

Research Article

A Separation Strategy for Connected and Automated Vehicles: Utilizing Traffic Light Information for Reducing Idling at Red Lights and Improving Fuel Economy

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Vehicle platoon composed of a group of connected and automated vehicles (CAVs), a coordinated movement strategy, has been widely proposed to address a range of traffic problems. The motion of vehicle in the platoon passing signalized intersections can significantly affect their total trip time and fuel consumption. With the development of advanced communication technology such as V2V and V2I, CAVs can automatically obtain and use the upcoming traffic light timing information to find optimal velocity profiles that can avoid idling at red lights. This paper proposes an optimal velocity control and separation strategy for the platoon to minimize the trip time and reduce fuel consumption as much as possible. Simulation results show that with the introduction of the velocity control and separation strategy, the total trip time and fuel consumption decrease by 19.2% and 18.1%, respectively. Thus the effectiveness of the proposed strategy is demonstrated.

1. Introduction

In the connected and automated vehicles (CAVs) system, vehicles are capable of sharing information and sensing local environment with each other via the advanced communication technologies (e.g., V2V and V2I). The vehicles' information (e.g., location and velocity) and the road transportation infrastructure information (e.g., the traffic light timing, including the phase cycle length, the green phase length, and the start of the first green phase) will be obtained by every vehicle. After receiving such information, the internal decision-making mechanism will make corresponding driving decisions and then achieve the level of automatic driving. Under this circumstance, all CAVs will be platooned through communication and automated control technologies [1]. With CAV platooning, consecutive vehicles are similar to two concatenated carriages of a train and thus shall have much less time headway compared with a pair of conventional human driven vehicles.

All these potential benefits are linked to the expectation that CAVs can significantly improve traffic capacity, efficiency, and safety [2–5]. Studies by Lioris et al. have

shown that traffic capacity at signalized intersections could be doubled when vehicles on the road are connected to an intelligent network without changing the signal control [6, 7]. Chang and Edara also examined whether the road traffic efficiency could be further improved under CAVs environment [8].

World Oil Outlook 2016, issued by Organization of Petroleum Exporting Countries (OPEC), predicted that most of the oil consumed today and in the future will come from the road transportation sector. By 2040, the road transportation sector will represent 44% of global oil demand [9]. All the benefits provided by vehicle platooning are also linked to reduce fuel consumption. Lammert et al. conducted a comprehensive investigation on the effect of platooning on fuel consumption of class 8 vehicles, and they found saving of up to 6% for the leading vehicle and 10% for the following vehicle [10]. Alam et al. proposed a particular test to study the fuel reduction that heavy duty vehicle platooning enables and the analysis with respect to the influence of a commercial adaptive cruise control on the fuel consumption [11]. Tsugawa et al. presented an automated truck platoon that has been developed under a national ITS project named Energy ITS;

the results in their study show that the fuel can be saved by about 14 % [12].

Even if vehicle platooning has a certain advantage in traffic capacity improvement and fuel-saving, a huge wastage of traffic capacity and fuel will occur due to the stoppage at signalized intersection during its red phase. Idling at red lights will decrease traffic capacity and increase fuel consumption from many aspects:

(1) **Stop-and-go motion.** X. Zhang et al. proved that fuel consumption and exhaust gas emission can remarkably decrease when the acceleration and deceleration of vehicles are pretty gentle; idling at red light or traveling in a mode of stop-and-go will consume more fuel and emit more greenhouse gases comparing with the vehicles in free flow [13]. Research by Wan N et al. emphasized that, due to vehicles' stop-and-go motion, they need to consume more energy than that during cruising [14].

(2) **Intersection delays.** Intersection delays may include queue delay and control delay. Ch. Ravi Sekhar et al. estimated delay and fuel loss during idling at signalized intersections. The simulation results showed that heavy delays and a huge wastage of fuel at intersections are caused due to stoppage of vehicles during the red phase of the signals, because many vehicles need to stop as a consequence of their arrival either during the red interval or during the green interval when the queue of vehicles that had formed during the previous red interval has not yet fully dissipated [15].

(3) **Congestion.** On the other hand, heavy delays at intersections may result in traffic congestion especially in heavy volume arterial corridor, which will cause a large amount of financial loss, including more traffic capacity and fuel loss. INRIX, a joint traffic data company in London, quantitatively analyzed the impact of traffic congestion on Britain, France, Germany, and the United States. In 2013, the four countries lost 200 billion dollars caused by traffic congestion, accounting for 0.8% of the total GDP of the four countries.

Therefore, a number of benefits can be obtained in limiting the idling time at red light. These benefits include increasing traffic efficiency, saving in fuel use, reduction in exhaust emissions, and even vehicle life extension. In recent years, the exponential increase in the number of vehicles in urban city has resulted in congestion and more fuel consumption at intersections. Traffic efficiency improvement and fuel economy have been paid more attention than ever. Thus, from the perspective of traffic efficiency improvement, travel comfort, and traffic energy conservation, it is of great importance to keep the traffic flow smooth and reduce red light idling.

