to-Vehicle (V2V) communication technologies, platooning enhances fuel savings and operational efficiency, especially when applied on heavy-duty freight trucks [1]–[8]. Despite these advantages, CAV platooning introduces new challenges, particularly regarding its safe integration into mixed traffic environments shared with human-driven vehicles (HDVs) [9]–[15]. One of the most pressing concerns is that HDVs often struggle to navigate around these closely spaced convoys. Safety risks are heightened in situations where overtaking maneuvers are necessary [10], [16]. The limited gaps within the platoon can obstruct a clear path for human drivers. These risks are amplified on two-lane undivided highways, where passing vehicles must share the same lane with opposing traffic, making overtaking maneuvers both complex and hazardous [9], [10], [17]–[19].

The safety implications of overtaking platoons on two-lane highways bring the need for adaptive strategies to accommodate HDVs. A key aspect of this challenge is to determine when and how the platoon should dynamically adjust its formation to create a sufficient gap for overtaking. Failure to provide adequate space could lead to incomplete overtaking and collisions with oncoming traffic. Conversely, if the platoon splits unnecessarily, it may compromise the efficiency benefits of platooning, undermining its primary advantage of reduced aerodynamic drag.

Guided step-by-step overtaking is a potential solution to address the safety challenges in HDVs overtaking of CAV platoons [20], [21]. In guided step-by-step overtaking, the passing vehicle overtakes part of the platoon in each step, and overtake the entire platoon with multiple steps. In each step, the passing vehicle is provided message of where in the platoon is safe to merge into to avoid collision with oncoming traffic. The message can be provided using indicator or message sign displays on platoon vehicles [17], [22], or transmitted directly onto the passing vehicle's in-vehicle driver assistance devices [23], [24].

There are two major control tasks in guided overtaking of platoons: (1) determination of a suitable gap in platoon for the passing vehicle to merge into; and (2) control the gap's follower vehicle to timely and smoothly open the gap to a length that can safely accommodate the passing vehicle. Prior studies have focused on either task but not integrating both. Existing research on merge gap identification has focused on modeling and incorporating the passing vehicle's driving behavior in the overtaking platoon scenarios, formulating the problem from the passing vehicle's perspective, and developing algorithms to solve for optimal passing vehicle movements to complete the step-by-step overtaking [20], [21]. While providing a driver assistance solution for the overtaking platoon problem is significant progress, to truly guarantee safety and efficiency

This work was partially sponsored by the Center for Transformative Infrastructure Preservation and Sustainability (CTIPS). CTIPS is funded by a grant from the US Department of Transportation's University Transportation Centers Program, Grant No. 69A3552348308 (IIJA / BIL).

of step-by-step overtaking, more work can be done from the platoon's perspective. An advantage to develop platoon vehicle control solution for the overtaking problem is that platoon vehicles are already equipped with CAV technologies, which provide the necessary platform and resources for implementation of sophisticated control algorithms. Additionally, existing gap opening controller designs are available and are developed based on the CACC framework, although mostly for handling cut-in or on-ramp merging scenarios [25]–[31], they can be easily adapted to handle step-by-step overtaking once we incorporate scenario-specific setup parameters and constraints in the control decision process. Our controller design considers constraints such as the variability in HDV behavior, real-time adjustments to opposing traffic dynamics, and the need to optimize platoon stability during gap opening.

This paper's objective is to address the technical challenges in accommodating HDVs in overtaking of CAV platoons by developing a platoon control strategy to identify the optimal gap in platoon to open to facilitate safe and efficient overtaking, as well as the optimal time to start the gap opening maneuver. This paper extends existing gap opening controller design, from ramp merging applications in [28], [29], to the overtaking context, incorporating scenario-specific dynamics and restrictions. The strategy consists of a set of algorithms that determine the key parameters for gap opening (i.e., gap location, start and end times) based on real-time dynamics of passing and opposing vehicles and the platoon vehicles, ensuring that the maneuver can be completed efficiently and accurately, without compromising safety. We focus on the partial overtaking scenario, where the platoon temporarily adjusts to open a gap for a single vehicle. We aim to provide a robust solution for this basic and more general problem, so it can be further expanded to resolve more complex problems of step-by-step and multi-passing-vehicle step-by-step overtaking of platoons on two-lane undivided highways.

This section is followed by a formulation of research problem in Section II. Section III introduces the details of control strategy design, including the algorithms for determining optimal gap to open and optimal gap opening start time. Section IV presents simulation results and discusses the performance and potential further improvements of the control strategy. Section V concludes the paper and provides recommendations on applications.

II. Problem Statement

Overtaking a platoon involves critical challenges, including ensuring safe interactions of the passing vehicle (HDV) with opposing traffic and the control reliability of vehicle platoon when opening a gap to accommodate the passing vehicle. Therefore, a robust strategy is needed for guiding the passing vehicle during overtaking of a platoon, and simultaneously providing a safe space for the vehicle to merge into the platoon.

Assumptions used in this paper are:

(1) Only the platooned vehicles are CAVs with CACC capabilities, and all other vehicles are HDVs without any active data sharing with the platoon vehicles. All vehicle kinematics of the HDV is assumed to be detected by the platoon vehicles and used in the CAV platoon's control decision-making. The CAV platoon provides guidance messaging to the passing HDV which is assumed to follow the guidance when overtaking.

(2) The scenario of overtaking on two-lane undivided highway has a similar merging maneuver with the on-ramp scenario, but the constraints considered in selection of merging gap are related to the movement of vehicles in the opposing direction and not static geometric constraints.

(3) Considering that a passing vehicle starts its overtaking maneuver near the tail of a platoon, the platoon can start guiding the passing vehicle when it is still following the tail. Therefore, in circumstances where the passing vehicle has a clearance to overtake multiple platoon vehicles, the spatial and temporal clearances should allow us to optimize the control strategy to maximize accuracy and reliability.

Variables used throughout this paper and their definitions are listed in TABLE I.

TABLE I
Variables and Definitions

Variable	Definition
$a_i(t)$	Acceleration of i-th platoon vehicle
$d_i(t)$	Gap between i-th and $(i-1)$-th platoon vehicles
$d_{r,i}(t)$	Desired gap between i-th and $(i-1)$-th platoon vehicles
$e_{1,i}$, $e_{2,i}$, and $e_{3,i}$	Gap, speed, and acceleration errors of i-th platoon vehicle
e_{pred}	Vehicle trajectory prediction error
$\gamma_i(t)$	Gap opening term of i-th platoon vehicle
γ_{ini} and γ_{end}	Initial and final gap increase
$J_{error,k}$	Gap opening controller error of the k-th platoon vehicle
k	ID of the platoon vehicle to be primarily controlled to open gap between itself and its preceding vehicle
k_p and k_d	Control gain parameters
L_i	Summation of platoon vehicle's length, standstill distance, and following gap
λ	Polynomial fitting weight decay parameter
n	Platoon size (total number of vehicles in platoon)
$q_p(t)$ and $q_p^*(t)$	Position and predicted position of passing vehicle
$q_o(t)$ and $q_o^*(t)$	Position and predicted position of opposing vehicle
$q_t(t)$ and $q_t^*(t)$	Position and predicted position of platoon head (front bumper of 1st platoon vehicle)
Q_p, Q_o, and Q_t	Sets of passing, opposing, and platoon vehicle position data
$t_{current}$	Current time
t_{end}	Time to complete merge for passing vehicle, also time to complete gap opening
t_{start}	Time to start gap opening
τ	Platoon vehicle driveline dynamics parameter
u_i	Control input of i-th platoon vehicle
$v_i(t)$	Speed of i-th platoon vehicle
w_i	Weights on the i-th data point for polynomial fitting

Note: List is not exhaustive. Definitions provided in main text.

