PALM: Platoons Based Adaptive Traffic Light Control System for Mixed Vehicular Traffic

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***Abstract*—With the development of autonomous vehicles, a mixed traffic flow scenario of Connected Autonomous Vehicles (CAV) and Human-Driven Vehicles (HVs) would be popular in the near future. The traditional traffic light control systems (TLCSs) for HVs do not make full use of traffic information collected via VANET; meanwhile emerging traffic light systems for CAV assume complicated and quick reactions, which human drivers may not be able to handle. Therefore, they are not suitable for the mixed scenario. This paper proposed a novel TLCS, named PALM, for tackling the challenge for handling mixed traffic scenarios. PALM considers the traffic flow at each intersection and adjacent ones and adjusts the traffic lights schedule for the next few phases accordingly. It also optimizes the signal timing and phases to better serve the platoons formed by CAV. The simulation results show that our approach achieves up to 75.34% and 33.02% drop in the average waiting time compared to the static and actuated TLCS, respectively.**

***Index Terms*—Traffic light control system, Connected Autonomous Vehicles, Intelligent transportation, Smart City.**

I. Introduction

There has been a rapid development of autonomous vehicle (AV) technologies in recent years. AVs are expected to become the mainstream due to improved road safety, and increased driver convenience [1]. Yet, there are more than 1.282 billion human-driven vehicles in operation worldwide [2] with the average vehicle longevity exceeding 12 years [3]; it is thus expected that AV and HVs will co-exist in near future [4]. The coexistence will make the traffic management even harder. The efficiency of traffic management is closely correlated with TLCSs at the intersections. Indeed, traffic lights continue to be a major contributor to reducing congestion.

CAVs, combining AVs and Vehicular Ad-hoc Networking (VANET), can facilitate traffic management [5], where a TLCS factors in incoming traffic in advance to provide the best traffic lights schedule, e.g., to minimize the average waiting time. CAV can accelerate and decelerate based on TLCS guidance [5]. In addition, CAV can form platoons automatically to reduce the space between each other, leading to full use of the road capacity. According to [6], the vehicle density on highways can be up to 8,000 vehicles per lane per hour when using platoons compared with today's 2,000 HVs only. This pattern leads to a significant traffic improvement. Furthermore, the traffic light infrastructure is not even needed since CAVs can communicate with each other and negotiate the best order for intersection crossing.

However, those TLCSs designed for CAV are not suitable for human drivers. Firstly, they make use of the CAV ability to act quickly. Obviously, human drivers cannot respond that fast. Secondly, traffic lights are necessary for safe coordination and determining the right to pass for human drivers. Consequently, a TLCS design is needed to handle the presence of CAVs and HVs. This paper proposed an Platoons Based Adaptive Traffic Light Control System for Mixed Traffic of CAV and HVs. It extends our previous TLCS system [7] designed for HVs to tackle the challenge of mixed traffic flow scenarios. After analyzing the traffic flow at each intersection and their nearby intersections, the phases and signal timing are dynamically adjusted. Furthermore, our approach takes platoons into consideration in optimizing the average waiting time. The simulation results indicate that the average waiting time reduction is as large as 75.34% and 33.02%, compared to the traditional static and actuated traffic light systems, respectively.

The following sections are organized as follows: Section II covers related work. Section III introduces the relevant parameters. The details of our proposed approach are provided in section IV. Section V presents the simulation results. Finally, the paper is concluded in Section VI.

II. Related Work

Dynamic adjustment of traffic lights has been pursued for improving HV traffic flow in urban setups [7]. Work that focuses on TLCS for HVs can be classified into two categories based on whether a single or multiple intersections are considered in determining the signal timing. For a single intersection, the objective is to optimally schedule the green signal. For example, in [8] the TLCS is assumed to know the destination of vehicles coming at the intersection; two green light scheduling strategies are proposed, namely, least minimum and least average distance to destination with the objectives of reducing average waiting/travel time. Similarly, K. Pandit et al. [9] model the signal timing at one intersection as a job scheduling problem on processors, where jobs and processors correspond to platoons and traffic lights, respectively. Our approach avoids such complication and pursues heuristics. Meanwhile, the focus of [10] is on reducing the number of stops to ameliorate CO_2 emission.

Moreover, S. Kwatirayo et al. [11] opt to improve the conventional pre-timed traffic light signals where the timing of G/Y/R/all-R cycle (GYRCT) is determined based on average traffic load. The approach enables the support of multiple traffic patterns, e.g., cycles within the day, where the duration of GYRCT is adjusted based on the anticipated traffic pattern. However, the approach is quasi-static in nature and does not adapt to unanticipated traffic fluctuations. Meanwhile, Hu and Wang [12] strive to decrease the average waiting time at an intersection by considering upstream and downstream traffic density. A wireless sensor network is used to monitor the traffic condition. B. Zhou et al. [13] also rely on street-mounted sensor nodes to assess traffic and use the collected data to adjust green lights in order to improve the waiting time, and number of stops. The focus of [14] is on reducing the time and space complexity for solving the traffic signal control problem to improve the average waiting time.