Besides the fuel wastage at intersection due to the operation of signals, fuel consumption can also be affected by other factors along the entire trip, such as cruising speed, the intervehicle distance, and traffic conditions [16]. With the advanced control system installed on CAVs, all the vehicles can realize autonomous velocity control along the entire trip. Motivated by the problems mentioned above, this paper investigates one optimal platoon velocity control and separation strategy defined to find the optimal velocity

profiles on signalized arterials that can avoid idling at red lights and improve fuel economy along the entire trip.

The rest of this paper is organized as follows. Section 2 introduces the conceptualization of vehicle platoon and analyzes the optimization goals in this study. Section 3 proposes the optimal platoon separation and velocity control strategy used in this paper to minimize the trip time and reduce the fuel consumption. The simulation results are presented and discussed in Section 4, and conclusion is given in Section 5.

2. Problem Statement

In this section, the conceptualization of the vehicle platoons in a short length is firstly introduced. Then the objective function of reducing the platoons idling at red lights is formulated. Finally, the formula for the minimum fuel consumption is introduced.

2.1. Conceptualization of Vehicle Platoons. Maiti et al. provided a detailed concept of vehicle platoon [1]. A vehicle platoon generally consists of one leader vehicle and a number of follower vehicles. The leader vehicle takes all decisions on behalf of the whole platoon and controls all the platoon members accordingly; all vehicles in the same platoon share the same velocity. Each platoon has its own ID. And the size of platoon is a dynamic property, which implies the current number of vehicles in platoon; the maximum size of a platoon means the maximum number of vehicles grouping together in a platoon. Each vehicle in a platoon also has its vehicle ID. As mentioned above, the role of a vehicle can be divided into leader vehicle and follower vehicle; the role may get updated by platoon operations (e.g., separation or merging), which means follower vehicle may change into leader vehicle when doing the separation operation, and leader vehicle will also become follower vehicle when the merging operation happens.

A platoon of CAVs is actually a network of dynamical systems, S. E. Li et al. presented a four-component framework to model, analyze, and synthesize a platoon of CAVs from the perspective of multiagent consensus control [17]. When a platoon is driving on the road, the leader vehicle can communicate with the transportation infrastructure relying on the V2I technology. The leader vehicle transmits the platoon's position, size, destination, and other traffic parameters to the transportation infrastructure, to avoid idling at red lights; the leader vehicle can obtain feedback velocity information from the control center who can give feedback on optimal velocity to the leader vehicle according to the green light duration and traffic flow information. When the leader vehicle receives the velocity information, it will transfer this velocity information to other follower vehicles immediately through V2V technology. Therefore vehicles in the same platoon can share the same velocity and then achieve unified operation; the platoon driving schematic diagram can be shown in Figure 1. As for the quality of information flow exchange among vehicles, some scholars addressed the internal stability and scalability issue for platoon under different information topologies; e.g., Y. Zheng et al. have studied the influence of information flow topology on the

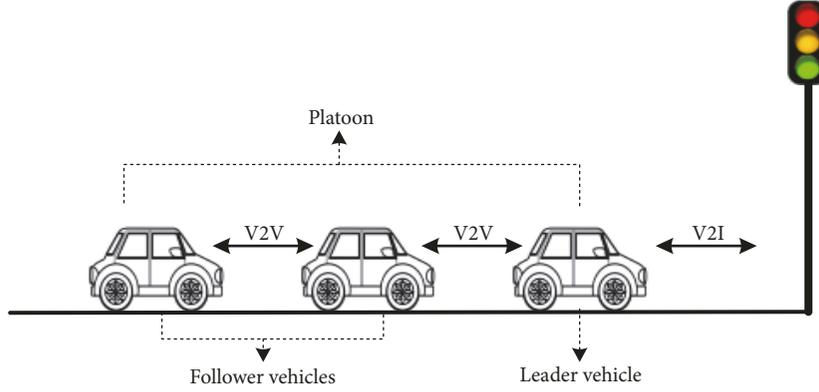


FIGURE 1: Platoon driving schematic diagram.

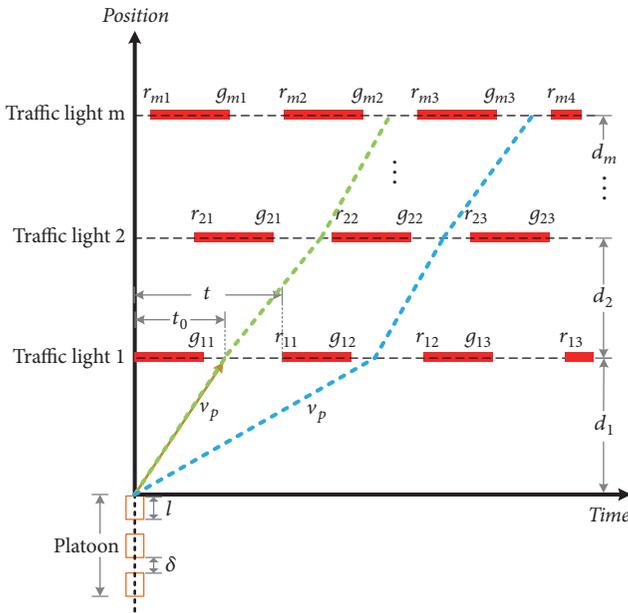


FIGURE 2: Schematic of the trajectory and velocity of leader vehicle.

internal stability and scalability of homogeneous vehicular platoon [18].

