Intersection Management Protocol for Mixed Autonomous and Human-Operated Vehicles

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Abstract

This article proposes a Hybrid Autonomous Intersection Management protocol (H-AIM), which is a variant of the formerly presented Autonomous Intersection Management protocol (AIM). Similar to AIM, H-AIM coordinates the right of way for connected and autonomous vehicles through an intersection in a way that is far more efficient compared to traditional traffic signals. Unlike AIM, H-AIM is shown to outperform traditional traffic signals also when traffic is mostly composed of human operated vehicles. H-AIM builds on top of existing traffic signal infrastructure, it assumes that human operated vehicles stop at red signals and cross the intersection on a green signal. By assuming the ability to detect incoming human operated vehicles, H-AIM is able to safely direct autonomous vehicles through the intersection even if they arrive on a lane that is assigned a red signal. Experimental results are provided showing that H-AIM can decrease traffic delay for autonomous vehicles even at 1% technology penetration rate. Furthermore, the presented results suggest that restricting human operated vehicles turning options in each lane e.g., they can only turn right on the rightmost lane as opposed to also having the option to continue straight, is beneficial for autonomous vehicles. Apart from presenting H-AIM this article also provides general guidelines as to how to assign lanes with turning options for human operated and autonomous vehicles.

1 Introduction

Autonomous driving capabilities are becoming increasingly common on vehicles. Such capabilities present opportunities for developing safer, cleaner and more efficient road networks. Looking towards a future when most vehicles are autonomous and connected, researchers are developing reservation based intersection management protocols (Dresner and Stone, 2008; Au et al., 2015; Bento et al., 2013). By relying on the fine and accurate control of connected and autonomous vehicles (CAVs) along with communication capabilities, intersection managements protocols coordinate multiple vehicles simultaneously across an intersection. Such protocols were shown to lead to significant traffic delay reductions when compared to traditional traffic signals. One prominent example of such a protocol is the autonomous intersection management (AIM) protocol (Dresner and Stone, 2008).

The AIM protocol defines two types of autonomous agents: intersection managers, one per intersection, and driver agents, one per vehicle. An intersection manager is responsible for directing incoming vehicles through its assigned intersection, while the driver agents are responsible for controlling the CAV to which they are assigned.
To improve the throughput and efficiency of the system, the driver agents “call ahead” to the intersection manager and request a path reservation (space-time sequence) within the intersection. The intersection manager then determines whether or not this request can be met by checking whether it conflicts with any previously approved reservation or a potential human operated vehicles (HV). HVs are assumed to occupy all trajectories that are allowed by the traffic signal, i.e., originating from a green signal. If the intersection manager approves a driver agent’s request, the driver agent must follow the assigned path through the intersection. On the other hand, if the intersection manager rejects a driver agent’s request, the driver agent may not pass through the intersection but may attempt to request a new reservation.

Assuming 100% of the vehicles are CAVs, AIM was shown to reduce the delay imposed on vehicles by an order of magnitude compared to traffic signals (Fajardo et al., 2011). On the other hand, AIM was shown to be not better than traffic signals when more than 10% of the vehicles are HVs (Dresner and Stone, 2008). In a similar way, the efficiency of most, if not all suggested intersection management protocols presented thus far, relies on traffic being mainly composed of CAVs.

Experts speculate that 90% CAV penetration will not occur anytime before 2045 (Bansal and Kockelman, 2016) deeming previous protocols to be not relevant in the near future. To this end, our paper suggests a new protocol denoted Hybrid AIM (H-AIM) that is suitable for early stages of the transition period. Unlike AIM, H-AIM assumes sensing of approaching vehicles which allows it to identify approaching HVs. This assumption is reasonable given technological advances allowing vehicle detection using video cameras (Coifman et al., 1998), radar (Hasch et al., 2012), and inductive loop detectors (Gajda et al., 2001). If a HV is detected on a given lane, then trajectories originating from that lane are assumed to be occupied, blocking CAVs from obtaining conflicting reservations. As such, reducing the number of trajectories originating from an incoming lane might be beneficial to CAVs. For example, a single lane entering a four-way intersection can allow three different turning possibilities (turn left, continue straight, turn right) or any combination of the three. Assigning all three turning possibilities to a given lane would result in blocking most of the intersection due to an approaching HV. On the other hand, if turning right is the only possible option, then an approaching HV would only block a very small portion of the intersection, allowing CAVs more flexibility in obtaining reservations.

Given the above, it is not surprising that the performance of H-AIM is sensitive to the assignment of allowed turns. This paper studies this effect by assigning different turning options to different lanes and to different vehicle types (HVs, CAVs).

The main contributions of this article are:

1. Defining the H-AIM protocol. Specifically, specifying how H-AIM utilize knowledge of incoming HVs (or the lack of such vehicles) towards granting reservations for CAVs.

