Reservation-based Dedicated Lane Method for Mixed Autonomous and Human-operated Vehicles at Intersections

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Abstract. This paper develops a reservation-based dedicated lane (RDL) mechanism for mixed autonomous and human-operated vehicles at intersections in connected vehicle environment. The RDL mechanism is proposed to coordinate hybrid transport at intersections under the condition of dedicated land, improve the capacity of intersections, reduce delay and the number of stops. The overall RDL architecture consists of two essential sub-modules: a connected and autonomous vehicles (CAVs) speed guidance application, a signal-control application for human-operated vehicles (HVs). Thus, the proposed RDL strategy enables HV/CAV/signal cooperation in a connected vehicle environment. A set-projection algorithm and a three-segment linear speed profile are employed to control the trajectories of the CAV. The performance of the proposed method is evaluated by simulating various traffic conditions on an actual urban network. The simulation evaluation results show that, compared with the traditional signal control method, the model can significantly reduce the travel delay. The simulation experiments indicate that the penetration rate of CAV reaches 30%-40%, and proposed method can achieve considerable results.

Keywords. Reservation-based dedicated lane, Human-operated vehicles, Capacity, Connected vehicle environment.

1. Introduction
Traffic congestion not only disrupts the normal life order of the city, but also brings a series of problems such as excessive energy consumption and pollution emission. Implementing scientific and efficient traffic control is a more direct way than bus priority and demand management to solve the problem of traffic congestion. The practices of many cities such as London, Sydney, Beijing, Guangzhou show that traditional signal control (including SCATS, SCOOT, etc.) has emerged great limitations in the era of the intelligent connected vehicle. Currently, internet giants and well-known automobile companies including Google, Baidu, BMW, Volvo and Toyota, have invested heavily in research and development of autonomous vehicles (AVs), making great progress in environmental perception and high-precision control. In addition, US Moody's Investor Service pointed out through extensive market research that connected and autonomous vehicles (CAVs) cannot achieve 100% penetration by 2045 [1]. CAV is unstoppable, and one of the questions that follow is how to safely and efficiently manage CAVs and human-operated vehicles (HVs) at intersections in a CAV market penetration environment of various sizes.

As early as 2005, Professor Peter Stone of the University of Texas at Austin (UT Austin) began to research on vehicle-road integration control. In recent years, the Peter Stone team has proposed an Autonomous Intersection Management (AIM) based on the reservation mechanism [2]. The AIM...
protocol relies on precise control of the CAV to coordinate multiple vehicles (without signal control) to cross intersections. Compared with signal control, AIM can reduce vehicle delay at intersections by several orders of magnitude when the CAV market penetration rate reaches 100%. The study also pointed out that when the market penetration of CAV is less than 90%, AIM cannot make a significant improvement in traffic control [3].

There is no consensus on the intersections crossing mechanism under the conditions of mixed CAV and HV, and some research about cooperative traffic [4] and vehicle actuated control [5] involve this issue. Sharon and Stone [6] propose a hybrid autonomous intersection management (H-AIM) system based on the AIM protocol. The system reduces the traffic delay by setting steering strategies of CAV and HV. Other related studies [7-9] show that: CAV dedicated lane can implement advanced control strategies such as platoon formation and non-signal cooperative traffic. It is the mainstream organizational mode of mixed CAV and HV. However, the question of whether a dedicated phase should be set in the CAV lane, and how to coordinate the CAV flow in different directions should be studied in depth.

The research of Dresner and Stone [2] has a profound impact on the development of AIM. The proposed “first come, first served + signal” (FCFS-Signal) policy uses a reservation-based mechanism to manage vehicles and meets the needs of mixed traffic through signalized. Simulation results show that the method is superior to traditional signal control in the aspect of time delay and security. Sharon and Stone [6] extend the FCFS-Signal policy and propose a H-AIM policy which can reduce traffic congestion and delay when the CAV market penetration exceeds 1%. In addition, Carlino et al. [10] improve the FCFS AIM protocol and propose a method which can distinguish the priority of vehicles approaching the intersections. Bashiri et al. [11] propose a "vehicle negotiation" method to optimize the AIM scheduling strategy and reduce V2I communication traffic. Li and Zhou [12] propose a phase-time-traffic hypernetwork method that considers communication and minimizes the total control delay. The simulation results show that the method can improve the consistency of traffic flow. Moreover, the V2I-based control strategies proposed by some researchers such as Liu [13], and Chouhan [14] show certain technical advantages in some scenarios. Lin et al [15] propose an Automatous and Cooperative Crossing (ACC) method based on the buffer-assignment mechanism, which can greatly improve the capacity of intersections.