Guided step-by-step overtaking of platoon is an operation for a situation that a passing vehicle attempting to overtake a multi-vehicle platoon on a two-lane undivided highway but cannot complete it in one step due to restrictions from

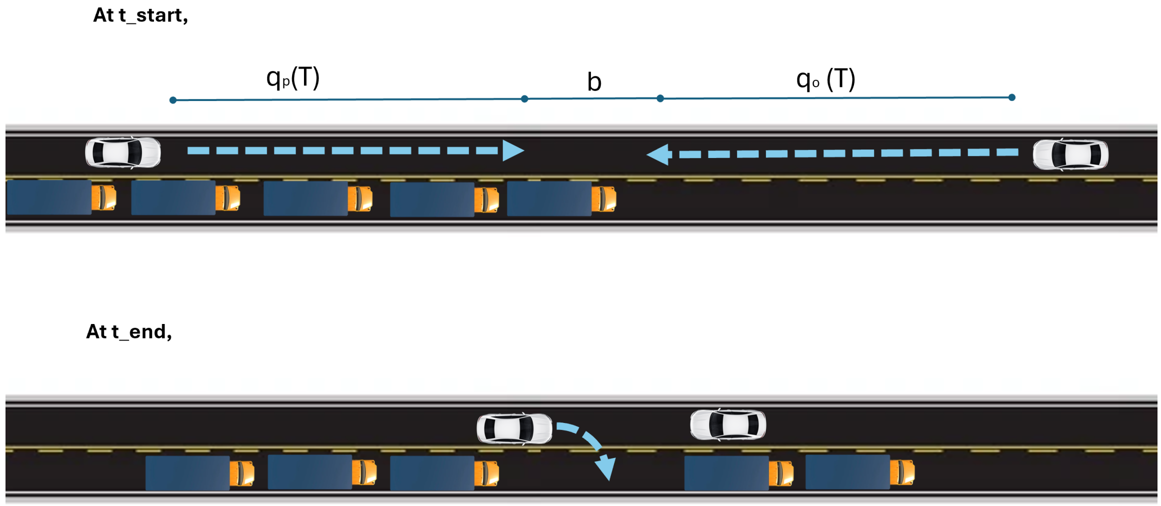

Fig. 1. Illustration of the "single vehicle overtaking part of a platoon" scenario and the gap opening problem. Parameters in the figure: t_{start} and t_{end} are time points to start and end the gap opening process; $q_p(T)$ and $q_o(T)$ are the distances covered by passing and opposing vehicles by time T, respectively and b is the safety buffer distance between the two vehicles.

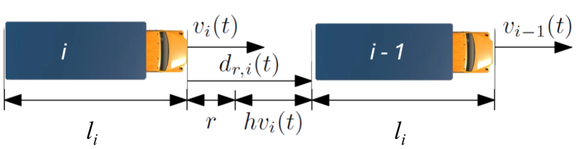

Fig. 2. Following gap between two adjacent platoon vehicles and relevant variables. Parameters in the figure: l_i and l_{i-1} are lengths of the follower and preceding vehicles, v_i and v_{i-1} are their speeds, $d_{r,i}(t)$ is the desired following gap, r and h are standstill distance and time gap, respectively. Adapted from [28].

opposing traffic. The step-by-step operation allows the passing vehicle to overtake part of the platoon (i.e., m out of n vehicles, where n is the size of the platoon and $m < n$) in one step and complete overtaking the entire platoon (of n vehicles) in multiple steps. In each step, the passing vehicle is guided by messages sent by the platoon indicating when is safe to start passing and where is safe to merge. Each step is a basic scenario of "single vehicle overtaking part of a platoon", as shown in Fig. 1. To safely accommodate the passing vehicle in each basic scenario, the platoon tracks and predicts all vehicle trajectories, to determine the gap position, as well as the start and end times for gap opening. Since the control strategy operates iteratively in real time, the trajectory predictions and outputs are updated at each time step.

A. Identifying the Gap

Identifying the gap is the first important task of the gap opening strategy. We define sets $Q_p = \{q_p(t)|0 \leq t \leq t_{current}\}$, $Q_o = \{q_o(t)|0 \leq t \leq t_{current}\}$, and $Q_t = \{q_t(t)|0 \leq t \leq t_{current}\}$, representing real-time position data of the passing, opposing, and platoon vehicles. Predictions of positions at a future time point $T > t_{current}$ can be obtained at each $t_{current}$ and are denoted by $q_p^*(T)$, $q_o^*(T)$, and $q_t^*(T)$. We assume that to avoid collision, the passing vehicle needs to complete merging back into its original lane and still is away from the opposing vehicle by a certain distance, b. Therefore, by the end of the described scenario, we have a relationship of $q_o^*(T) - q_p^*(T) - b = 0$. Using the relationship, we can determine if the passing vehicle can complete overtaking the entire platoon or a gap needs to be opened in the platoon to safely accommodate the passing vehicle.

B. Opening the Gap

Fig. 2 shows the variables in maintaining a platoon's inter-vehicle following gap. The gap is between two adjacent vehicles, a preceding vehicle $(i-1)$ and a follower vehicle i. A CAV platoon using CACC keeps a constant time gap h as short as 0.3 - 0.5 s. The actual gap is the sum of a constant standstill distance r and the multiplication of constant time gap and vehicle speed $hv_i(t)$. To open the gap, we must add an extra distance upon the existing following gap. We can achieve that by setting up a function of desired following gap, $d_{r,i}(t)$, which consists of $r + hv_i(t)$ and a term for additional gap length, $\gamma(t)$, and increasing $\gamma(t)$ over time, until the gap is large enough to safely accommodate the passing vehicle. The desired gap size can be pre-determined based on platoon speed and a typical time gap that is comfortable for human drivers (e.g., 2-3 seconds).

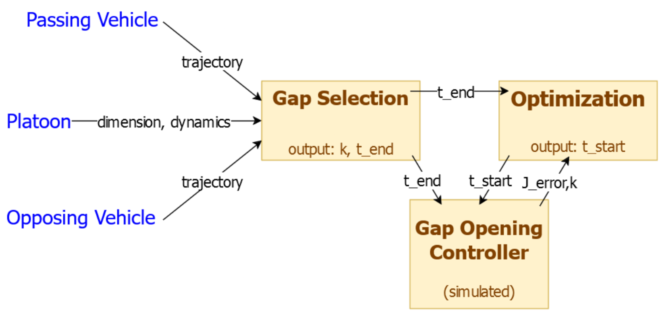

Fig. 3. The gap opening decision-making process. Arrows indicate data flows.

C. Optimizing the Process

As mentioned in the assumptions, the gap opening process can be optimized to ensure maximum control accuracy and reliability. The potential parameters for implementing gap opening control are the gap location and gap opening start and end times. The gap location is denoted by k, representing the gap between the $(k-1)$-th and k-th platoon vehicles. The start and end times are denoted by t_{start} and t_{end}. Given that the gap selection process will determine k and t_{end}, we identify a trade-off, with respect to t_{start}, between the gap selection accuracy, gap opening control reliability, and platoon string stability. With the trade-off identified, we can add an optimization component to the control strategy to determine the optimal t_{start}, as shown in Fig. 3. The cost function is formulated as: $\min_{t_{start}} -\alpha t_{start} + \beta J_{error,k}(t_{start}) + \theta J_{ss}(t_{start})$ to reflect the trade-off, where $J_{error,k}(t_{start})$ and $J_{ss}(t_{start})$ are the error generated by controlling the k-th platoon vehicle for gap opening and the error generated by k-th vehicle's follower vehicles for assessing string stability; the parameters α, β, and θ are weights on the three cost terms. By solving the optimization problem, we can obtain a t_{start} that minimizes the overall cost.

III. Control Strategy

This section presents the details of platoon gap opening control strategy designed for the scenario of a single vehicle overtaking part of the platoon. The control strategy is explained in three sections: Gap Selection, Gap Opening, and Optimal Start Time for Gap Opening.

A. Gap Selection

1) Real-time merge gap identification: As assumed, the platoon is equipped with sensors that track the passing and opposing vehicles' position in real time. The positions are used in predicting passing and opposing vehicles' trajectories, which are fitted as fifth-degree polynomials, as what has been implemented in prior research for modeling vehicle longitudinal trajectories [32], [33]. Higher-degree polynomials are not used to reduce risk of overfitting. The polynomials are:

$$q_p^*(t) = \alpha_1 t^5 + \alpha_2 t^4 + \alpha_3 t^3 + \alpha_4 t^2 + \alpha_5 t + \alpha_6 \quad (1)$$

$$q_o^*(t) = \beta_1 t^5 + \beta_2 t^4 + \beta_3 t^3 + \beta_4 t^2 + \beta_5 t + \beta_6 \quad (2)$$

where α_1 ... α_6 and β_1 ... β_6 are coefficients of the passing and opposing vehicle polynomials, respectively.