2.2. Idling at Red Light. The process of vehicle stopping at the red light and leaving when the light turns green is actually the stop-and-go motion, as mentioned in Section 1; in order to enhance vehicles' safety, energy efficiency, and mobility, the idling at the red light should be reduced as much as possible.

The schematic of the candidate trajectory and velocity of the leader vehicle at each intersection is shown in Figure 2; the green and the blue dotted lines denote the candidate trajectories of the leader vehicle in a platoon at different velocity, with the parameters defined as follows:

- (1) The traffic light information of i th intersection is represented by $\{r_{ij}, g_{ij}\}; i = 1, 2, \dots, m, j = 1, 2, \dots, \infty$, where r_{ij} is the start of j th red phase and g_{ij} is the start of j th green phase at i th signalized intersection.

- (2) d_i is the distance between consecutive intersections, that is, the distance between the i -1st traffic light and the i th traffic light (called i th segment); in particular, for a platoon, d_1 is the distance to the first upcoming traffic light and the d_2 is the distance between the first upcoming traffic light and the second traffic light, which can be estimated from the vehicle's GPS and the traffic light's location information.

- (3) Let l denote average length of a vehicle and δ represent Gap distance between a pair of consecutive vehicles in a platoon

Our goal is to find a permit velocity of platoon which aids in minimizing idling at the red light. The problem of idling at the red light can be transformed into the platoon's waiting time at the traffic light. Based on the signal timing information and platoon information, total waiting time of all vehicles at all traffic lights can be calculated as

$$Z = \sum_{k=1}^n \sum_{i=1}^m \left\{ t_r^i - \text{mod} \left[\frac{d_i + \theta v_p^i(k) + (k-1)(l + \delta)}{v_p^i(k) t_{cycle}^i} \right] \right\} \quad (1)$$

where

Z is the sum of the platoon's waiting time at all the traffic lights;

k is the vehicles' ID number in a platoon, $k = 1, 2, \dots, n$;

i is the traffic lights' number during the trip, $i = 1, 2, \dots, m$;

t_r^i is the red light duration in the i th traffic light, $t_r^i = g_{ij} - r_{ij}$;

θ is the compensation time, for the case of $r_{i1} \neq 0$;

$v_p^i(k)$ is the passing velocity of k th vehicle in a platoon at i th signalized intersection;

t_{cycle}^i is the cycle of traffic signals at the i th traffic light;

$t_{cycle}^i = g_{i,j} - g_{i,j-1}$ or $r_{i,j} - r_{i,j-1}$.

Vehicles in the same platoon share the same velocity; *i.e.*, $v_p^i(k) = v_p^i$, where v_p^i denotes the passing velocity of a platoon at i th signalized intersection whose unit is m/s. Specifically, Z only takes a result greater than 0; that is, when the operation result of Z is less than 0, the final result of Z is equal to 0.

2.3. Fuel Consumption. Before studying the influence of idling at red light and velocity on fuel consumption, we introduce the fuel consumption model. Many efforts have been made to understand the relationship between traffic activities and fuel consumption rate; many researchers modeled fuel consumption as a function of vehicle load and average speed [19–22]. There are a number of microscopic fuel consumption models; we use the model proposed by Kamal et al. [23]. This is because of its simplicity; calculating the fuel consumption only uses the instantaneous velocity of platoon. Based on this model, optimal velocity could be found to minimize fuel consumption. Kamal et al. sampled sufficient data from a passenger size vehicle and fitted it into a third order polynomial curve that approximates the relation between fuel consumption rate and velocity. In this model, the fuel consumption rate \dot{m} is estimated as

$$\dot{m} = \alpha_0 + \alpha_1 v_p^i + \alpha_2 (v_p^i)^2 + \alpha_3 (v_p^i)^3 \quad (2)$$

where α_0 , α_1 , α_2 , and α_3 are corresponding coefficients, whose values are presented in Table 3.

Hence, during the whole trip, for each vehicle in the same platoon, the fuel consumption can be calculated as

$$J = \left[\alpha_0 + \alpha_1 v_p^i + \alpha_2 (v_p^i)^2 + \alpha_3 (v_p^i)^3 \right] t_i(k) \quad (3)$$

where $t_i(k)$ represents the trip time of k th vehicle of platoon in i th segment.

Assuming that all the vehicles run at constant speed in each segment ignoring the acceleration or deceleration process, then, for all vehicles in a platoon passing all the intersections without idling, the total fuel consumption can be calculated as

$$J = \sum_{k=1}^n \sum_{i=1}^m \left[\frac{\alpha_0}{v_p^i} + \alpha_1 + \alpha_2 v_p^i + \alpha_3 (v_p^i)^2 \right] \cdot [d_i + (k-1)(l+\delta)] \quad (4)$$

2.4. Optimization Problem and Complexity Analysis. The objective of this paper is to minimize two performance indexes $Z = f(v_p^i(k))$ and $J = f(v_p^i(k))$, *i.e.*, the waiting time at red lights and fuel consumption, by determining velocity profiles $v_p^i(k) = \{v_1, v_2, \dots, v_m\}$ for each vehicle at each segment subject to certain constraints, which will be introduced in detail in Section 3. Obviously, the total waiting time at all the traffic light can be reduced to 0 as long as all the vehicles pass with a suitable velocity to ensure no idling at red light.