In summary, researchers have carried out a series of fruitful work to build a traffic management system that adapts to the "intelligent connected and autonomous driving" era. However, there are still some deficiencies in the following aspects: First, the existing signal light control technology cannot meet the requirements of coordinate CAV and HV cross the intersections. Second, there are no consensuses on the operation mechanism of the new-generation traffic control system, and there are disputes on whether to set up dedicated lanes and the passage policy in the case of dedicated lanes. Based on the previous research, this paper establishes a new method for coordinated intersection control in a CAV and HV environment. In addition, we have improved the AIM strategy in the following areas: (1) a novel design for intersection control of hybrid traffic flow, including CAV and HV; (2) dedicated lands for CAV and HV; (3) a traffic detector is used to detect HV which controlled by signal light; and (4) the green light time occupied by HV is equivalent to the time occupied with CAV, which effectively reduces the calculation complexity. Moreover, we firstly apply the method to a representative road network in Guangzhou by model building.

The remaining parts of this paper are organized as follows. Section 2 introduces the background of three protocols of the ACC method. Section 3 proposes the intersection management method for mixed traffic. Section 4 shows the simulation results, and the conclusions and future work are discussed in Section 5.

2. Overview of Automatous and Cooperative Crossing Method

The method proposed in this paper is based on the ACC method [15]. This section briefly reviews buffer-assignment mechanism (BAM), conflict section time occupancy model (TOM), and autonomous vehicle trajectory control model (TCM).
2.1. Revisit of BAM

In brief, the BAM protocol for vehicle-intersection coordination proceeds as follows:

- Given an intersection, in order to coordinate the vehicle movements, several roadside units (RSU) and a connected vehicle centre (CVC) are built. The trajectories of the CAVs can be observed by the CVC through traffic detection devices, for example, LiDAR-based sensors or radar.
- Each CAV will try to connect with the CVC when approaching and periodically transmit its information to the CVC. Each CAV receives and strictly follows the corresponding commands of the CVC. The measurement error of the CAV state is small and can be ignored.
- IEEE 802.11p is set as the communication protocol between the CAV and the RSUs.
- Only CAV is considered in this method. The CAV will transmit its information to the CVC when approaches a buffer area (BA). The BA is covered by a communication protocol. The responsibility of CAV is to follow the CVC commands. The CVC will try to assign a crossing span for the CAV until the CAV is practicable to cross the intersection, then the CVC will guide the CAV to enter the intersection by adjusting its corresponding speed and entry time. Each CAV can enter the intersection only if it has a cross command from the CVC.

There are two critical factors that ensure all CAVs can collaborate pass the intersection safety and without hindrance.

- First, the CAV follow the commands to enter the intersection.
- Second, the CVC must assign a crossing span that is specific for an individual CAV and send commands to the CAV.

These two factors are formulated by the conflict section TOM and autonomous vehicle TCM, respectively. Finally, figure 1 illustrates the complete intersection channelization.

![Figure 1. Intersection channelization.](image)

2.2. Revisit of Conflict Sections TOM

Traffic management at the intersection is a multi-vehicle queuing problem, and every conflict section (CS) is specially used at any time. Given a period of time $Q$ which is the total travel time of all vehicles, the problem is aiming to minimize the $Q$. We divide the $Q$ into several sufficiently small discrete intervals: $Q = Q_1 + Q_2 + \ldots + Q_M$.

And then, the time occupancy model of CSs can be described as following:

$$\min Y = \sum_{m=1}^{M} \sum_{k=1}^{N_m} t(V_k)$$

where $t(V_k)$ is travel time of the $k$-th vehicle traveling the intersection, $N_m$ is the number of vehicles passing the intersection in the $m$-th time interval, and $Y$ represents all vehicles’ total travel time.