The polynomials are fitted in real-time using exponentially weighted least squares method. The objective function for the polynomial fitting is to minimize the weighted least squares error:

$$J_{poly} = \sum_{i=1}^{n} w_i (q(t_i) - q^*(t_i))^2 \quad (3)$$

where n is the total number of data points; w_i is weight of the i-th data point defined as $w_i = e^{-\lambda(t_{current} - t_i)}$, with λ a weight decay parameter controlling how quickly older data points lose importance and $t_{current}$ the current time; and $q(t_i)$ and $q^*(t_i)$ are the true and polynomial-estimated vehicle position of the i-th data point (i.e., time point t_i).

For the passing vehicle to safely complete an overtaking or partial overtaking, we need to make sure that the passing vehicle safely return to its original lane before the opposing vehicle reach the same position. So the positions of the two vehicles has the following relationship at the time point t_{end}:

$$q_o(t_{end}) - q_p(t_{end}) = b \quad (4)$$

where $q_o(t_{end})$ and $q_p(t_{end})$ are the positions of opposing and passing vehicles at time point t_{end}, and b is a safety buffer distance, which can be preset as a constant.

We can use the predicted passing and opposing vehicle trajectories and the above relationship to solve for the time t_{end}, which would be the time the passing vehicle should complete the merging into a gap in the platoon or in front of the platoon head.

From time point 0 to time point t_{end}, the platoon is also assumed to be able to track its own moving trajectory and predict the platoon head position at time t_{end}, $q_t^*(t_{end})$. Assuming that vehicles in the platoon has the same length, we can then identify the k-th vehicle, which is the follower vehicle of the merge gap for passing vehicle to avoid collision with opposing traffic:

$$k = \lceil \frac{q_t^*(t_{end}) - q_p^*(t_{end})}{L_i} \rceil + 1 \quad (5)$$

where $L_i = l_i + r + hv_i$ is the "footprint" of a platoon vehicle. It is the sum of each platoon vehicle's length, l_i, standstill distance, r, and following gap, hv_i, determined by the platoon's constant time gap following policy, h, and the vehicle's speed, v_i. If $k \leq 1$, the passing vehicle can safely overtake the entire platoon.

Pseudo code of the gap selection algorithm is presented in Algorithm 1. The algorithm takes inputs of the current time $t_{current}$, step size Δt related to sensor sampling rate $1/\Delta t$ in Hz, sets of passing and opposing vehicle positions $Q_p = \{q_p(t) | 0 \leq t \leq t_{current}\}$ and $Q_o = \{q_o(t) | 0 \leq t \leq t_{current}\}$, function of platoon position $q_t^*(t)$ which is assumed to be readily available for the platoon controller, passing-opposing safety buffer b, exponential weight decay parameter λ for polynomial fitting, and platoon vehicle's footprint L_i. The outputs are the gap identifier k and the gap opening and passing vehicle merge end time t_{end}. Algorithm 1 consists of major steps including fitting the passing and opposing vehicle polynomials, solving for t_{end}, and calculating k.

Algorithm 1 GapSelection

Input: t_{current}, Δt, Q_p, Q_o, $q_t^*(t)$, b, λ, L_i.
Output: Predicted gap k and merge time t_{end} for the current time t_{current}.
$s \leftarrow \lfloor t_{current}/\Delta t \rfloor$
if $s+1 < 6$ **then**
  return None, **None** ▷ Not enough data for fitting
end if
Fit polynomial $q_p^*(t)$ with $(Q_p[0:s], \lambda)$
Fit polynomial $q_o^*(t)$ with $(Q_o[0:s], \lambda)$
Solve for t_{end} from $q_o^*(t_{end}) - q_p^*(t_{end}) - b = 0$
if $q_t^*(t_{end}) > q_p^*(t_{end})$ **then**
  $k \leftarrow \lceil (q_t^*(t_{end}) - q_p^*(t_{end}))/L_i \rceil$
else
  $k \leftarrow 1$
end if
return k, t_{end}

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2) Complexity of Algorithm 1: The relevant inputs affecting complexity are s and the sets of Q_p and Q_o, the size of which can all be represented by $s+1 = \lfloor t_{current}/\Delta t \rfloor + 1$, with step size Δt. The operation to check if $t_{data} < 6$ has complexity of $O(1)$. The polynomial fitting steps involve fitting a polynomial of degree d, and the complexity is typically $O(d^3)$, where $d = 5$ under the current setup, and $d < s$. Assume that m is the number of iterations required for solving the equation $q_o^*(t_{end}) - q_p^*(t_{end}) - b = 0$ for t_{end}, then the process costs $O(m)$. Evaluating polynomial values $q_p^*(t_{end})$ and $q_o^*(t_{end})$ have complexity of $O(d)$, and the final calculations of $q_t^*(t_{end})$, k, and others have complexity of $O(1)$. Therefore, the overall complexity is primarily determined by polynomial fitting ($O(d)$), equation solving ($O(m)$), and processing the data set ($O(s+1)$). We can expect that $d < s+1$ and $m < s+1$, thus, the complexity of Algorithm 1 is $O(s+1)$, where s is dependent on Δt determined by sensor sampling rate in Hz. For a sampling rate of 1 Hz (1 sample per second, i.e., $\Delta t = 1$ s), the complexity would be $O(t_{current} + 1)$. Since $t_{current} + 1 \leq t_{end}$, the final complexity is $O(t_{end})$.

3) Accuracy of gap selection: At each time point, $t < t_{end}$, Algorithm 1 iterates once to identify the merge gap, k, and time to complete the merge, t_{end}. We noted that as $(t_{end} - t)$ reduces, meaning that t moving closer and closer to t_{end}, the accuracy of gap prediction improves, thus we formulate the following subroutine as a small proposition:

At time t, if we determine the gap to open and start the opening maneuver, we would base our decision on the passing and opposing vehicle polynomials fitted at time t and their corresponding predictions of t_{end} and $q_p(t_{end})$. The prediction error can be expressed as:

$$e_{pred} = \sum_{t_i=t}^{t_{end}} (q_p(t_i) - q_p^*(t_i))^2, t \leq t_{end} \tag{6}$$

where $q_p(t_i)$ and $q_p^*(t_i)$ are the true and predicted positions of passing vehicle at time point t_i.

As t moves closer to t_{end}, the number of time points between t and t_{end} reduces, so the number of terms in the error summation reduces, thus, the prediction error decreases. This analysis shows that the later the gap is selected before time t_{end}, the more accurate the selection will be.

B. Gap Opening

1) Vehicle model and controller: The vehicle dynamics, error dynamics, and control law designs are adopted from [28], [29], [34], for CACC-based vehicle platoon gap opening to handle on-ramp merging scenarios.

The vehicle dynamics are modeled as follows:

$$\dot{q}_i(t) = v_i(t) \tag{7}$$
$$\dot{d}_i(t) = v_{i-1}(t) - v_i(t) \tag{8}$$
$$\dot{v}_i(t) = a_i(t) \tag{9}$$
$$\dot{a}_i(t) = \frac{1}{\tau}u_i(t) - \frac{1}{\tau}a_i(t) \tag{10}$$

The desired inter-vehicle following gap based on the constant time gap policy is:

$$d_{r,i}(t) = r + hv_i(t) + \gamma_i(t) \tag{11}$$

where $\gamma_i(t)$ is a term of increased gap, which is adjusted by the gap opening controller.