2. Presenting a comprehensive empirical study showing that H-AIM improves over traditional traffic signals even for as low as 1% CAV penetration. To the best of our knowledge H-AIM is the first protocol that is shown to be beneficial for low CAV penetration rates.

3. Presenting guidelines, potentially useful for practitioners, for assigning allowed turning options from each incoming lane to both CAVs and HVs such that different traffic measurements are optimized.

2 Background

The work presented in this paper builds on the FCFS+Signals policy which is part of the Autonomous Intersection Management (AIM) protocol (Dresner and Stone, 2008). This section provides an overview of both AIM and the FCFS+Signals policy as well as surveying other relevant work.
2.1 Autonomous Intersection Management

AIM is a reservation-based protocol in which CAVs request to reserve trajectories crossing an intersection. The AIM protocol assumes that computer-controlled vehicles attempt to obtain a right of passage through the intersection by sending a reservation request message to the intersection manager. When using a “first come, first served” (FCFS) policy, the intersection manager approves reservation requests that do not conflict with any previously approved reservation or potential HVs. In brief, the protocol proceeds as follows.

1. An approaching CAV, $v$, sends a message to the intersection manager requesting a reservation. The request-reservation message contains data such as the vehicle’s size, predicted arrival time, velocity, acceleration, and arrival and departure lanes.

2. The intersection manager processes the request message by simulating the trajectory of $v$ through the intersection, the simulated trajectory is denoted by $\text{path}(v)$.

3. If $\text{path}(v)$ does not conflict with any previously approved reservations or potential HVs then the intersection manager issues a new reservation based on $\text{path}(v)$ and sends an approve message containing the new reservation details back to $v$.

4. If $\text{path}(v)$ does conflict with a previously approved reservations or potential HVs then the intersection manager sends a reject message to $v$ which, after a predefined time period, may request a new reservation.

5. After receiving an approve message, it is the responsibility of $v$ to arrive at, and travel through, the intersection as specified in $\text{path}(v)$ (within a range of error tolerance). A CAV may not enter the intersection unless it successfully obtained a reservation.

6. Upon leaving the intersection, the CAV informs the intersection manager that its passage through the intersection was successful.

The AIM protocol does not rely on communication capabilities between vehicles (V2V) but only between vehicles and the intersection manager (V2I). The protocol is robust to communication failures: if a message is lost, either by the intersection manager or by the CAV, the system’s efficiency might be reduced, but safety is not compromised. Safety is guaranteed also when considering a mixed scenario where both HVs and CAVs are present. For such cases Dresner and Stone (Dresner and Stone, 2008) introduced the FCFS+Signals policy.

2.1.1 FCFS+Signals

The FCFS+Signal policy (Dresner and Stone, 2008) is a combination between AIM and traditional traffic signals. Whenever the traffic signal is green for a given lane, all vehicles arriving at that lane have the right of passage. However, when the traffic signal shows a red signal, only CAVs which were granted a reservation may drive through the intersection.

Since the protocol is not assumed to know the location and trajectory of HVs, such vehicles are assumed to occupy all trajectories that are approved by the traffic signal. In this paper we define such trajectories as green trajectories.

Definition 1 (Green trajectories). A trajectory through the intersection is green if its incoming lane is assigned a green signal.

Figure 1 shows an example of green trajectories across an intersection (both the solid and dashed lines represent green trajectories). Note that green trajectories are dynamically changing; once the signal changes,
Figure 1: Four-way intersection. A green signal is assigned to all northbound lanes while all other lanes are assigned a red signal. Green trajectories marked with solid or dashed green lines across the intersection. Active green trajectories marked only by dashed green lines.

the green trajectories will also change. The signal’s timing is assumed to be known to the intersection manager so it is able to predict green trajectories in advance.

FCFS+Signals prohibits CAVs from obtaining reservations that conflict with green trajectories. In our example from Figure 1 all reservation requests will be automatically denied except those made by south or eastbound CAVs that are requesting to turn right.

2.1.2 Experimental Results for AIM

Dresner and Stone (Dresner and Stone, 2008) reported average delay for a mixture of CAVs and HVs obtained from the AIM simulator running the FCFS+Signals policy.

Definition 2 (Delay). Delay is defined as the increase in travel time for a vehicle caused by red traffic signals or other vehicles. In other words, it is the difference between the vehicles observed travel time and its theoretical travel time in free-flow conditions (no congestion) with full right of way (green signals).

For CAV penetration of 90% and below, FCFS+Signals yielded a mild improvement over traditional traffic signals. The improvement is attributed to CAVs that make right turns on red. If HVs are assumed to be able to turn right on red (as is common in the USA) or turning right has a designated lane bypassing the intersection, then this policy would likely result in no improvement at all.