In the second category of work, multiple neighboring intersections are considered in the traffic flow optimization. For example, rule-based reinforcement learning with an additional hierarchical observer/controller component is presented in [15], where coordination with TLCS of neighboring intersections is pursued to optimize the performance. Moreover, multi-agent based algorithms have been applied to TLCS [16]–[21]. Mario et al. employ multiple fuzzy logic controllers, interconnected using IEEE 802.15.4 technology, and dynamically order phases and calculate green time while factoring turns [16]. In addition, M. Elgarej et al. [17] employ sensors to monitor traffic volume variations, based on which they use a distributed multi-agent system to find the shortest green period so that the experienced waiting time at intersections is minimized. Multi-agent reinforcement learning algorithms are exploited in [18]–[21], where the reactions by local and nearby intersections are considered to adjust the traffic lights timing. Moreover, Aleko et al. synchronize multiple traffic lights at consecutive junctions to reduce traffic congestion based on the dynamic updates of information obtained from vehicles waiting at each intersection [22].

Although the aforementioned work focuses on reducing the average waiting time at an intersection the presence autonomous vehicles is not considered. Research on TLCS for mixed traffic of HVs and CAV has received little attention. Qi et al. improve the signal coordination scheme designed for only HVs, for managing mixed traffic flows [23]. To decrease delays at an intersection i_C, they propose a mixed-flow platoon dispersion model which captures vehicles' progression between the neighboring upstream and downstream intersections and compute the optimal cycle length, green duration and offset of traffic lights at i_C. In addition, some studies have considered mixed platoon control of automated and human-driven vehicles at an intersection [24], [25]; yet these studies do not consider traffic light control.

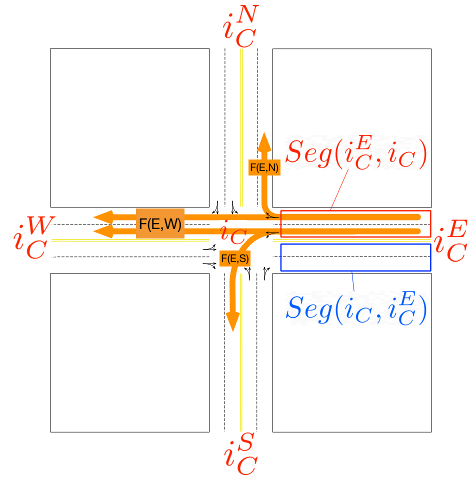

Fig. 1. Intersection, Segment and Traffic Flow.

III. Parameter Definitions

Parameters will be used in this paper are listed below:

- i_C refers to the currently considered intersection, as shown in the Fig. 1. The adjacent four intersections are presented by $i_C^N, i_C^E, i_C^S, i_C^W$, respectively.
- $Seg\left(i_C^{sou},\ i_C^{tgt}\right)$ represents the road segment from intersection i_C^{sou} to intersection i_C^{tgt}, where "sou"and "tgt" denote "source" and "target", respectively. For example, $Seg\left(i_C, i_C^E\right)$ is the directed road segment from i_C to i_C^E. Meanwhile, $Seg\left(i_C^E, i_C\right)$ is the opposite directed segment from i_C^E to i_C.
- $F\left(sou,\ tgt\right)$: Traffic flow moving from the source side of intersection i_C, i.e., i_C^{sou}, to its target side, i.e., i_C^{tgt}, where $tgt\ \neq sou\ \&\ tgt,\ sou\ \in \{E,\ S,\ W,\ N\}$. For example, in Fig. 1, $F\left(E, W\right)$ is the traffic moving from i_C^E to i_C^W.
- Cyc_t is the smallest period during which all flows are served at least once. A cycle consists of a sequence of phases; each corresponds to a green signal for a specific direction. $Cyc_{t-1},\ \ Cyc_t$, and Cyc_{t+1} refer to the previous, current and next cycle at i_C, respectively. Cyc_t of i_C may not be synchronized with the corresponding cycle of adjacent intersections, e.g., when i_C is at $phase$ 1 of Cyc_t, i_C^E might be still at $phase$ 4 of Cyc_{t-1}.
- $GLDur_t\left(F\left(sou, tgt\right)\right)$ represents the duration of the green light for flow $F\left(sou, tgt\right)$. In other words, it is the length of the time period during which vehicles in flow $F\left(sou, tgt\right)$ are permitted to pass an intersection i_C in cycle Cyc_t.
- $Ph_t\left(F\left(sou, tgt\right)\right)$ denotes a phase Ph for which a flow $F\left(sou, tgt\right)$ is served during Cyc_t. The phase length for $F\left(sou, tgt\right)$ should be equal to the duration of the green light for that flow, i.e., (1). For example, $Ph_t\left(F\left(E,\ S\right)\right), Ph_t\left(F\left(E,\ W\right)\right)$ and $Ph_t\left(F\left(E,\ N\right)\right)$ could be within the same phase, since vehicles turning left, going straight and turning right share the same traffic light.

$$\left|Ph_t\left(F\left(sou,\ tgt\right)\right)\right| = GLDur_t\left(F\left(sou, tgt\right)\right) \tag{1}$$

- $Ph_t(i), i \in \{1, 2, 3 \ldots\ldots\}$ is also used to represent the i^{th} phase during the cycle Cyc_t.
- $PhDur_t(i), i \in \{1, 2, 3 \ldots\ldots\}$ reflects the duration of i^{th} phase during Cyc_t. Ideally, it should be long enough for all flows, which are served during this phase, to pass i_C, for all $F(sou, tgt)$ served in $Ph_t(i)$, i.e., (2).

$$\begin{aligned} PhDur_t(i) &= MAX\{|Ph_t(F)|\} \\ &= MAX\{GLDur_t(F)\} \end{aligned} \tag{2}$$