The error is defined as $e_i = d_i - d_{r,i}$. The error states are $[e_{1,i}\ e_{2,i}\ e_{3,i}] = [e_i\ \dot{e}_i\ \ddot{e}_i]$ The error dynamics of the controller are:

$$e_{1,i} = d_i - d_{r,i} \tag{12}$$
$$e_{2,i} = v_{i-1} - v_i - \dot{\gamma} - ha_i \tag{13}$$
$$e_{3,i} = a_{i-1} - a_i(1 - \frac{h}{\tau}) - \ddot{\gamma} - \frac{h}{\tau}u_i \tag{14}$$
$$\dot{e}_{3,i} = -\frac{1}{\tau}e_{3,i} + \frac{1}{\tau}u_{i-1} - \frac{1}{\tau}\xi_i \tag{15}$$

where $\xi_i = h_i\dot{u}_i + u_i + \ddot{\gamma}_i + \tau\dddot{\gamma}_i$. By designing the function as: $\xi_i = k_pe_{1,i} + k_de_{2,i} + u_{i-1}$, with control parameters k_p and k_d, the control law is derived as:

$$\dot{u}_i = \frac{1}{h}(k_pe_{1,i} + k_de_{2,i} + u_{i-1} - u_i\ddot{\gamma}_i - \tau\dddot{\gamma}_i) \tag{16}$$

2) Gap opening term, γ: The γ trajectory is modeled as a fifth-degree polynomial to ensure C^2 continuity, so that the third derivative, $\dddot{\gamma}$, can be obtained at all time [28]. For this paper, coefficients in the γ function are preset or calculated based on specific constraints of the vehicle overtaking platoon scenario.

$$\gamma(t) = c_1 + c_2t + c_3t^2 + c_4t^3 + c_5t^4 + c_6t^5 \tag{17}$$

The coefficients are:

$$c_1 = \gamma_{ini},\ c_2 = \dot{\gamma}_{ini},\ c_3 = 0.5\ddot{\gamma}_{ini} \tag{18}$$

$$c_4 = \frac{20(\gamma_{end} - \gamma_{ini}) - 3T(4\dot{\gamma}_{ini} + T\ddot{\gamma}_{ini})}{2T^3} \tag{19}$$

$$c_5 = \frac{-30(\gamma_{end} - \gamma_{ini}) + T(16\dot{\gamma}_{ini} + 3T\ddot{\gamma}_{ini})}{2T^4} \tag{20}$$

$$c_6 = \frac{12(\gamma_{end} - \gamma_{ini}) - T(6\dot{\gamma}_{ini} + T\ddot{\gamma}_{ini})}{2T^5} \tag{21}$$

where $T = t_{end} - t_{start}$ is the amount of time between the start and end of the gap opening process.

The controller is designed to reach γ_{end} at time t_{end}, so that the preceding ($(k-1)$-th) and follower (k-th) vehicles should be able to accommodate the passing vehicle in between. For gap opening, the initial γ value is set to γ_{ini} = 0. The final γ value, γ_{end}, is preset based on the length of passing vehicle and typical following gaps that human drivers feel comfortable with (e.g., 2-3 seconds). The gap opening end time, t_{end}, is determined by Algorithm 1 based on vehicle trajectories in the overtaking process, and t_{start} will be determined by solving the optimization problem of balancing trade-off between gap selection accuracy, control error, and platoon string stability.

3) Controller error and string stability: The gap opening controller follows a feed-forward design and increases the gap between the k-th and $(k-1)$-th platoon vehicles by slowing down the follower, k. As the maneuver tries to follow a desired gap-increase trajectory, the induced errors between the actual and desired trajectories should be assessed.

Over the period between the start and end times of the gap opening maneuver, t_{start} and t_{end}, the controller error can be measured as a root mean squared error (RMSE):

$$J_{error,k}(t_{start}) = \sqrt{\frac{\int_{t_{start}}^{t_{end}} \sum_{i=1}^{3} e_{i,k}^2(t)dt}{t_{end} - t_{start}}} \tag{22}$$

where k indicates the k-th vehicle in the platoon, which is the primarily controlled vehicle to achieve gap opening.

As the k-th vehicle reduces speed to open its following gap, the platoon vehicles following the k-th vehicle (i.e., the $(k+1)$-th, $(k+2)$-th, ..., and n-th vehicles) are disturbed. Following the CACC control dynamics, the follower vehicles will need to adjust their speed along with the k-th vehicle. Considering potential error propagation, we want to make sure that the gap opening process does not cause a significant disturbance and the platoon stays string stable. String stability can be quantified by measuring the amplification of velocity errors between consecutive vehicles and the propagation of position or gap errors over time. For simplicity, we can measure the sum of follower vehicles' control errors as follows and ensure the gap opening process minimizes it.

$$J_{ss}(t_{start}) = \sum_{j=k+1}^{n} \sqrt{\frac{\int_{t_{start}}^{t_{end}} \sum_{i=1}^{3} e_{i,j}^2(t)dt}{t_{end} - t_{start}}} \tag{23}$$

Instead of having a increasing $\gamma(t)$ in the desired following gap and error dynamics, the follower vehicles use regular CACC error dynamics as the model adopted from [34], with $\gamma(t)$ = 0, aiming to keep a following gap of $d_{r,i} = r + hv_i$ with their corresponding preceding vehicles. The control law is instead $\dot{u}_i = (k_p e_{1,i} + k_d e_{2,i} + u_{i-1} - u_i)/h$.

C. Optimal Start Time for Gap Opening

1) Formulation of optimization problem: At each current time point, $t_{current}$, during the overtaking process, before the passing vehicle reaches the gap determined by Algorithm 1 as the safe merge gap, we need to decide on a time point, denoted by t_{start}, to start the gap opening maneuver. The value of t_{start} affects the accuracy of gap selection as well as the controller error and platoon string stability, we formulate the following optimization problem to determine the optimal t_{start}.

$$\min_{t_{start}} -\alpha t_{start} + \beta J_{error,k}(t_{start}) + \theta J_{ss}(t_{start}) \tag{24}$$

$$\text{s.t. } t_{current} < t_{start} < t_{end} \tag{25}$$

The α, β, and θ parameters are weights on corresponding parts of the objective function that represent gap selection accuracy, gap opening controller error, and control error related to string stability, respectively. The optimization problem is solved concurrently with the gap selection algorithm and a simulation of the gap opening controller. The gap selection algorithm provides real-time estimation of t_{end}, and the controller simulation provides estimations on errors and string stability effects. To solve the optimization problem, sequential quadratic programming (SQP) is used to handle the dynamic constraints.

Algorithm 2 OptimalTstart

Input: t_{current}, t_{end}, h, r, τ, α, β, θ, γ_{end},
initial state $[q_k, d_k, v_k, a_k, u_k]$, parameters k_p, k_d.
Output: Optimal start time $t_{\text{start\_optimal}}$.
if t_{end} != None **AND** $t_{\text{current}} < t_{\text{end}}$ **then**
  Define constraints:

$$t_{\text{current}} < t_{\text{start}} < t_{\text{end}}$$

  Define objective function:

$$J(t_{\text{start}}) = -\alpha t_{\text{start}} + \beta J_{\text{error,k}}(t_{\text{start}}) + \theta J_{\text{ss}}(t_{\text{start}})$$

  where J_{error}: integrated error based on system dynamics.
  Solve optimization problem using `SLSQP`:

  Minimize $J(t_{\text{start}})$ subject to constraints.

  Obtain optimal t_{start}: $t_{\text{start\_optimal}}$
  if $t_{\text{current}} \geq t_{\text{start\_optimal}}$ **then**
    return None
  end if
else
  return None
end if
return $t_{\text{start\_optimal}}$

Pseudo code of the optimization process to determine optimal t_{start} is shown in Algorithm 2. At each time step, Algorithm 2 runs concurrently with Algorithm 1. Algorithm 2 takes inputs of the current time $t_{current}$, gap opening end time t_{end} determined by Algorithm 1, platoon following time gap h, standstill distance r, vehicle driveline parameter τ, weights objective function terms α, β, and θ, final gap increase γ_{end}, k-th platoon vehicle initial state $[q_k, d_k, v_k, a_k, u_k]$, and control parameters k_p and k_d. The output is optimal gap opening start time $t_{start\_optimal}$. The primary steps in Algorithm 2 are the steps of solving the optimization problem using sequential least squares programming (SLSQP).