Y. Zheng et al. analyzed the complexity of a known green light optimal velocity (GLOV) problem, finding, *e.g.*, optimal

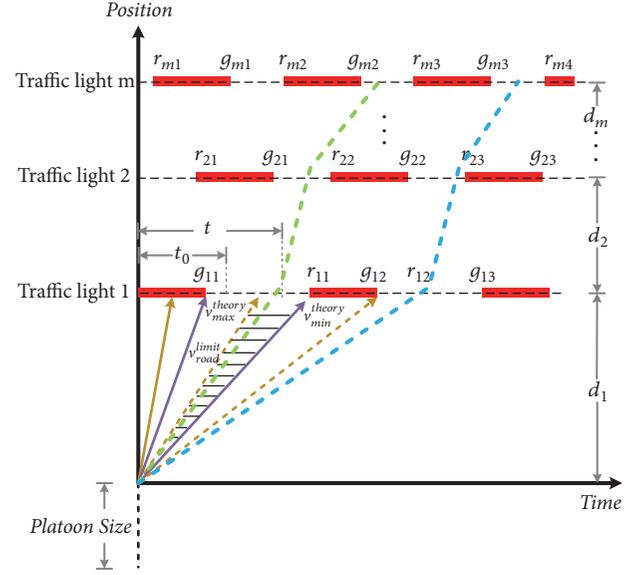


FIGURE 3: Allowable velocity bound for platoon.

velocity that can avoid idling at red lights and minimize the trip time [24]. The complexity analysis shows that GLOV with binary velocity choices belongs to NP-complete, which means it cannot be numerically solved in polynomial time unless $P=NP$. Intuitively, it is much more difficult to solve this problem with more velocity choices; the number of possible solutions will increase exponentially.

In order to ensure effective solution to our proposed problem, approximation algorithm is proposed in the following optimization strategy. We consider finding optimal velocity profiles for each platoon to save fuel consumption as much as possible while ensuring the improvement of traffic efficiency, that is, to let the maximum number of vehicles pass without idling at red light as much as possible even if the current velocity does not guarantee the lowest fuel consumption.

3. Optimization Strategy

This section focuses on the introduction and analysis of optimization strategy to solve the problem defined in Section 2.

3.1. Allowable Bounds Analysis for Optimal Velocity Selection.

To ensure that all the vehicles in the platoon could pass all the traffic lights without idling at red lights, it must be firstly met that the leader vehicle in a platoon can pass through the intersection during its green phase. The allowable velocity bound for a platoon is shown in Figure 3, with the parameters defined as follows:

- (1) $v_{max}^{theory}(i, j)$ and $v_{min}^{theory}(i, j)$ represent the maximum and minimum theory velocity of the leader vehicle of a platoon to pass the i th traffic light without idling during its j th green phase, respectively. Assuming that the vehicles run at constant speed in each segment ignoring the acceleration or deceleration process, then the maximum and minimum theory

velocity for the leader vehicle can be calculated as $v_{max}^{theory}(i, j) = d_i/g_{ij}$, $v_{min}^{theory}(i, j) = d_i/r_{ij}$.

- (2) v_{road}^{limit} denotes the maximum velocity limit of the road, which is specified by the government agency on each segment. In this paper, assuming that it is the same for all segments along the road and setting it as 20m/s in following simulation, it is worth noting that its value may be greater or less than v_{max}^{theory} , or even equal to v_{max}^{theory} .
- (3) Let $v_{max}^{permit}(i, j)$ present the maximum passing velocity for a platoon to pass the intersection without idling.

For example, if $[v_{min}^{theory}(1, 1), v_{max}^{theory}(1, 1)] \cap [0, v_{road}^{limit}] \neq \emptyset$ and the leader vehicle wants to pass the first upcoming traffic light during the first green light, the passing velocity v_p should belong to the set intersection $[v_{min}^{theory}(1, 1), v_{max}^{theory}(1, 1)] \cap [0, v_{road}^{limit}]$, as shown in the shaded part in Figure 2. In this case,

$$v_{max}^{permit}(i, j) = \begin{cases} \min\{v_{max}^{theory}(i, j), v_{road}^{limit}\}, & \text{if } v_{max}^{theory}(i, j) \neq v_{road}^{limit} \\ v_{max}^{theory}(i, j) = v_{road}^{limit}, & \text{otherwise.} \end{cases} \quad (5)$$

However, if $v_{road}^{limit} < v_{min}^{theory}(1, 1)$ which means $[v_{min}^{theory}(1, 1), v_{max}^{theory}(1, 1)] \cap [0, v_{road}^{limit}] = \emptyset$, the leader vehicle has to decrease current velocity and pass the first upcoming traffic light in its second green phase only if $[v_{min}^{theory}(1, 2), v_{max}^{theory}(1, 2)] \cap [0, v_{road}^{limit}] \neq \emptyset$, as shown by the blue dotted line in Figure 3; the passing velocity should also follow the restriction of $v_p \in [v_{min}^{theory}(1, 2), v_{max}^{theory}(1, 2)] \cap [0, v_{road}^{limit}]$.