- $CycDur_t$ is the length of Cyc_t. The beginning time and ending time of a cycle of two intersections might be different since they may not have the same length.

$$CycDur_t = \sum_{i=1}^{4} PhDur_t(i) \tag{3}$$

- Green light session consists of one green light phase and the following yellow light phase in one direction and corresponding red light phase in orthogonal direction. The yellow light phase duration is usually set as a constant value by default. In the example of Fig. 2 there are two green light sessions. The length of a cycle is the sum of these two green light session duration. The idea of importing this concept is that vehicles move during each green light signal making the traffic flow condition changing. Hence, rescheduling the traffic lights plan for every green light session rather than every cycle provides a quicker response to the change.
- $PV_t(F(sou, tgt))$ is the number of vehicles in a flow $F(sou, tgt)$ which have passed through i_C during the corresponding green light duration of Cyc_t. The sum of $PV_t(F(sou, tgt))$ for all flows at intersection i_C becomes the throughput of the intersection in Cyc_t, as captured by (4), where $tgt, sou \in \{E, S, W, N\}$.

$$PV_t(i_C) = \sum_{sou \neq tgt} PV_t(F(sou, tgt)) \tag{4}$$

- $DV_t(F(sou, tgt))$ means the number of delayed vehicles of a flow which cannot pass the intersection before the end of Cyc_t and have to wait for Cyc_{t+1} or even future cycles. The delayed vehicles may join the incoming edges (road segments) in the current cycle or even earlier cycles.

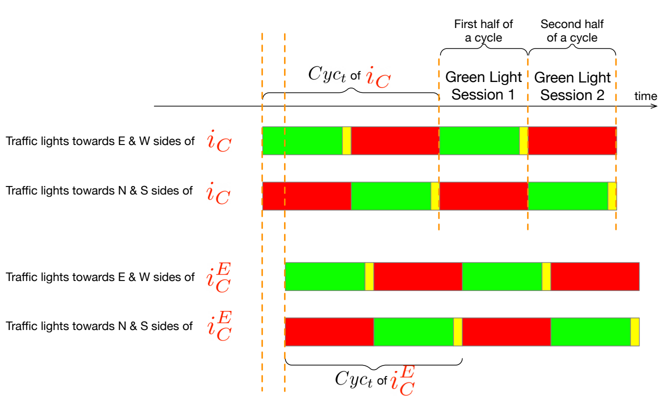

Fig. 2. A cycle of distinct intersections may cover different time period.

- $AWT_t(F(sou, tgt))$ represents the average waiting time of those delayed vehicles, i.e., $\in DV_t(F(sou, tgt))$.
- $EV_t(F(sou, tgt))$ denotes the number of expected vehicles which will join the flow $F(sou, tgt)$, i.e., those coming from adjacent intersections i_C^{sou}, passing through the current intersection i_C, and going to the target intersections i_C^{tgt} in the next cycle Cyc_{t+1}. It is measured by counting the vehicles that will join the incoming segment $Seg(i_C^{sou}, i_C)$ with their planned turns in the next cycle Cyc_{t+1}.

In addition, some relationships between the above parameters can be clarified. On the one hand, the number of all vehicles NV of flow $F(sou, tgt)$ that need to be served during current cycle Cyc_t is:

$$\begin{aligned} NV_t(F(sou, tgt)) &= DV_{t-1}(F(sou, tgt)) \\ &+ EV_{t-1}(F(sou, tgt)) \end{aligned} \tag{5}$$

Usually, $NV_t(F(sou, tgt))$ is always larger than $PV_t(F(sou, tgt))$ since not all vehicles have the chance to be served during Cyc_t. On the other hand, we have:

$$\begin{aligned} NV_t(F(sou, tgt)) &= PV_t(F(sou, tgt)) \\ &+ DV_t(F(sou, tgt)) \end{aligned} \tag{6}$$

where $PV_t(F(sou, tgt))$ is a part of $NV_t(F(sou, tgt))$, which has passed through the intersection while $DV_t(F(sou, tgt))$is the part that has not passed through the intersection and got delayed.

- $NV_tinSeg(i_C^{sou}, i_C^{tgt})$ is the number of all vehicles at segment $Seg(i_C^{sou}, i_C^{tgt})$ in Cyc_t, and is define by (7), where $dirc \in goStraight, turnLeft, turnRight$.

$$\begin{aligned} & NV_tinSeg(i_C^{sou}, i_C^{tgt}) \\ &= \sum_{dircs} NV_tinSeg(i_C^{sou}, i_C^{tgt})_{dirc} \end{aligned} \tag{7}$$

- $CapSeg(i_C^{sou}, i_C^{tgt})$ is the capacity of $Seg(i_C^{sou}, i_C^{tgt})$. This parameter is a constant, and is calculated by:

$$\begin{aligned} & CapSeg(i_C^{sou}, i_C^{tgt}) \\ &= \frac{length\ of\ Seg(i_C^{sou}, i_C^{tgt}) \times \#\ lanes}{average\ vehicle\ length} \end{aligned} \tag{8}$$

- $RCSeg(i_C^{sou}, i_C^{tgt})$ is the segment remaining capacity, calculated as $CapSeg(i_C^{sou}, i_C^{tgt}) - NV_tinSeg(i_C^{sou}, i_C^{tgt})$.