2) Complexity of Algorithm 2: The key variables or components affecting complexity of Algorithm 2 are t_{end}, $J_{error}(t_{start})$, $J_{ss}(t_{start})$, and the SLSQP algorithm. The initialization of $t_{start\_initial}$ has a complexity of $O(1)$. The objective function involves three terms: (1) a linear term of $-\alpha t_{start}$ with complexity of $O(1)$, (2) an error term of $J_{error}(t_{start})$ with its complexity depending on the evaluation of system dynamics, which we can denote as C_{error}, and an string stability error term of $J_{ss}(t_{start})$, with a complexity depending on $(n-k)C_{error}$, where n is the total number of platoon vehicles, k is the gap opening platoon vehicle, and $(n-k)$ is the number of follower vehicles behind k. Based on the system dynamics, $C_{error} = O((t_{end} - t_{start})/\Delta t)$, with step size Δt related to the sensor sampling rate in Hz. The complexity of SLSQP algorithm is related to the number of iterations required by the optimizer, m, and the cost of evaluating $J(t_{start})$ in each iteration, C_{eval}. Thus, the SLSQP complexity is $O(m \cdot C_{eval})$. We assume that $C_{eval} = (n-k+1) \cdot C_{error} = O((n-k+1) \cdot (t_{end} - t_{start})/\Delta t)$, then the overall complexity of Algorithm 2 is $O(m \cdot (n-k+1) \cdot (t_{end} - t_{start})/\Delta t)$. For a sampling rate of 1 Hz (i.e., Δt = 1 s) and assuming $t_{current}$ = 0, m = 1, and k = 1, the complexity is $O(n \cdot t_{end})$, related to the size of platoon and passing vehicle merge time.

D. Control Strategy as a Whole

The gap opening control strategy as a whole determines k, t_{end}, and t_{start} iteratively in real time, from when a passing vehicle starts to overtake the platoon until t_{start}, during which Algorithms 1 and 2 are called at each time point. The process is presented as pseudo code in Algorithm 3. The algorithm takes all inputs needed for Algorithms 1 and 2, and generates outputs of k, t_{end}, and $t_{start\_optimal}$. Algorithm 3 runs iteratively while $t_{current} < t_{start\_optimal}$, and the gap opening controller will start executing the actual gap opening maneuver between the k-th and $(k-1)$-th platoon vehicles.

The complexity of Algorithm 3 is analyzed as follows. The **while** loop iterates when $t_{current} \leq t_{end}$ so the number of iterations $N = t_{end} - t_{current}$. Algorithms 1 and 2 have complexity of $O(t_{current}/\Delta t)$ and $O(m \cdot (n-k+1) \cdot (t_{end} - t_{current})/\Delta t)$, respectively, and are called in each iteration. Therefore, the overall complexity of Algorithm 3 is $O(N \cdot (t_{current} + m \cdot (n-k+1) \cdot (t_{end} - t_{current}))/\Delta t)$. For Δt = 1 s, and assuming m = 1 and k = 1, the overall complexity would be about $O(n \cdot t_{end}^2)$.

Algorithm 3 GapOpeningDecision

```
Input:
For GapSelection: t_current, Δt, Q_p, Q_o, q_t^*(t), b, λ, L_i.
For OptimalTstart: t_current, t_end, h, r, τ, α, β, θ, γ_end,
[q_k, d_k, v_k, a_k, u_k], k_p, k_d.
Output: k, t_end, t_start_optimal.
Initialize: t_current ← 0; t_end ← 1; k ← 1.
while t_current < t_end do
    k, t_end ← GapSelection(t_current, Δt, Q_p, Q_o, q_t^*(t),
    b, λ, L_i)
    t_start_optimal ← OptimalTstart(t_end, h, r, τ, α, β, γ_end,
    [q_k, d_k, v_k, a_k, u_k], k_p, k_d)
    Increment t_current ← t_current + 1
end while
Return k, t_end, t_start_optimal
```

TABLE II
PARAMETERS USED TO INITIATE SIMULATION

Parameter	Value or Relationship
Platoon head initial position	$q_t(0) = 200$ m
Platoon size	$n = 5$ vehs
Platoon vehicle length	$L_i = 15$ m
Platoon time gap	$h = 0.75$ s
Platoon standstill distance	$r = 5$ m
Platoon speed	$v_t(t) = 20$ m/s
Platoon head trajectory	$q_t(t) = q_t(0) + v_t(0)t$
Passing vehicle initial position	$q_p(0) = 0$ m
Passing vehicle initial speed	$v_p(0) = 22$ m/s
Passing vehicle acceleration	$a_p(t) = 0.05$ m/s^2
Passing vehicle trajectory	$q_p(t) = q_p(0) + v_p(0)t + 0.5a_p(t)t^2$
Opposing vehicle initial position	$q_o(0) = 2,000$ m
Opposing vehicle initial speed	$v_o(0) = 20$ m/s
Opposing vehicle deceleration	$a_o(t) = -0.03$ m/s^2
Opposing vehicle trajectory	$q_o(t) = q_o(0) - v_o(0)t - 0.5a_o(t)t^2$
Passing-opposing buffer	$b = 0$ m
Polynomial fitting weight decay parameter	$\lambda = 0.1$
Driveline dynamics parameter	$\tau = 0.1$; Source: [28]
Control gain parameters	$k_p = 0.2$; $k_d = 0.7$; Source: [28]
Initial and final gap increase	$\gamma_{ini} = 0$ m; $\gamma_{end} = 65$ m
Optimization objective weights	$\alpha = 0.05$; $\beta = 0.50$; $\theta = 0.45$

IV. SIMULATION

A. Simulation Setup

We present a numerical simulation to show how the gap opening control strategy works. In the simulation scenario, a vehicle following a platoon of n = 5 vehicles on a two-lane undivided highway and start to overtake the platoon. The parameters used to initiate the simulation are listed in TABLE II. In this simulation, the following assumptions are made to simplify the scenario and provide a clear illustration of the results: (1) the platoon moves at a constant speed; (2) the passing and opposing vehicles maintain constant acceleration and deceleration, respectively; and (3) the buffer distance between the passing and opposing vehicles is set to 0 m.

B. Results

Fig. 4 shows the time-position diagram that indicates the trajectories of platoon vehicles as well as the passing and opposing vehicles. As we set $b = 0$, the intersecting point between the passing and opposing vehicle trajectories is where in time and position the passing vehicle needs to completely merge into the platoon to avoid collision with the opposing vehicle. The gap-selection Algorithm 1 predicts the vehicle trajectories at every time step and the intersecting point, and generates the outputs, t_{end} and k, which are the time to complete merge and the gap (between the k-th and $(k-1)$-th platoon vehicles) to use for the merge, respectively. In the simulation, Algorithm 1's prediction of t_{end} = 47.09 s stabilized from $t_{current}$ = 5 s, and the predicted gap location is k = 3 (i.e., between the 3rd and 2nd platoon vehicles). The k-th vehicle then has two followers, $k+1$ and $k+2$.

While Algorithm 1 is predicting t_{end} and k at every time step, Algorithm 2 determines the optimal t_{start}. Fig. 5 presents the optimal t_{start} at every time step until the 16th second. The results were based on unstable trajectory prediction for $t_{current}$ = 0 to 5 s, and the optimal t_{start} stayed at 16.12 s afterwards. Therefore, the controller should start opening the gap at $t_{current}$ = 16.12 s.

The optimal t_{start} is determined based on the cost function (Eq. (24)) and constraints (Eq. (25)) to balance the trade-off between gap prediction accuracy and gap opening control and platoon string stability errors. Fig. 6 shows the simulated controller dynamics for t_{start} = 16.12 s and t_{end} = 47.09 s. We observe that the simulated "actual" gap trajectory closely follows the desired trajectory; the acceleration of the follower (k-th platoon vehicle) also closely follows the control input, leading to a smooth change in its speed and achieves the goal of gap opening within the 30.97 seconds between t_{start} and t_{end}. The $(k+1)$-th and $(k+2)$-th vehicles adjust their speeds and accelerations following the k-th vehicle and maintained their following gap well without a large deviation from 20 m. The following dissipates quickly after t_{end}, which are observed from the velocity and acceleration/control dynamics plots.

To verify that t_{start} = 16.12 s is the optimal start time of the gap opening maneuver given a determined t_{end}, we compare the controller dynamics and error results from using t_{start} = 16.12 s with those from using t_{start} = 20 s, 25 s, and 30 s. The comparison is shown in Fig. 7, from which we observe that the controller error $J_{error,k}$ increased from 0.44 to 0.73, 1.90 and 44.35 as t_{start} increases. The string stability related error J_{ss} increased from 0.0000 to 0.0001, 0.0004, and 0.0180. The increased errors can also be observed from the vehicle gap, velocity, and acceleration/control dynamics. As we use errors in all three dynamic measures in the calculation of $J_{error,k}$ and J_{ss}, the significant change in gap dynamics from an early t_{start} to a late one primarily contributes to the change in those errors, which can be viewed in the side-by-side comparison of the gap dynamics plots. We also observe increased oscillations in vehicle's velocity and acceleration with delayed t_{start}. These simulation results show again that as t_{start} moves closer to t_{end}, the controller will start struggling to fully open the gap and maintain string stability within the more limited amount of time.