For CAV penetration greater than 90% the one-lane signal policy was suggested which yielded a significant reduction in average delay. In the one-lane signal policy, right of passage for HVs (i.e., green signal) is given

\footnote{This paper assumes driving on the right side of the road. However, the ideas can trivially be generalized to a left side driving policy.}
to a single lane at a time instead of an entire road (all lanes arriving from the same direction). The one-lane signal policy results in a significant reduction in green trajectories at the cost of increased delay for HVs. As a result, the one-lane signal policy proved to be inefficient when considering lower CAV penetration (less than 90%).

### 2.2 Other Related Work

In recent years, different variants and enhancements to the basic AIM protocol were suggested. A line of work developed techniques for ordering reservation requests in ways that are more efficient than FCFS. The intuition behind such work is that, in some cases, approving a reservation that conflicts with several other requests is inefficient, even if that request was submitted first. Au et al. (2011) presented the notion of batch reservations where a batch of vehicles arriving from the same incoming road are granted right of passage as a group. This approach was shown to be superior to FCFS for imbalanced intersections where an arterial road intersects with a low capacity road. Zhu et al. (2009) suggested a protocol named LICP that uses a look-ahead approach where the intersection manager optimizes reservation allocation within a defined moving time window (the look-ahead). LICP presented up to 25% reduction in average delay compared to the traditional FCFS approach. In contrast to our work, LICP assumes that all vehicles are connected and autonomous.

Market-inspired approaches for ordering reservation requests were also presented (Vasirani and Ossowski, 2009; Carlino et al., 2013). In this line of work automated agents bid for right of passage through intersections and auction mechanisms are used to determine the winners. Such auction-based approach were shown to apply for traditional intersections using stop signs and traffic signals, as well as to intersection management protocols. These studies focus on fairness issues and network wide efficiency where vehicles travel through a network that is composed of several intersections. By contrast, our work focuses on minimizing delay and maximizing throughput in a single intersection.

Another line of work assumed that the intersection manager is able to control the speed of incoming vehicles (Lee and Park, 2012; Bento et al., 2012). Controlling the vehicle’s speed allows the intersection manager to precisely coordinate the vehicles’ time of arrival and crossing schedule in a way that dramatically reduces the vehicles’ need to stop which, in turn, reduces emissions and delays. Work covering this approach usually assume that all vehicles are connected and autonomous, and that the intersection manager is able to manipulate the speed and trajectory of incoming vehicles prior to entering the intersection. Our work makes none of these assumptions.

VanMiddlesworth et al. (2008) presented a protocol for coordinating CAVs through an unmanaged intersection. In the presented protocol vehicles negotiate right of passage amongst themselves. On the one hand, this protocol is cheap to implement as it doesn’t require any road side equipment but on the other hand it was shown to be less effective than AIM except in very low traffic volumes. To date, no version of this protocol that can handle a mixture of CAVs and HVs has been presented.

Bento et al. (2013) presented an intersection management protocol for mixed traffic named legacy early method for intelligent traffic management (LEMITM). When LEMITM detects an incoming HV it computes an upper and lower bound for its arrival time. LEMITM than tries to reserve all possible trajectories through the intersection for the given time interval. If the reservation does not conflict with any previous reservation, it is approved and a designated traffic signal will turn green indicating right of passage for the HV. Similar to FCFS+signals, LEMITM was shown to be efficient only for high CAVs penetration rates (≥ 90%). The focus of our work, by contrast, is early adoption stages where most of the traffic is composed of HVs.
3 Autonomous Intersection Management Protocol for Mixed Traffic

CAVs are expected to penetrate the automobile market gradually over many years. Reaching 90% AV penetration rates will probably not happen in the near future (Bansal and Kockelman, 2016). Hence, a new intersection management protocol is required for managing traffic that is comprised mostly of HVs.

3.1 Assumptions and Desiderata

When compared to traditional traffic signals, the new intersection management protocol should provide the following:

- Reduce the average delay experienced by vehicles crossing the intersection.
- Reduce queue length on incoming lanes. Once the vehicle queue is longer than the length of the incoming link, a phenomenon known as queue spillback occurs (Abu-Lebdeh and Benekohal, 1997). Queue spillbacks have a negative cascading effect and should be avoided as much as possible (Liu and Chang, 2011).
- Increase throughput. Higher intersection throughput helps reduce congestion accumulated on links leading to the intersection.
- Provide a relative advantage to CAVs over HVs so as to incentivize drivers to transition to CAVs which are assumed to be safer (Furda and Vlacic, 2011) and more efficient (Regele, 2008).
- Preserve safety guarantees. Similar to traditional traffic signals, the suggested protocol must guarantee that vehicles on conflicting trajectories are not given right of way simultaneously. This guarantee must hold also for cases of faulty communication and dropped messages.