To sum up, the leader vehicle will find the possibility of passing during j th green phase at i th signalized intersection until the set intersection $[v_{min}^{theory}(i, j), v_{max}^{theory}(i, j)] \cap [0, v_{road}^{limit}]$ is not empty. That is, to ensure that all vehicles can pass all the traffic lights without idling, our optimal velocity solution v_p^i for a platoon should satisfy

$$v_p^i \in \left[\frac{d_i}{r_{ij}}, \frac{d_i}{g_{ij}} \right] \cap [0, v_{road}^{limit}] \neq \emptyset, \quad j = 1, 2, \dots, \infty. \quad (6)$$

3.2. Velocity Control and Separation Strategy of Platoon. The detailed process of separation strategy of platoon will be introduced in this section.

According to the concept of vehicle platooning, all vehicles in the same platoon share the same velocity, which means the follower vehicles' trajectory will be parallel to the trajectory of the leader one. If we draw a line parallel to the v_p^i velocity line of the leader vehicle, the intercept on the position axis is the maximum platoon size that can pass the i th intersection during one of its green phases, as shown in Figure 4. It is easy to find that the number of vehicles of a platoon that can pass without idling will increase with the increase of passing velocity.

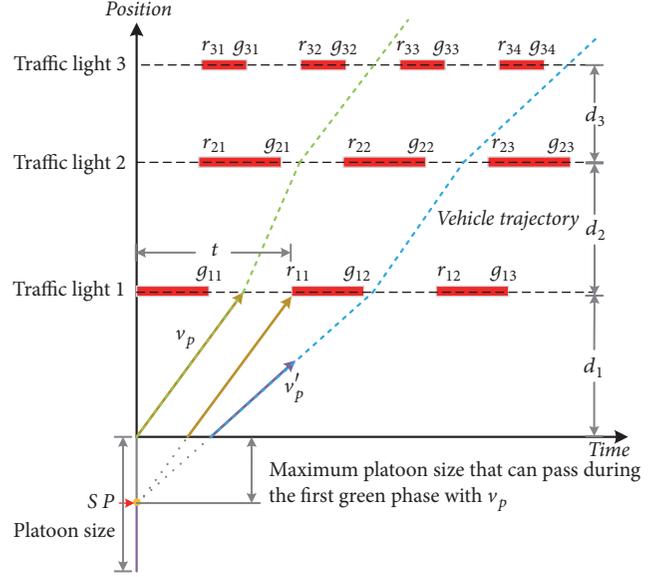


FIGURE 4: Schematic of the separation strategy.

Let $L(v_p)$ denote the maximum platoon size at velocity v_p and $L(platoon)$ represent the real platoon size.

$$L(v_p) = v_p r_{ij} - d_i \quad (7)$$

$$L(platoon) = (n - 1)(l + \delta)$$

If $L(v_p)$ is less than $L(platoon)$, some follower vehicles will stop at the red light if they keep the current velocity. To avoid idling at red light for the rest vehicles, they need to decelerate to pass during the next green phase. In other words, the rest vehicles should separate from the original platoon and recombine to a new platoon, that is, our proposed velocity and separation strategy. A new replanning velocity v_p' will be given to this new platoon to ensure that the maximum number of vehicles in this new platoon can pass the traffic light in the next green light.

The maximum number of vehicles that can pass during the first green phase at the first upcoming intersection can be calculated as

$$n_p = \left\lceil \frac{v_p t - d_1}{l + \delta} \right\rceil. \quad (8)$$

As introduced in Section 2.1, each platoon has its own ID, and the vehicles in each platoon also have their own IDs, respectively (e.g., the leader vehicle, 2nd vehicle, ..., n_p th vehicle, $(n_p + 1)$ th vehicle, ..., m th vehicle). When the platoon needs to do the separation strategy, the leader vehicle will send the separation command to the $(n_p + 1)$ th vehicle, who will become the new leader vehicle of a new platoon and obtain a replanning velocity v_p' . Therefore, there exist a separation point (SP) between n_p th vehicle and $(n_p + 1)$ th vehicle, as shown in Figure 4.

Vehicles before the separation point (SP) belong to the original platoon, which will pass the first intersection during

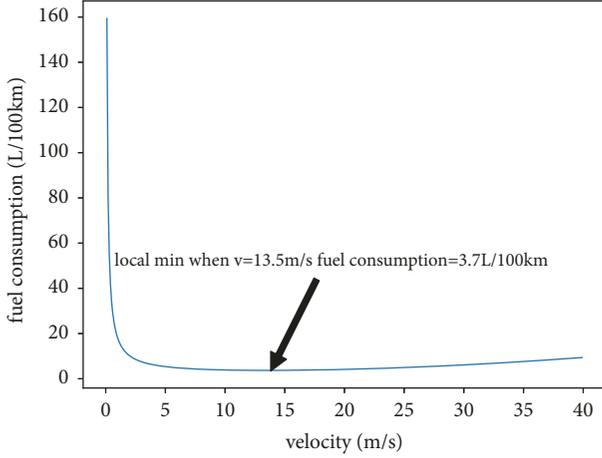


FIGURE 5: The fuel consumption at different velocity.

its first green phase. The new platoon consists of those vehicles behind SP that need to decelerate to v_p' to avoid idling at red light. The velocity space for the replanning velocity v_p' is similar to the passing velocity v_p except $j = 2, 3, \dots, \infty$.

$$v_p' \in \left[\frac{v_p^t}{r_{ij}}, \frac{v_p^t}{g_{ij}} \right] \cap [0, v_{road}^{limit}] \neq \emptyset, \quad j = 2, 3, \dots, \infty \quad (9)$$

Let $v_{optimal}^{fuel}$ denote the optimal velocity in case of lowest fuel consumption. According to the fuel consumption formula (4) with the parameters' value in Table 3, we can see that when the velocity is equal to 13.5m/s, the fuel consumption is minimal, as shown in Figure 5. That is $v_{optimal}^{fuel} = 13.5m/s$.