C. Discussion

As shown by the simulation results, the proposed algorithms successfully provided suggestions of optimal gap location and start and end times for gap opening based on predicted passing and opposing vehicle trajectories. The amount of time between the t_{start} and t_{end} determined by the algorithms is enough for the gap opening controller to smoothly conduct the maneuver, with minimal control error and impact on string stability.

There are some challenges the proposed Algorithms 1 and 2 face and could be further addressed in future work:

(1) Fitting a 5th degree polynomial of the position-time trajectories of passing and opposing vehicles is only one method of tracking and predicting the vehicles' movements. Predictions based on those polynomials may not be accurate if adversarial movements such as frequent acceleration changes happen. We used an exponentially decayed weighting method to address the issue but techniques such as incorporating physical models or Kalman filter into polynomial fitting will be tested in future studies.

(2) To determine the optimal start time t_{start}, the objective function can incorporate other types of costs such as energy consumption and emission related costs. We only considered the gap prediction inaccuracy and gap opening control and string stability error costs because we found a significant trade-off relationship with regard to t_{start} between those costs. To incorporate other costs, the relationship between the newly introduced costs and existing ones need to be investigated.

(3) For simplicity purposes, the proposed algorithms use the same t_{end} as the end time of both the passing vehicle merge and platoon gap opening maneuvers. For a more sophisticated decision process, the gap opening maneuver can be restricted to complete just before the start of the passing vehicle's merge maneuver. To achieve that, the algorithms need to incorporate prediction of the passing vehicle's lateral movement. Polynomial fitting techniques similar to what is used for longitudinal trajectory prediction may be investigated to examine feasibility for lateral trajectory prediction.

V. Conclusion

The proposed control strategy for guided step-by-step overtaking of CAV platoons on two-lane undivided highways demonstrates its effectiveness in addressing the safety and efficiency challenges posed by mixed traffic environments. Through simulation, the gap-selection algorithm successfully identified the optimal location and duration for gap opening to ensure that passing vehicles could merge safely into the platoon. The optimization algorithm determined optimal timing for initiating the gap opening maneuver, balancing the trade-off between gap prediction accuracy, controller performance, and platoon string stability. The results confirm the feasibility of implementing the proposed solution in CAV platooning systems to ensure safe integrations with HDVs.

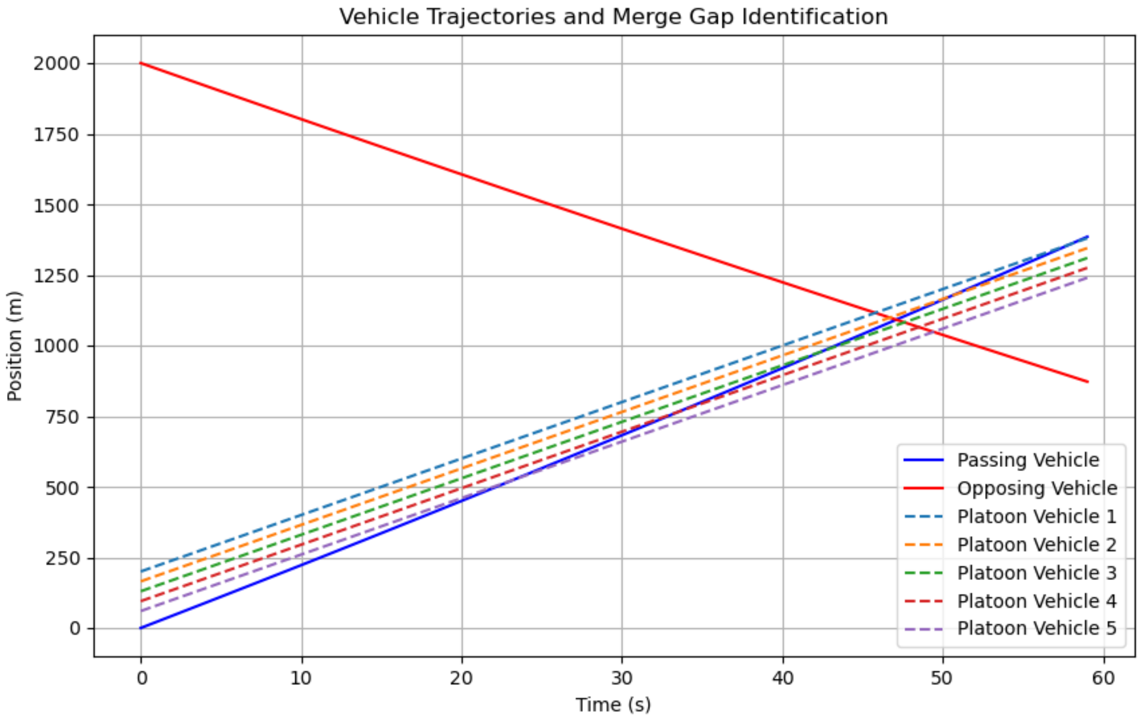

Fig. 4. Simulated vehicle trajectories and merge gap.

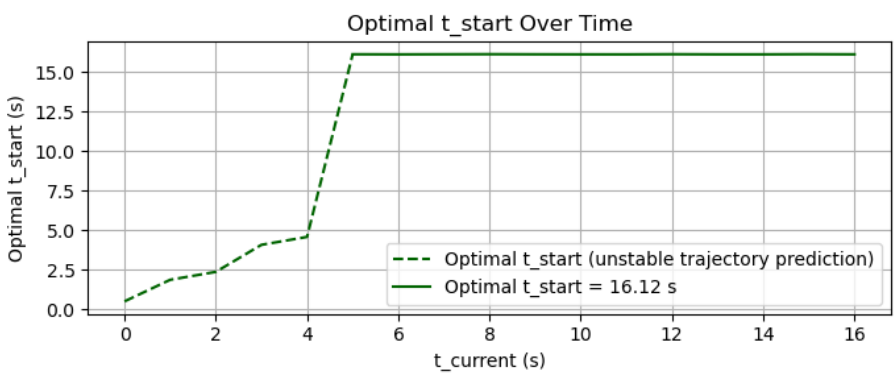

Fig. 5. Optimal t_{start} determined at each time point.

In addition to the promising performance of the proposed control strategy, this paper also identifies directions for future improvement. Enhancing trajectory prediction accuracy through advanced methods such as incorporating physical models or Kalman filtering could mitigate errors in adversarial traffic conditions. Expanding the cost function for optimal start time to include considerations like energy efficiency and emissions would further refine the system's effectiveness and sustainability. Additionally, separating the end times of the gap opening and merging maneuvers by integrating lateral movement predictions could optimize maneuver coordination and reduce unnecessary delays. By addressing these challenges, future research can build upon the foundational framework established in this paper to develop more comprehensive and adaptive solutions for safe and efficient CAV platooning in diverse traffic environments.

References

[1] U. Franke, F. Bottiger, Z. Zomotor, and D. Seeberger, "Truck platooning in mixed traffic," in *Proceedings of the Intelligent Vehicles '95. Symposium*, pp. 1–6, Sept. 1995.

[2] B. van Arem, C. J. G. van Driel, and R. Visser, "The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics," *IEEE Transactions on Intelligent Transportation Systems*, vol. 7, pp. 429–436, Dec. 2006. Conference Name: IEEE Transactions on Intelligent Transportation Systems.