IV. TLSC for Mixed Vehicle Traffic

This section presents the proposed Platoon based Adaptive traffic Light control system for Mixed vehicular traffic (PALM). PALM consists of four modules:

- Traffic Flow Watcher (TFW): observes the traffic at each intersection and collects measurements, e.g., PV, etc.
- Traffic Light Controller (TLC): schedules the next green light sessions based on the TFW measurements.
- Green Light Extender (GLE): grows current green duration if there barely are vehicles in orthogonal directions while there is continuous traffic flow coming in current directions.
- Platoon Coordinator (PC): adjusts the schedule for near future made by TLC when there are platoons existed.

A. Traffic Flow Watcher (TFW)

The TFW module monitors the traffic situation at each intersection and their nearby intersections and collects the traffic data for future use. Vehicles share their routes, location, velocity and other information via VANET and then report to to the traffic light system via Vehicles to Infrastructure (V2I) communication. In order to respond to the real time traffic situation rapidly and accordingly, TFW calculates the $RCSeg\left(i_C^{sou}, i_C^{tgt}\right)$ at the end of each green light session. Different reactions will be taken accordingly by TLC based on the result. In addition, it also observes and records the platoons information on all incoming segments of each intersection, including platoon size, velocity, distance between platoon leader, last follower and the intersection they are heading for. This information are used by GLE and PC.

To assess the traffic trend, TFW also monitors eight parameters relating the current and previous cycles, i.e., Cyc_t and Cyc_{t-1}. TFW calculates and uses four ratios of these eight parameters to analyze the traffic flow conditions at Cyc_t and estimate what will happen in Cyc_{t+1}. Based on this information, the TLC takes proper actions to adjust the phase lengths of Cyc_{t+1} and reschedule its traffic lights. Such a rescheduling process is performed after Cyc_t ends and before Cyc_{t+1} starts. The four ratios are:

- γ_{PV}: is the throughput ratio for $F\left(sou, tgt\right)$ at i_C during the previous two cycles, i.e., $PV_t\left(F\left(sou,\ tgt\right)\right)$ and $PV_{t-1}\left(F\left(sou,\ tgt\right)\right)$. If γ_{PV} exceeds one, it means the throughput of that flow grows at i_C, which is regarded as a sign that the traffic conditions are improving, and congestion is unlikely to happen.

$$\gamma_{PV} = \frac{PV_t\left(F\left(sou,\ tgt\right)\right)}{PV_{t-1}\left(F\left(sou,\ tgt\right)\right)} \tag{9}$$

- γ_{DV}: represents the ratio of the number of delayed vehicles of flow $F\left(sou, tgt\right)$ of previous two cycles. When the ratio exceeds one, the load is getting larger with growing possibility of congestion.

$$\gamma_{DV} = \frac{DV_t\left(F\left(sou,\ tgt\right)\right)}{DV_{t-1}\left(F\left(sou,\ tgt\right)\right)} \tag{10}$$

- γ_{AWT}: is the ratio of the average waiting times of vehicles on road segment $Seg\left(i_C^{sou}, i_C\right)$ in the previous two cycles. A value bigger than one means that the vehicles have to wait for longer time to pass the intersection and consuqently the probability of congestion is growing.

$$\gamma_{AWT} = \frac{AWT_t\left(F\left(sou,\ tgt\right)\right)}{AWT_{t-1}\left(F\left(sou,\ tgt\right)\right)} \tag{11}$$

- γ_{EV}: denotes the ratio of the numbers of expected vehicles of flow $F\left(sou, tgt\right)$ during the previous two cycles. If γ_{EV} surpasses one, the load during Cyc_{t+1} is expected to rise.

$$\gamma_{EV} = \frac{EV_t\left(F\left(sou,\ tgt\right)\right)}{EV_{t-1}\left(F\left(sou,\ tgt\right)\right)} \tag{12}$$

Furthermore, the combined and cross analysis of the above four ratios help to better understand current traffic conditions and trends. More cases are analyzed in the next subsection.

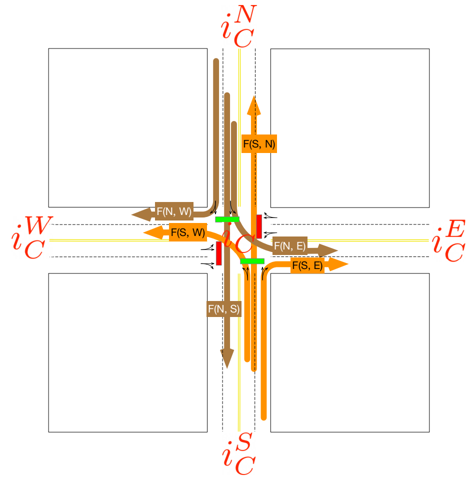

Fig. 3. An example of a classical four phases traffic light cycle.