On the one hand, our first goal in this paper is to improve traffic efficiency by avoiding idling at red light; at each section for a platoon, we can choose the maximum passing velocity v_{max}^{permit} for a platoon, which can ensure that maximum number of vehicles can pass without idling. On the other hand, a goal to minimize fuel consumption as much as possible is also taken into consideration in this paper as mentioned in Section 2. Obviously, the optimal fuel velocity does not necessarily satisfy the need for letting maximum number of vehicles pass at each green phase. In other words, the maximum passing velocity v_{max}^{permit} is not necessarily the most fuel-efficient. Hence, a velocity control strategy is also considered based on the separation strategy. The velocity control and separation strategy to obtain the optimal platoon velocity profiles for all vehicles in the platoon is shown in Figure 6.

Take the first intersection, for example; one optimal solution to the problem defined in Section 2 can be constructed by the following steps:

Step 1. Check if $v_{optimal}^{fuel}$ belongs to the interval $[v_{min}^{theory}(1, 1), v_{max}^{permit}(1, 1)]$, where $v_{max}^{permit}(1, 1)$ satisfies (5); if it belongs to it, turn to Step 2; otherwise, turn to Step 3.

Step 2. Compare the maximum platoon size $L(v_{optimal}^{fuel})$ at velocity $v_{optimal}^{fuel}$ and the actual platoon size $L(platoon)$, which can be calculated according to (7). If $L(v_{optimal}^{fuel}) \geq L(platoon)$, which means that all vehicles in the original platoon can pass the first intersection during its first green phase with velocity $v_{optimal}^{fuel}$, then choose the passing velocity $v_p = v_{optimal}^{fuel}$. Otherwise, turn to Step 3.

Step 3. Compare the platoon size $L(v_{max}^{permit})$ with velocity v_{max}^{permit} and the actual platoon size $L(platoon)$. If $L(v_{max}^{permit}) \geq L(platoon)$, which means that the platoon can pass the intersection with a velocity below v_{max}^{permit} , taking into account fuel economy, the platoon pass with velocity v_p that minimizes the fuel consumption:

$$v_p = \begin{cases} v_{min}^{all} & \text{if } J(v_{min}^{all}) \leq J(v_{max}^{permit}) \\ v_{max}^{permit} & \text{if } J(v_{min}^{all}) > J(v_{max}^{permit}) \end{cases} \quad (10)$$

where v_{min}^{all} means the minimum velocity that can ensure all vehicles pass without idling when $L(v_{max}^{permit}) \geq L(platoon)$.

$$v_{min}^{all} = \frac{(n-1)(l+\delta) + d_1}{r_{11}} \quad (11)$$

If $L(v_{max}^{permit}) < L(platoon)$, which means that all vehicles cannot pass the intersection during its first green phase, even with the max velocity, then turn to Step 4.

Step 4. The original platoon is separated into two new platoons: platoon 1.1 and platoon 1.2. To ensure that as many vehicles as possible can pass the intersection within a green phase, the new platoon 1.1 will pass the intersection with velocity v_{max}^{permit} . And for the new platoon 1.2, return to Step 1 again to find an optimal passing velocity v_p' to pass the intersection during its next green phase.

For the remaining intersections, the process to find the optimal velocity solution is almost similar to the above steps, except that at Step 1, we check if $v_{optimal}^{fuel}$ belongs to $[v_{min}^{theory}(i, 1), v_{max}^{permit}(i, 1)]$ for i th intersection.

4. Simulation Case Studies

The route is assumed to have 4 intersections, and the parameters of the traffic light location and timing information are shown in Table 1. The platoon and road information is shown in Table 2. The parameter values of fuel economy model (5) are shown in Table 3. The simulations are run in MATLAB on an Intel® Core™i7 processor with 3.40 GHz processing speed per core, 8 GB of RAM.

4.1. Simulation 1: Conventional Strategy without Separation Strategy. Firstly, we study the case of conventional strategy; the separation strategy is not activated.