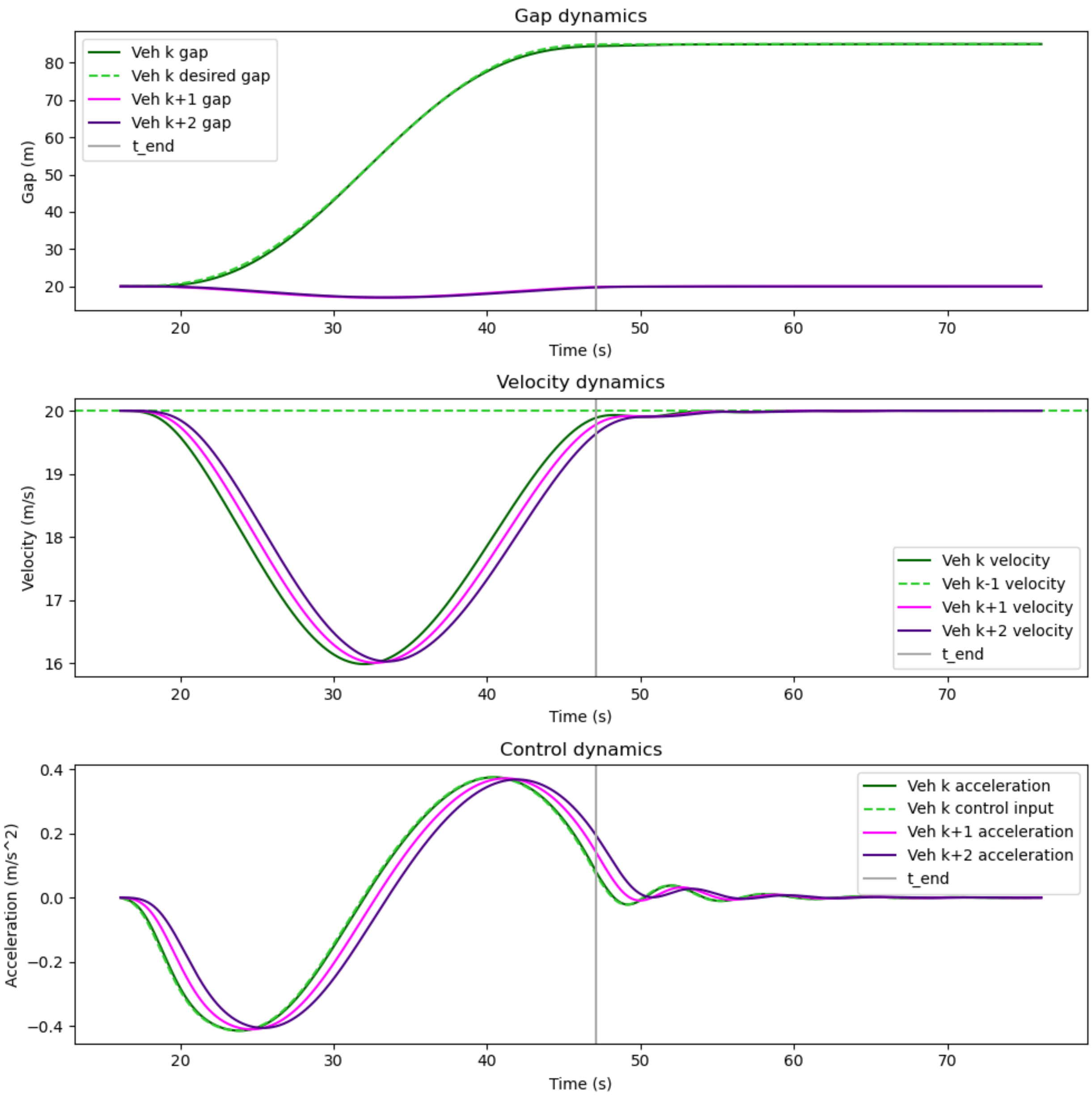

Fig. 6. Gap, velocity, and acceleration/control dynamics, with optimal t_{start} = 16.12 s and t_{end} = 47.09 s.

[3] M. Neubauer and W. Schildorfer, "Towards Truck Platooning Deployment Requirements," in *Energy-Efficient and Semi-automated Truck Platooning* (A. Schirrer, A. L. Gratzer, S. Thormann, S. Jakubek, M. Neubauer, and W. Schildorfer, eds.), pp. 21–39, Cham: Springer International Publishing, 2022. Series Title: Lecture Notes in Intelligent Transportation and Infrastructure.

[4] R. Janssen, H. Zwijnenberg, I. Blankers, and J. de Kruijff, "Truck Platooning: Driving the Future of Transportation," tech. rep., TNO: Netherlands Organization for Applied Scientific Research, 2015.

[5] B. McAuliffe, M. Croken, M. Ahmadi-Baloutaki, and A. Raeesi, "Fuel-economy testing of a three-vehicle truck platooning system," Tech. Rep. LTR-AL-2017-0008, National Research Council Canada, 2017.

[6] B. McAuliffe, M. Lammert, X.-Y. Lu, S. Shladover, M.-D. Surcel, and A. Kailas, "Influences on Energy Savings of Heavy Trucks Using Cooperative Adaptive Cruise Control," in *WCX18: SAE World Congress Experience*, pp. 2018–01–1181, Apr. 2018.

[7] B. McAuliffe, A. Raeesi, M. Lammert, P. Smith, M. Hoffman, and D. Bevly, "Impact of Mixed Traffic on the Energy Savings of a Truck Platoon," Tech. Rep. NREL/CP-5400-78218, National Renewable Energy Laboratory, Apr. 2020.

[8] S. Shladover, X.-Y. Lu, S. Yang, H. Ramezani, J. Spring, C. Nowakowski, and D. Nelson, "Cooperative Adaptive Cruise Control (CACC) For Partially Automated Truck Platooning:Final Report," tech. rep., University of California, Berkeley, Aug. 2018.

[9] M. T. Haq, A. Farid, and K. Ksaibati, "Estimating passing sight distances for overtaking truck platoons–Calibration and validation using VISSIM," *International Journal of Transportation Science and Technology*, 2021. ISBN: 2046-0430 Publisher: Elsevier.

[10] Y. F. Song, "Integrated Overtaking Model and Safety Analysis for Truck Platooning Requirements on Two-Lane Undivided Highways," *Transportation Research Record*, p. 03611981231220635, Jan. 2024. Publisher: SAGE Publications Inc.

[11] T. Faber, S. Sharma, M. Snelder, G. Klunder, L. Tavasszy, and H. van Lint, "Evaluating Traffic Efficiency and Safety by Varying Truck Platoon