B. Traffic Light Controller (TLC)

The TLC module applies various strategies to schedule the traffic light phases and set the length of the next green light session. In contrast to other approaches which re-schedule for each cycle, PALM algorithm re-schedules the traffic lights every session, which rapidly adapts to the latest traffic flow conditions. Traffic flow is categorized based on the remaining road segment capacity into two cases, as follows:

1) Sufficient remaining capacity: If the remaining capacity after Cyc_t of the target segment $Seg_t\left(i_C, i_C^{tgt}\right), tgt \in \{E, S, W, N\}$ is larger than the number of vehicles which will cross from all source segments, then TLC will just let all vehicles pass. TLC will extend the green duration of that phase, $GLDur\left(ph\left(i\right)\right)$, as long as needed for all applicable vehicles. To know how many vehicles will go to the target segment $Seg_t\left(i_C, i_C^{tgt}\right)$ through i_C, we consider all flow directions. In the example of Fig. 3, to know how many vehicles will join $Seg\left(i_C, i_C^W\right)$, we need to count the vehicles of $F(N, W)$ and $F(S, W)$. Meanwhile, for $Seg\left(i_C, i_C^S\right)$ only $F(N, S)$ is considered. All these can be achieved by using the number of vehicles which are already on $Seg\left(i_C^S, i_C\right)$ and $Seg\left(i_C^N, i_C\right)$ and their turning information. For the $N-S$ green light session, it should be:

$$\begin{aligned} RCSeg\left(i_C, i_C^W\right) \quad & \geq NV_t inSeg\left(i_C^N, i_C\right)_{turnRight} \\ & + NV_t inSeg\left(i_C^S, i_C\right)_{turnLeft} \end{aligned} \tag{13}$$

$$RCSeg\left(i_C, i_C^N\right) \geq NV_t inSeg\left(i_C^S, i_C\right)_{goStraight} \tag{14}$$

$$\begin{aligned} RCSeg\left(i_C, i_C^E\right) \quad & \geq NV_t inSeg\left(i_C^N, i_C\right)_{turnLeft} \\ & + NV_t inSeg\left(i_C^S, i_C\right)_{turnRight} \end{aligned} \tag{15}$$

$$RCSeg\left(i_C, i_C^S\right) \ \geq NV_t inSeg\left(i_C^N, i_C\right)_{goStraight} \tag{16}$$

When any of these four conditions in (13) - (16) are met, the green light duration of this phase is calculated via (17).

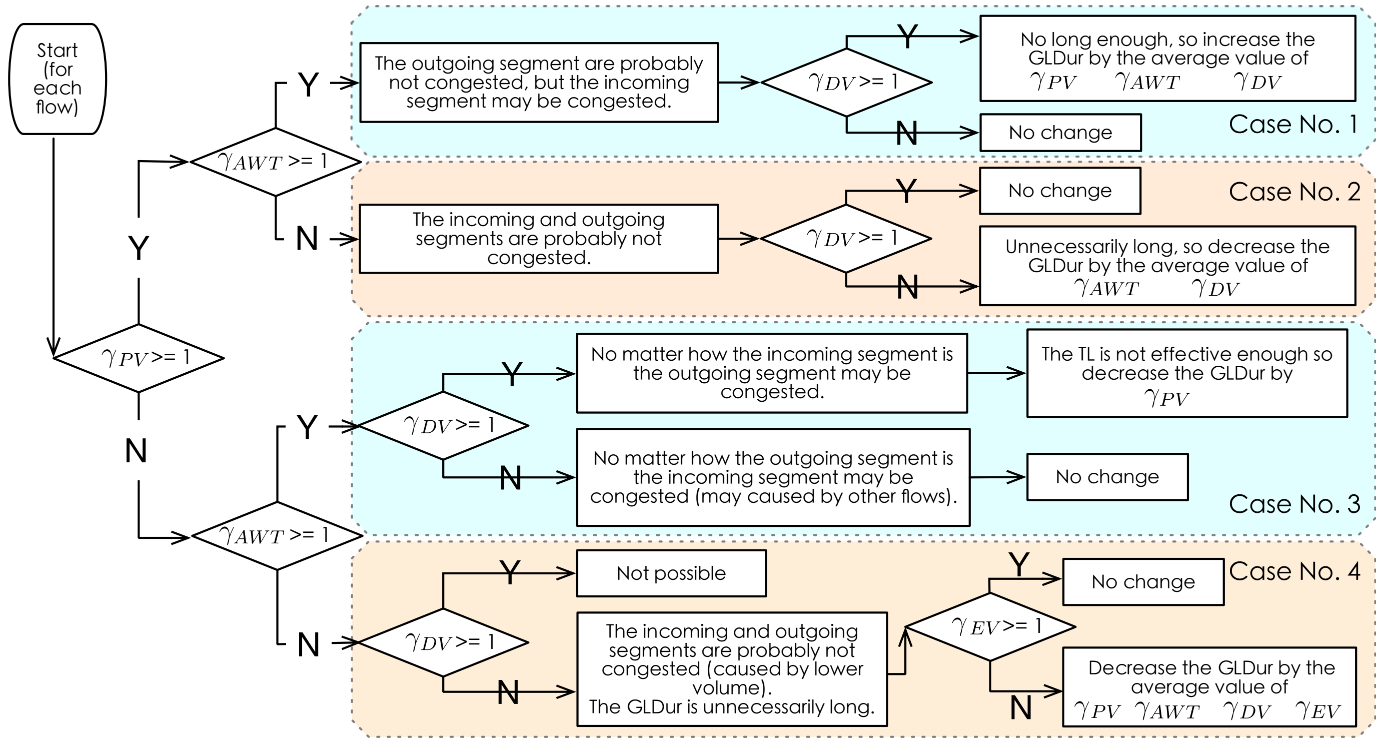

Fig. 4. Detailed flowchart description of the operation of the TLC module.

$$GLDur = max\left\{\frac{Farthest\ Distance\ to\ i_C}{SL*(1-Occupancy\ Ratio)}\right\} \tag{17}$$

The farthest distance to i_C means the distance between the target intersection and the vehicle which is farthest from the target intersection on $Seg_t\,(i_C^{sou},\ i_C)$. The SL is short for "speed limit"of corresponding segment. Considering the vehicle actual velocity varies depending on how crowded that segment is, the coefficient "$1-OccupancyRatio$" is used to reflect this impact. The occupancy ratio is calculated via the number of vehicles on the segment relative to its capacity. This approach works only when the remaining capacity of any of four target segments is enough. The next case deals with when no segment has sufficient capacity.