In the simulation, we consider a platoon of 20 vehicles. Figure 7 shows the simulation results of the velocity profile of

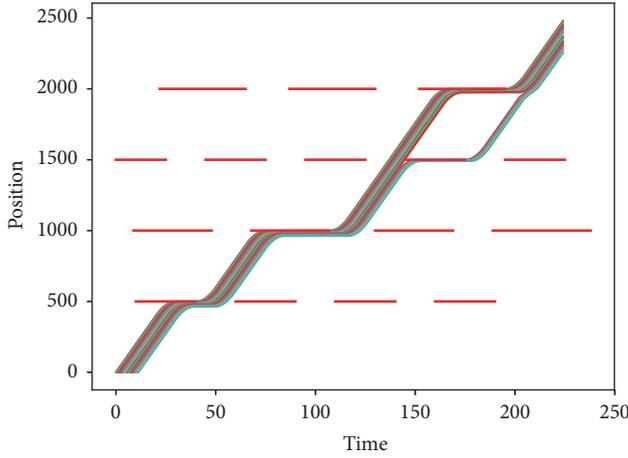


FIGURE 7: Trajectory of vehicles of platoon without separation strategy.

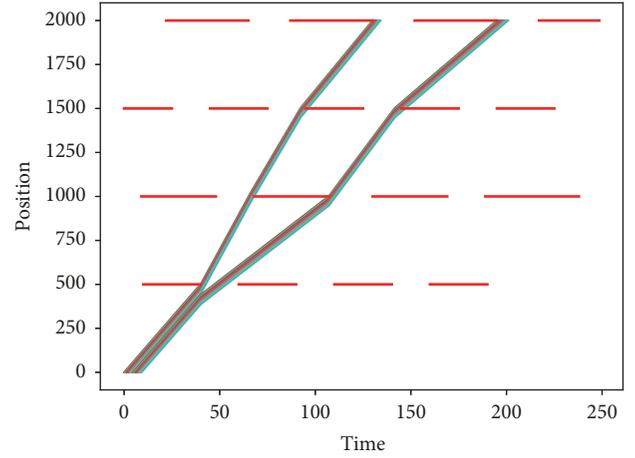


FIGURE 9: Vehicles' trajectory of platoon with separation strategy (*maximum passing velocity*).

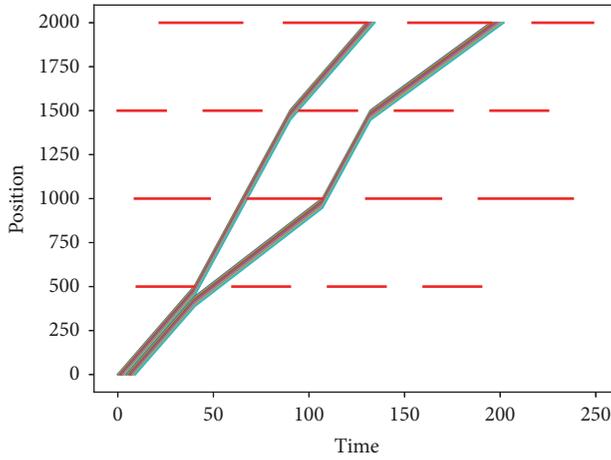


FIGURE 8: Trajectory of vehicles of platoon with separation strategy (*minimum fuel consumption*).

shown in Figure 8. One can see that the separation of original platoon occurs at the first intersection, dividing it into two new platoons. The separation point is located at the 11th vehicle, and the velocity profile of 1st vehicle and 11th vehicle is

$$\begin{aligned} v_p(1) &= \{12.5m/s, 20m/s, 18.6m/s, 13.1m/s\} \\ v_p(11) &= \{12.5m/s, 8.3m/s, 14.5m/s, 9.3m/s\}. \end{aligned} \quad (12)$$

4.3. Simulation 3: Separation Strategy without Considering Fuel-Saving. In order to better understand how our proposed velocity control and separation strategy achieves fuel-saving under the premise of guaranteeing that maximum number of vehicles can pass the intersection without idling, we implement another simulation in which all the vehicles choose the maximum velocity to pass intersections without considering fuel-saving. This simulation is almost similar to simulation 2 except that all vehicles pass all the intersections with maximum passing velocity v_{max}^{permit} . Figure 9 shows velocity

profile of each vehicle in the platoon under this circumstance. The velocity profile of 1st vehicle and 11th vehicle with this strategy is as follows:

$$\begin{aligned} v_p(1) &= \{12.5m/s, 20m/s, 20m/s, 12.5m/s\} \\ v_p(11) &= \{12.5m/s, 8.3m/s, 20m/s, 7.9m/s\}. \end{aligned} \quad (13)$$

Comparing with our proposed separation strategy that considers fuel-saving, we find that the main difference between these two different situations is reflected at the third intersection. Under the premise of ensuring that all vehicles can pass without idling, our proposed separation strategy chooses the velocity that can minimize the fuel consumption, but this strategy chooses the maximum velocity to pass the intersection.

4.4. Evaluation of Proposed Velocity Control and Separation Strategy. Figure 10 shows that the fuel consumption and total travel time decrease with the introduction of our proposed velocity control and separation strategy.

One can see that the fuel consumption of each vehicle decreases dramatically with our proposed separation strategy. For the platoon with 20 vehicles, the total fuel consumption decreases by 18.1% comparing with the conventional strategy. By minimizing the fuel costs, we also implicitly increase some of the societal benefits of our proposed platoon separation strategy. Minimizing fuel consumption is equivalent to minimizing emissions [25]. Also, when we minimize the fuel costs, longer platoons are preferred as the total savings will be higher with more following vehicles in the system.