The vehicles’ time occupancy in different CSs is projected on the starting line of the CA based on the time lags.
\[ TOT(VID) = \left(TO(CSID_1) - \frac{d_1}{v}\right) \cup \left(TO(CSID_2) - \frac{d_2}{v}\right) \cup \cdots \cup \left(TO(CSID_n) - \frac{d_n}{v}\right) \]  

(2)

where \( TO(CSID_n) \) means the set of the time occupancy of a CS with ID number \( n \). And \( TOT(VID) \) represents the projection set of the vehicles’ time occupancy in different CSs. \( TO(CSID) - \frac{d}{v} \) is means that the \( TO(CSID) \) moves back \( \frac{d}{v} \) on the time axis. \( d \) means the distance between the CSs to the beginning line, and \( v \) is the navigation speed in the CA. Finally, the optimization result of the vehicle passing through the intersection is:

\[ \min Z = t_b + \frac{L_v}{v} \]  

(3)

\[ \text{s.t. } \left[t_b - \Delta t, t_b + \frac{VL_k}{v} + \Delta t\right] \cap TOS(VID) = \emptyset \]  

(4)

where \( L_v \) is the length of route of the vehicle in the CA, \( t_b \) is the time when the vehicle is arriving the CA, \( \Delta t \) represents the basic safe time gap, and \( VL_k \) means the vehicle length.

2.3. Revisit of Autonomous Vehicles TCM

The CVC must send a speed curve to the CAV based on the crossing span, when a feasible CAV crossing span is got. When the vehicle reaches the BA, its initial state \( S_0(v_0, t_0) \) is obtained, where \( v_0 \) is the initial speed and \( t_0 \) is the initial time stamp. The state when the vehicle is arriving at the CA is \( S_1(v_1, t_1) \). According to the obtained \( S_0 \) and \( S_1 \), we can find the dynamic parameters of the vehicle in the BA, the method called three-segment control is as follows: 1) uniform variable motion with acceleration/deceleration \( a_1 \) and duration \( t_1 \); 2) uniform motion with velocity \( v_{12} \) and duration \( t_2 \); 3) uniform variable motion with acceleration/deceleration \( a_2 \) and duration \( t_2 \). Note that all of the dynamic parameters must follow the standard in [15].

3. Intersection Management Method for Mixed Traffic

3.1. Assumptions and Desiderata

The following assumptions are provided by the method of new intersection management:

- At every intersection, a CVC and numerous RSU are settled to coordinate the movement of all vehicles. The RSU can examine CAV’s trajectories through traffic detection devices, such as LiDAR-based sensors or radar, and then transfer information to CVC. The CVA also controls the signal timing (for HVs). The HV dedicated lane is equipped with a vehicle detector that can detect the approaching HVs information (number of HVs waiting for a green light and waiting time).
- Each approaching CAV strives to link to the CVC and transfers its destination, position, acceleration, and speed to the CVC cyclically. The errors of measurement of the States of the CAVs are so small that it can be ignored. Each CAV receives and obeys exactly the instructions of the CVC accordingly.
- We employ 5G URLLC (Ultra reliable low latency communications) slice to ensure low delay and highly reliable communication.
- Only automobiles, like CAVs and HVs, are considered in this work.
- HVs and CAVs may turn right on red light if the path is clear. This is a common case in the China.

Figure 1 illustrates a complete intersection channelization.

3.2. Hybrid AVIC

Based on the BAM, figure 2 describes the movements of CAVs. We introduce a signal-occupancy base on the previous BAM. We now present the Hybrid- Automatous and Cooperative Crossing (H-ACC) protocol for mixes intersection management. Like ACC, H-ACC grant TOM and TCM.
However, H-ACC sets dedicate lands and introduces signal lights. When the signal light in a certain entrance direction lights up, the CSs become a long-term occupancy state, at this time the time occupancy is denoted as $TOS(CSID_n)$. The projection set of TOT of vehicle VID is:

$$\begin{align*}
TOT(VID) &= (TO(CSID_1) - \frac{d_1}{v}) \cup (TO(CSID_2) - \frac{d_2}{v}) \cup \ldots \cup (TO(CSID_n) - \frac{d_n}{v}) \\
\cup TOS(CSID_1) - \frac{d_1}{v} \cup TOS(CSID_2) - \frac{d_2}{v} \cup \ldots \cup TOS(CSID_n) - \frac{d_n}{v}
\end{align*}$$

$$\text{(5)}$$

Properties of the intersection are described in figure 3. In this paper, we employ the one-phase-one-approach for the dedicate HV lands. Generally, the signal light is red, and does not turn green until the detector detects that the number of vehicles in the HV lane reaches 5 or the waiting time of the first car behind the first stop line reaches 30 seconds. In terms of safety and according to the green light period for HVs, all CSs in their route will preserve the occupancy of the entire period. Like this, a HV is similar to a CAV for the buffer-assignment mechanism, that is, the former one just resorts more occupancy time of the CSs. As can be seen from the figure 3, the HV dedicate land employ one-phase-one-approach, thus, the CAs of HV path can be classified as the CAs produce by CAV. In this way, the projection set of TOT is:

$$\begin{align*}
TOT(VID) &= (TO(CSID_1) - \frac{d_1}{v}) \cup (TO(CSID_2) - \frac{d_2}{v}) \cup \ldots \cup (TO(CSID_n) - \frac{d_n}{v})
\end{align*}$$

$$\text{(6)}$$

The H-AVIC protocol assumes that CAV and HV (controlled by traffic lights) attempt to obtain the permission of passage through the intersection by sending a reservation request message to the CVC. The FCFS policy is employed, thus, the CVC approved reservation requests that it does not conflict with any previous approved reservation. The steps of the H-AVIC can be described as following:

- The CVC identifies the approaching vehicle type and destination, and then guides the vehicle into the corresponding lane.
- If the vehicle is a CAV, the CVC will arrange the time and speed for CAV to reach the intersection according to the time occupancy table. If the vehicle is a HV, the CVC will arrange the time for traffic light to turn green. Finally, CVC will count the scheduled time into the time occupancy table.
- The CVC arranges the corresponding three-stage control strategy for each CAV.
- If the simulation time is equal to the pre-set time cut-off, the vehicle executes the corresponding acceleration and deceleration operations and the traffic light executes the corresponding phase.

![Figure 2. Time occupancy and its projections on the beginning line of CA and vehicle trajectories.](image1.png)

![Figure 3. Properties of the intersection.](image2.png)
4. Simulation Results
A simulation environment is built in SUMO. A typical urban network located in Guangzhou is selected as the experiment site (figure 4 and figure 5) for verification of our method. There is a specified CAV lane that supports going straight and left-turn, and one dedicated HV lane which also supports going straight and left-turn, and a specified right-turn lane for both CAV and HV in all intersections.

![Figure 4. Visualization of H-ACC experiments. HV controlled by traffic lights and CAV controlled by vehicle coordination.](image)

![Figure 5. Visualization of traditional semaphore control experiments. All vehicles controlled by traffic lights.](image)

Additionally, figure 3 shows the conflict areas’ the distribution pattern. Table 1 shows the main simulation parameters and the traffic components.

To estimate the performance of the H-ACC protocol, we also use the traditional signal control method as a comparative example. We conduct all simulation experiments in an environment of connected vehicle and an environment of traditional signal control separately. Each traffic volume input varies from 400 \( \text{veh/h} \) to 1600 \( \text{veh/h} \), and the signal timing plan adopt four-phase strategies.

Figure 6 and figure 7 are the simulation results. Figure 6 presents average delay in seconds (y-axis) versus different CAV penetration levels (x-axis) with traffic level in 900 \( \text{veh/h} \) of each traffic input.

In figure 7, there are some traditional signal control method data that are unavailable, because of the traditional signal control method is oversaturated if each input traffic volume is more than 1100 \( \text{veh/h} \). The experiment results indicate that the proposed method can significantly decrease travel delay when comparing to the traditional signal control method. Moreover, it indicates that the penetration rate of CAV reaches 30%-40%, and H-ACC protocol can achieve considerable results.

| Parameter                  | Value         | Parameter                  | Value         |
|----------------------------|---------------|----------------------------|---------------|
| Max speed \((km/h)\)       | 21.6m/s       | Min space gap(m)           | 2.5           |
| Min navigation speed \((km/h)\) | 5m/s           | Traffic composition       | HV 1%-100%   |
| \(a_{\text{max}}\)         | 2m/s²         | Phase time(s)              | 15            |
| \(a_{\text{min}}\)         | -3m/s²        | Green light trigger condition | 5 vehicle or 30s |
| Length of BA(m)            | 180 m         | Other parameters           | SUMO’s default |
| Depart speed               | random        |                            |               |
Figure 6. Average delays for different CAV percentages with 900 veh/h of each traffic input.

Figure 7. Performance of proposed method and the signal control method.

5. Conclusions and Future Work
To coordinate hybrid transports at intersections under the condition of dedicated land, to improve the capacity of intersections, and to reduce delay and the number of stops, this study develops a reservation-based dedicated lane mechanism for mixed autonomous and human-operated vehicles at intersections in a connected vehicle environment. This paper proposes a novel dedicated land and passage rules for mixed traffic intersection management. Furthermore, based on previous research, we introduce semaphore control, and classify the time occupancy of traffic light as a longer time occupancy of CAV.

The future work may concentrate on the influence of three-way intersection and varied number of vehicle lands. Moreover, the plateau is necessary to further evaluate in our method because the platoon-based intersection management can also reduce average waiting time of per vehicle.

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