2) Insufficient remaining capacity: The TLC will dynamically adjust the durations of each phase. The TFW module tracks γ_{PV}, γ_{DV}, γ_{AWT}, and γ_{EV}; TLC uses these ratios to estimate the traffic intensity in the next cycle Cyc_{t+1}. Thus, implicitly, the TLC factors in the vehicle density at adjacent intersections i_C^E, i_C^S, i_C^W and i_C^N, when setting the signal timing for the next green light session at intersection i_C. For each flow, TLC extends or shortens the green light duration, $GLDur_{t+1}\,(F\,(sou,tgt))$, using (2). Generally, there are four cases, as captured in Fig. 4 and discussed below.

- Case # 1: When both γ_{PV} and γ_{AWT} are bigger than one, the motion speeds in the vehicle flow passing i_C is trending down. The vehicular throughput is high, yet the traffic becomes dense with the space between two vehicles getting smaller and consequently AWT is growing and congestion becomes possible. Whether congestion may happen or not depends on γ_{DV}. With γ_{DV} less than one, the vehicle density in this area is still acceptable and no adjustment is needed. On the contrary, exceeding one implies that vehicles are passing slower than normal, and congestion is likely to happen; hence signal timing adjustment is warranted. If there are no platoon, PALM increases the green light duration of that traffic flow as follows:

$$\begin{aligned}&GLDur_{t+1}\,(F\,(sou,tgt)) = AVG\{\gamma_{PV},\gamma_{AWT},\gamma_{DV}\}\\&\times GLDur_t\,(F\,(sou,tgt))\end{aligned} \tag{18}$$

If there are platoons, the PC module is engaged to adjust the green light duration based on the above result.

- Case # 2: When γ_{NV} grows and γ_{AWT} diminishes, vehicles cross i_C smoothly. However, if γ_{DV} is lower than one, it can be concluded that the road segments are becoming empty, and it is likely that the green light duration is longer than necessary. If there are no platoons in those traffic flows, PALM decreases the green time of that flow in Cyc_{t+1} using (19). When there are platoons in the flow, the green light duration will be shortened while ensuring no platoon will be broken.

$$\begin{aligned}&GLDur_{t+1}\,(F\,(sou,tgt)) = AVG\{\gamma_{AWT},\gamma_{DV}\}\\&\times GLDur_t\,(F\,(sou,tgt))\end{aligned} \tag{19}$$

- Case # 3: This case corresponds to $\gamma_{PV} < 1$ and $\gamma_{AWT} \geq 1$. Since the throughput is decreasing and the AWT is increasing, the area is getting more and more crowded. If

γ_{DV} is also lower than one, then it is highly likely that the source segment is getting congested, but not the current intersection. Nothing needs to be done in this case for the current intersection, as shown in Fig. 4. On the contrary, if γ_{DV} exceeds one, the target segment is experiencing congestion and the green time should be reduced to let fewer vehicles pass the intersection and consequently relieve the stress of the target segment. When there is no platoon, the green time is proportional to γ_{PV}. In contrast, when there are platoons, the PC constrains the reduction in order to sustain the integrity of the platoon.

$$
\begin{aligned}
&GLDur_{t+1}\left(F\left(sou,tgt\right)\right) \\
&= \gamma_{PV} \times GLDur_{t}\left(F\left(sou,tgt\right)\right)
\end{aligned} \tag{20}
$$

- Case # 4: In this case both γ_{PV} and γ_{AWT} are lower than one, which indicates that the traffic is diminishing in the area. Having $\gamma_{EV} > 1$ implies more vehicles are coming, and consequently there is no worry about wasted road segment capacity. In contrast, if γ_{EV} is lower than one, fewer vehicles will come and join, leading to more spaces between vehicles and the road segment capacity becomes underutilized. Therefore, the green time will be reduced by a factor of γ_{AWT} in the absence of platoons, where $\gamma_{AWT} < 1$.

$$
\begin{aligned}
&GLDur_{t+1}\left(F\left(sou,tgt\right)\right) \\
&= AVG\{\gamma_{PV}, \gamma_{AWT}, \gamma_{DV}, \gamma_{DE}\} \\
&\times GLDur_{t}\left(F\left(sou,tgt\right)\right)
\end{aligned} \tag{21}
$$

C. Green Light Extender (GLE)

GLE works at the last second of every green light duration. It checked out whether there are vehicles in orthogonal directions within a certain proximity to the intersection i_C at this moment. Such proximity is defined as three seconds times the speed limit of the corresponding segment. If none, meanwhile if there are continuous uninterrupted vehicle flow coming to i_C , GLE will determine to extend current green light when encountering any of the following two cases.