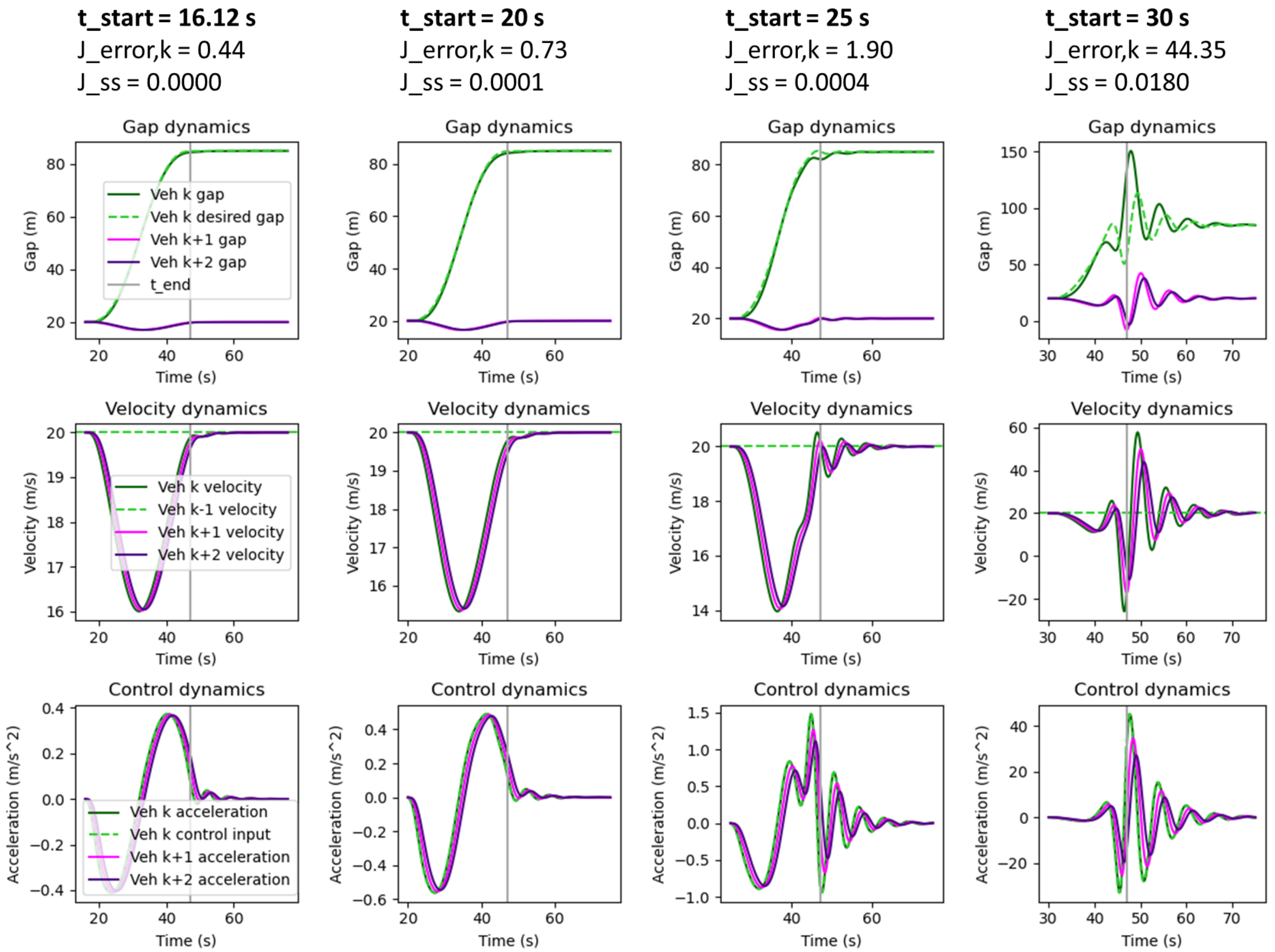

Fig. 7. Comparison of vehicle dynamics and gap opening controller and string stability errors with different t_{start} and the same t_{end} = 47.09 s.

Characteristics in a Critical Traffic Situation," *Transportation Research Record*, vol. 2674, pp. 525–547, Oct. 2020. Publisher: SAGE Publications Inc.

[12] M. Wang, S. van Maarseveen, R. Happee, O. Tool, and B. van Arem, "Benefits and Risks of Truck Platooning on Freeway Operations Near Entrance Ramp," *Transportation Research Record*, vol. 2673, pp. 588–602, Aug. 2019. Publisher: SAGE Publications Inc.

[13] J. Axelsson, "Safety in Vehicle Platooning: A Systematic Literature Review," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, pp. 1033–1045, May 2017. Conference Name: IEEE Transactions on Intelligent Transportation Systems.

[14] C. Nowakowski, S. E. Shladover, X.-Y. Lu, D. Thompson, and A. Kailas, "Cooperative Adaptive Cruise Control (CACC) For Truck Platooning: Operational Concept Alternatives," tech. rep., UC Berkeley: California Partners for Advanced Transportation Technology, 2015.

[15] E. van Nunen, F. Esposto, A. K. Saberi, and J.-P. Paardekooper, "Evaluation of safety indicators for truck platooning," in *2017 IEEE Intelligent Vehicles Symposium (IV)*, pp. 1013–1018, June 2017.

[16] P. F. Hanley and D. J. Forkenbrock, "Safety of passing longer combination vehicles on two-lane highways," *Transportation Research Part A: Policy and Practice*, vol. 39, pp. 1–15, Jan. 2005.

[17] A. Garcia and D. Pastor-Serrano, "Determination of minimum horizontal curve radius for safe stopping sight distance of vehicles overpassing truck platoons," *Computer-Aided Civil and Infrastructure Engineering*, vol. 37, no. 5, pp. 539–557, 2022. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/mice.12758.

[18] V. Branzi, M. Meocci, L. Domenichini, and M. Calcinai, "A Combined Simulation Approach to Evaluate Overtaking Behaviour on Two-Lane Two-Way Rural Roads," *Journal of Advanced Transportation*, vol. 2021, p. e9973138, Aug. 2021. Publisher: Hindawi.

[19] R. Zhang, B. Qiong, K. Brijs, E. Hermans, Q. Qu, and Y. Shen, "Overtaking maneuvers on two-lane highways under the microscope: Exploration of a multidimensional framework for the analysis of safety, comfort and efficiency using simulator data," *Accident Analysis & Prevention*, vol. 202, p. 107613, July 2024.

[20] J. Chen, W. ShangGuan, B. Cai, M. Bhat, and Y. Du, "Intelligent Platoon Operating Slot Optimization Method based on Drivers' Overtaking Behavior," in *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, pp. 1947–1952, Oct. 2019.

[21] J. Chen, M. Bhat, S. Jiang, and D. Zhao, "Advanced Driver Assistance Strategies for a Single-Vehicle Overtaking a Platoon on the Two-Lane Two-Way Road," *IEEE Access*, vol. 8, pp. 77285–77297, 2020. Conference Name: IEEE Access.

[22] S.-F. Chao, S. M. Roldan, M. Jannat, M. Arnold, and I. Leidos, "Human Factors Issues Related to Truck Platooning Operations," Tech. Rep. FHWA-HRT-24-065, Federal Highway Administration, Mar. 2024.

[23] M. Walch, M. Woide, K. Mühl, M. Baumann, and M. Weber, "Cooperative Overtaking: Overcoming Automated Vehicles' Obstructed Sensor Range via Driver Help," in *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '19, (New York, NY, USA), pp. 144–155, Association for Computing Machinery, Sept. 2019.

[24] R. Fu, W. Liu, H. Zhang, X. Liu, and W. Yuan, "Adopting an HMI for overtaking assistance - Impact of distance display, advice, and guidance

information on driver gaze and performance," *Accident Analysis & Prevention*, vol. 191, p. 107204, Oct. 2023.

[25] V. Milanés, S. E. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura, "Cooperative Adaptive Cruise Control in Real Traffic Situations," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, pp. 296–305, Feb. 2014. Conference Name: IEEE Transactions on Intelligent Transportation Systems.

[26] V. Milanés and S. E. Shladover, "Handling Cut-In Vehicles in Strings of Cooperative Adaptive Cruise Control Vehicles," *Journal of Intelligent Transportation Systems*, vol. 20, pp. 178–191, Mar. 2016. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/15472450.2015.1016023.

[27] S. Bang and S. Ahn, "Control of Connected and Autonomous Vehicles with Cut-in Movement using Spring Mass Damper System," *Transportation Research Record*, vol. 2672, pp. 133–143, Dec. 2018. Publisher: SAGE Publications Inc.

[28] W. J. Scholte, P. W. A. Zegelaar, and H. Nijmeijer, "Gap Opening Controller Design to Accommodate Merges in Cooperative Autonomous Platoons∗," *IFAC-PapersOnLine*, vol. 53, pp. 15294–15299, Jan. 2020.

[29] W. J. Scholte, P. W. A. Zegelaar, and H. Nijmeijer, "A control strategy for merging a single vehicle into a platoon at highway on-ramps," *Transportation Research Part C: Emerging Technologies*, vol. 136, p. 103511, Mar. 2022.

[30] Y. Lu, L. Huang, J. Yao, and R. Su, "Intention Prediction-Based Control for Vehicle Platoon to Handle Driver Cut-In," *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, pp. 5489–5501, May 2023. Conference Name: IEEE Transactions on Intelligent Transportation Systems.

[31] L. Song, X. Ma, E. Hashemi, and H. Wang, "A Defensive Motion Framework for Autonomous Platoon to Handle Cut-in Maneuvers," in *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*, pp. 2590–2597, Sept. 2023. ISSN: 2153-0017.

[32] M. Patel, M. Khatun, R. Jung, and M. Glaß, "Simulation-based Analysis Of Highway Trajectory Planning Using High-Order Polynomial For Highly Automated Driving Function," in *2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*, pp. 1–6, Oct. 2021.

[33] Y. Kou and C. Ma, "Dual-objective intelligent vehicle lane changing trajectory planning based on polynomial optimization," *Physica A: Statistical Mechanics and its Applications*, vol. 617, p. 128665, May 2023.

[34] J. Ploeg, B. T. M. Scheepers, E. Van Nunen, N. Van De Wouw, and H. Nijmeijer, "Design and experimental evaluation of cooperative adaptive cruise control," in *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, (Washington, DC, USA), pp. 260–265, IEEE, Oct. 2011.