With our proposed separation strategy, the total travel time decreases by 19.2% compared with the conventional strategy. The first ten cars are particularly noticeable thanks to velocity control and separation strategy. In other words, traffic efficiency has improved. And longer platoons are associated with more efficient road utilization since the vehicles within a platoon drive closer together. The reduced space utilization as a result of platooning might help improve the traffic throughput.

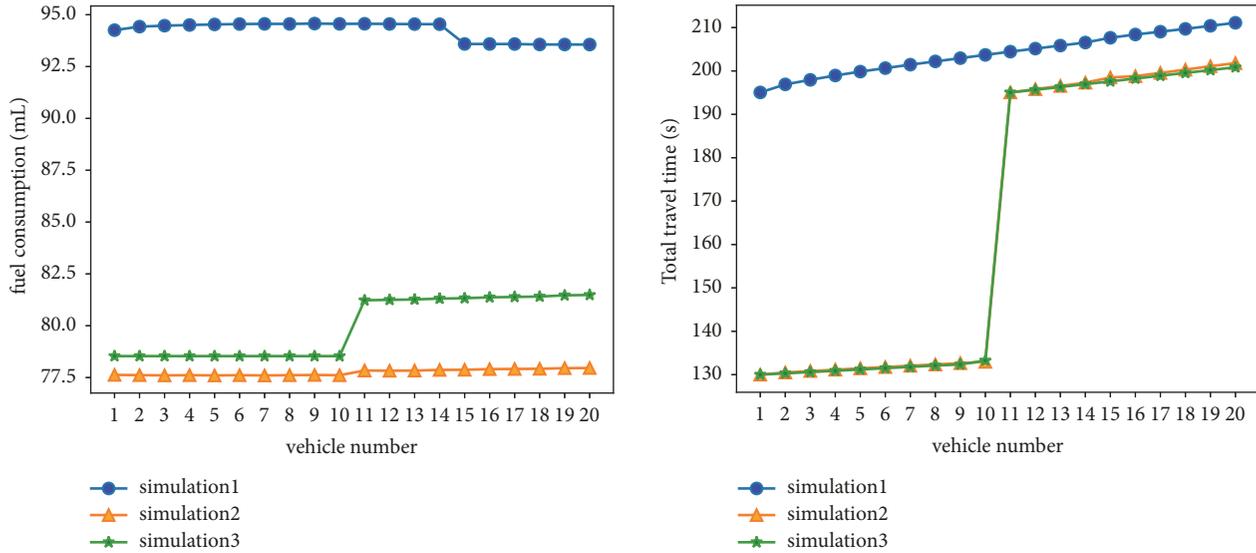


FIGURE 10: The total fuel consumption and the total travel time of each vehicle.

Intuitively, passing with the maximum velocity means that the travel time is the minimum. It is worth noting that this conclusion is only valid for a single intersection. Interestingly, for multiple intersections, the total travel time is not necessarily the smallest even if the maximum velocity is selected at each intersection, which is determined by the difference of signal phase between two consecutive signalized intersections. If the green phase difference of two adjacent intersections is very gentle, vehicles cannot pass these two intersections continuously during the same green phase due to the maximum velocity limit. In other words, even if the maximum speed is selected at the previous intersection, the platoon can only pass the consecutive intersection until its next green phase by reducing more velocity. This will probably lead to a decrease in the overall average speed, which in turn increases the total travel time. As we can see in Figure 10, the travel time of 10th–20th vehicle in simulation 2 is slightly less than that in simulation 3, although maximum velocity is selected at each intersection in simulation 3. This is because the green phase difference between 3rd and 4th intersection is very gentle. Therefore, passing with the maximum velocity may not necessarily improve traffic efficiency; on the contrary, choosing the optimal fuel consumption may even improve traffic efficiency in some cases.

5. Conclusion

A velocity control and separation strategy aimed at avoiding idling at red light and reducing fuel consumption as much as possible was proposed in this paper. The simulation results suggested that our proposed strategy effectively improves the performance of the platoon. The total travel time and the fuel consumption were reduced by 19.2% and 18.1%, respectively. The ultimate objectives of platooning are to enhance highway safety, improve traffic utility, and reduce fuel consumption. The main novelty and contribution of this work is providing an optimal platoon velocity control method

and a separation strategy at signalized intersection that considers both traffic utility improvement and fuel economy. Additionally, it is worth noting that the using scenarios of this strategy involve multiple intersections instead of only one single signalized intersection, and this strategy can be applied to full autonomous or semiautonomous vehicles in the future.

Several extensions to the present study are desired in the future. Some assumptions made in this study could be violated, and we caution against generalizing the results. We would like to mention that the simulation results are based on the assumption that all vehicles run at a constant velocity ignoring the acceleration or deceleration process. Actually, the fuel consumption and the state of the platoon system may change with the acceleration or deceleration process. Additionally, this paper only considers the separation strategy of a single static platoon and ignores the dynamics of platooning process between multiple platoons. The dynamics increase the complexity of the decision-making process.

Therefore, each problem discussed above presents an important and very challenging research topic. In the future work, the impact of acceleration and deceleration process on fuel consumption and travel time needs to be investigated to examine the validation of the simulation results. Nevertheless, this paper provides an explicit strategy to better improve the traffic efficiency and fuel-saving in a vehicle platoon.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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