- Case # 1: When there is a platoon in current direction and the lead AV is within three seconds of i_C, GLE will firstly calculate how long the platoon need to pass the intersection via the distance between the last vehicle of the platoon and the intersection divided by the current velocity of this platoon. Then GLE extends the current green light duration by the calculated time.
- Case # 2: When there are no platoon and separate vehicles arrive within three seconds at i_C, GLE will extend the current green duration with three seconds to let these vehicles pass. The process is repeated to better serve the upcoming vehicles.

D. Platoon Coordinator (PC)

The PC is the agent which decides how to adjust the green light duration when there are platoons in the flow. The operating principle of the PC is to favor longer platoons and tries to keep them intact. As pointed out earlier, platoons have better performance due to space saving; therefore, the intersection will have bigger throughput when there are more and longer platoons among all vehicles. Yet, the length of platoons cannot be as long as they want since a longer platoon means vehicles in the orthogonal directions will wait more. The PC will adjust the green light duration based on the schedule of TLC and also divide platoons when necessary.

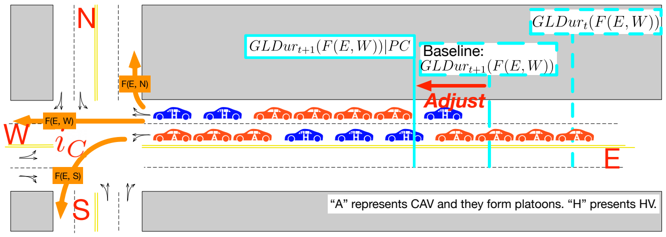

Fig. 5. The PC shortens the GLdur further to avoid cutting platoons.

While the TLC schedules the traffic lights for the next green session, the PC makes use of the information about platoons getting from Road Side Units (RSUs), adjacent intersections, and VANET to adjust the green light duration when necessary. When the PC is requested to update the green light duration of one flow, it will make use of the schedule made by the TLC as a baseline, i.e., $GLDur_{t+1}\left(F\left(sou,tgt\right)\right)$. If this baseline doesn't cut any platoon, no adjustment is needed. Otherwise, the PC will adjust it to minimum platoon cuttings, following the traffic flow trend. If there is a high possibility of congestion, like case #1 in the TLC subsection, the PC will shorten the baseline schedule further to avoid platoon cutting, notated as $GLDur_{t+1}\left(F\left(sou,tgt\right)\right)|PC$. If there are multiple affected platoons, the PC will choose proper $GLDur_{t+1}\left(F\left(sou,tgt\right)\right)|PC$ which would cut as few platoons as possible. An example is shown in Fig. 5.

V. Validation Experiments

To validate the effectiveness of PALM, several simulations have been conducted. The static traffic light system, which is most widely used worldwide. The Actuated Traffic Light (ATL) system is also implemented and compared with PALM. Our implementation is open source [26].

A. Static Traffic Light (STL) System

STL systems are the most commonly used as they are simple and easy to install. In our simulation we implemented the same STL system for all intersections. Such a system has 4 phases in each cycle, with duration of 42s, 3s, 42s and 3s. For four phases, the traffic light signal colors of the aforementioned lane directions, respectively, are:

1) North(GGGgg), East(rrrrr), South(GGGgg), West(rrrrr);
2) North(yyyyy), East(rrrrr), South(yyyyy), West(rrrrr);
3) North(rrrrr), East(GGGgg), South(rrrrr), West(GGGgg);
4) North(rrrrr), East(yyyyy), South(rrrrr), West(yyyyy).

The "G"stands for green light and during which the vehicles must pass, while "g"means vehicles pass while yielding to other vehicles that have higher priority. The abbreviation "y" and "r" indicate yellow and red lights, respectively.

B. Actuated Traffic Light (ATL) System

ATL system employs an adaptive traffic light controlling method which has been widely used in Germany [27]. It sets an induction loop detector at each lane of all incoming segments to detect the existence of successive vehicles. During unconstrained green lights ("G") phase in one direction, if successive vehicles are detected within a specific time, e.g., five seconds, this phase will be extended until it reaches the max green light duration. If no vehicles are detected, G will be shortened. This adjustment will not be inherited in the next cycle which will begin with the default schedule again. To detect vehicles, ATL uses the induction loop detectors placed under ground on all incoming segments. The distance between them and the intersection is determined by the speed limit on the corresponding segment times two seconds. The maximum and minimum G phase durations are 50 and 5 seconds, respectively. The default schedule of the traffic lights for all intersections is similar to STL's, discussed above.

C. Simulation Environment

We have used the Simulation of Urban Mobility (SUMO) v1.3.1 [27] and Python v3.7.2 as our developing tools. A grid road network with 20 intersections and traffic lights has been created in SUMO. All 20 intersections have the same configuration in terms of the number of lanes and allowable turns. Each segment has two lanes. Vehicles in the left lane can turn left or turn around. Vehicles in the right lane can turn right. Vehicles in all lanes can go straight. Thus, each side of an intersection has five directions, namely, (i) Lane 1, turn-right, (ii) Lane 1, go-straight, (iii) Lane 2, go-straight, (iv) Lane 2, turn-left, and (v) Lane 2, turn-around.

The grid spans an $640m \times 640m$ area. The length of the road segments between each intersection are 200 meters horizontally and 150 meters vertically. Vehicles' starting or ending points are set as out of the grid road network. Segments at the edge of the grid are extended by 20 meters to avoid vehicles starting or ending a trip at an intersection.

D. Traffic Flow Demand and Vehicle Types

To compare the performance of the different traffic light systems, we apply the exact same traffic flow demand to all approaches. However, the traffic flow demands for each simulation are different, which are 12000, 18000, 36000, 54000, 72000 and 144000 vehicles, respectively. The starting points and ending points (destinations) and the routes are generated randomly to mimic practical scenarios. Seven vehicle types have been considered in our simulations, including CAV sedans, autonomous buses, autonomous taxis, sedan HVs, human-driven buses, human-driven taxis and common human-driven emergency cars with 40%, 5%, 4.5%, 40%, 5%, 4.5% and 1% distribution, respectively. CAV and other autonomous vehicles can form or join platoons while all HVs cannot; a tool called 'simpla' supports such functionality in SUMO.

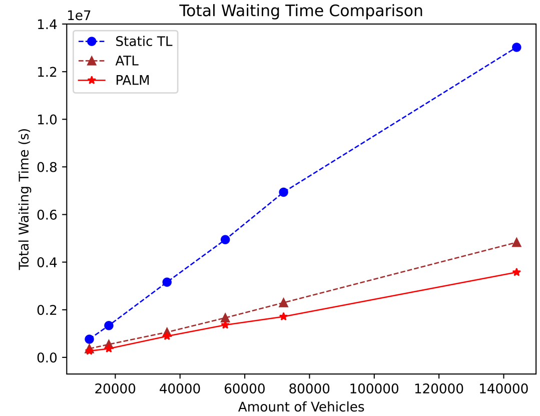

Fig. 6. Comaprsion of the total waiting time.

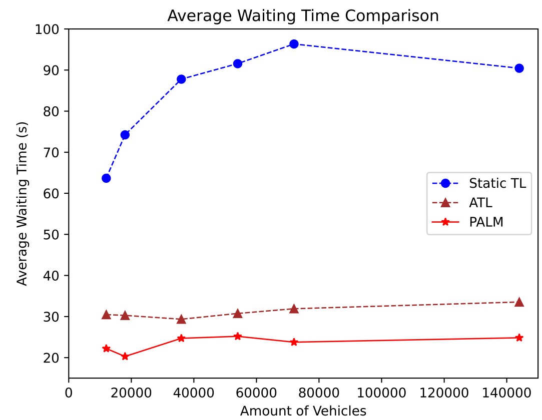

Fig. 7. Comparison of the average waiting time.

The emergency has higher priority than any other vehicles. All buses have a maximum speed of 30 m/s (108 km/h) and length of 14.63 m. All other vehicles have the same length and maximum speed, of 4.5 m, and 35 m/s (126 km/h), respectively.

E. Performance Comparison

Multiple simulation experiments have been conducted. The traffic flow demand, i.e., total number of vehicles, varies for each simulation. For each simulation we run STL, ATL and PALM. The total waiting time of all vehicles, the average waiting time, the start time and finish time of each vehicle are collected. The latter is used to track the number of active vehicles. Fig. 6 shows the total waiting time for different traffic flow demands. As indicated by the plots, PALM sustains a major advantage with the gap broadening with growth in traffic.

Fig. 7 illustrates the significant difference in the average waiting time experienced by vehicles using PALM compared to STL and ATL. PALM continues to have distinct advantages and adapts well with growth in demand. Meanwhile, with the

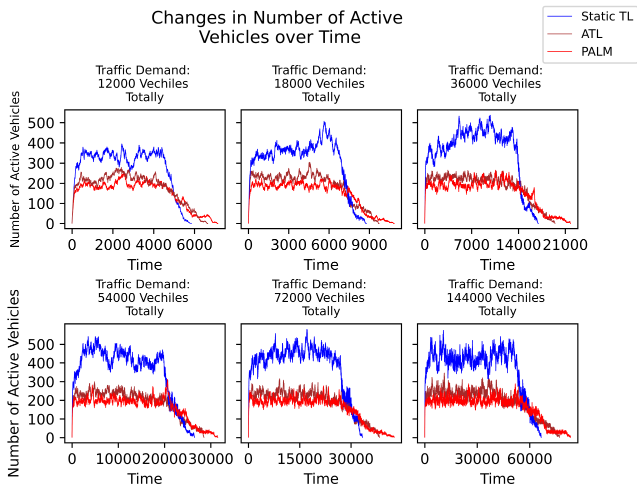

Fig. 8. Changes in number of active vehicles over time.

STL, the waiting time increases at a high rate as the demand leaps. The simulation results show that PALM achieves 26.2% to 49.92% reduction in the waiting time on the average. On the other hand, Fig. 8 displays the comparison of the STL, ATL and PALM in terms of the traffic density, gauged by the number of active vehicles in the road network at each moment over time. From the plots of the six different traffic flow demand scenarios, PALM consistently reduces the number of active vehicles compared to the STL and ATL systems.

VI. Conclusions

With the development of autonomous vehicles, the traffic on the road will soon involve a mix of CAV and HVs. Dynamic setting of traffic signal timing will be a challenge in such a scenario given the unconventional features that CAV introduces, e.g., platooning. To tackle the challenge, we have proposed, PALM, a novel approach that not only factors in the traffic flow information at nearby intersections but also takes the platoons into consideration. The simulation results for different traffic flow demands show that PALM has a better performance than the most widely used traffic light system. PALM reduces the average waiting time by as large as 75.34% and 33.02% compared to the static and actuated TLCS, respectively. In addition, it has a much more stable performance for different traffic flow demands. In future we would take the pedestrians into consideration to ensure the safety of pedestrians in future smart cities.

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