The protocol presented in this paper makes the same assumptions that were made by the AIM protocol. Namely:

- CAVs can communicate with the intersection manager through a commonly known message protocol.
- A CAV may not enter the intersection without a fitting reservation.
- When crossing the intersection a CAV precisely follows its reserved trajectory.
- A HV may not enter the intersection while its incoming lane is assigned a red signal (by a traditional traffic signal).

In addition to these assumptions, H-AIM also makes the following assumptions:

- Using a sensor (loop detector, camera or radar), the intersection manager is able to detect approaching vehicles on each lane (sensing speed and heading is not assumed).
- A CAV may not pose as a HV. Even if a CAV is arriving on a lane with a green signal, it may not enter the intersection unless it follows an approved reservation.
- HVs may not change incoming lanes within sensing distance. That is, it is safe to assume that once a HV is detected on an incoming lane, it will occupy the same lane until it enters the intersection.
3.2 Hybrid AIM

Next, we present the Hybrid-AIM (H-AIM) protocol. Similar to FCFS+Signals, H-AIM grants reservation in a FCFS order. However, while FCFS+Signals automatically rejects reservation requests that conflict with green trajectories, H-AIM rejects reservation requests that conflict with active green trajectories.

Definition 3 (Active green trajectories). A green trajectory (see Definition 2) is active if a HV is present on it or on its incoming lane.

Figure 1 illustrates active green trajectories shown as dashed green lines across the intersection (notice vehicle 1 on the incoming lane). Active green trajectories are a subset of the green trajectories making H-AIM at least as efficient as FCFS+Signals; there can be no reservation that is approved by FCFS+Signals and denied by H-AIM. The other way around, on the other hand, is possible. As an example consider the setting depicted in Figure 1. Assume vehicle 2 is a CAV and is heading north. Under the FCFS+Signals policy, vehicle 2 would be automatically denied a reservation as it crosses a green trajectory. H-AIM on the other hand, would consider such a reservation as it doesn’t cross an active green trajectory.

Note that the existence of a CAV on an incoming lane does not create an active green trajectory. As a result, the system is required to be able to identify whether an approaching vehicle is of type CAV or HV. For doing so we suggest the following procedure:

1. Let \( v \) = the number of vehicles detected on a given lane, \( l \).
2. Let \( r \) = the number of reservation requests from unique vehicles seeking to enter the intersection from lane \( l \). Reservations are considered only if the specified exit time is greater than the current time.
3. If \( v > r \) then assume a human vehicle on lane \( l \).

Note that the above procedure is safe in the sense that it will never misidentify a HV as a CAV. In the case of faulty communication this procedure might misidentify a CAV as a HV but doing so does not pose a safety issue. It might, however, hurt efficiency since a green trajectory might, mistakenly, be considered active. Safety can be compromised, however, if HVs are allowed to change lanes in close proximity to the intersection. For this reason HVs must be prohibited from changing lanes within detection range.

Figure 2 illustrates the H-AIM protocol. As in traditional traffic signals, HVs approaching the intersection may cross it only if a green signal is given to their incoming lane. Else, they may continue to approach the intersection but may not cross it. An approaching CAV, on the other hand, sends a reservation request to the intersection manager. The intersection manager checks if the reservation request’s exit time minus the current time is larger than the given threshold. The threshold represents the minimal duration of time taken between the identification of an approaching HV and the time that the same HV reaches the intersection. Considering requests that are within the threshold guarantees that all potentially threatening HVs are identified. If the exit time is beyond the given threshold, the intersection manager inquires whether the reservation request’s entrance time and entrance lane align with a green signal. If this is the case, it is still safe to consider the reservation as no conflicting green trajectories can exist. Once the intersection manager determines that it is safe to consider the reservation request, it examines whether the request conflicts with any previously approved reservations or active green trajectories. If this is not the case, the reservation request is approved and an approve message is sent to the CAV which, in turn, must precisely follow the reservation (or risk losing the right of way).
4 Reducing the Number of Green trajectories

Green trajectories (as a super-set of active green trajectories) can limit CAVs from obtaining reservations. As such, CAVs benefit from reducing the number of green trajectories to a minimum. On the other hand, HVs cannot cross the intersection unless traveling on a green trajectory. Thus, HVs generally benefit from an increased number of green trajectories.

Dresner and Stone (Dresner and Stone, 2008) presented the one-lane signal policy (see section 2.1.2). This policy results in green trajectories that originate from a single lane at a time which significantly reduces the number of green trajectories.”. On the other hand, the one-lane signal policy was shown to have a dramatic negative effect on HVs.

We suggest a more conservative approach for reducing the number of green trajectories. Revisiting Figure 1, assume vehicle 3 is autonomous and is heading west. When applying H-AIM, vehicle 3 is automatically denied a reservation since the requested reservation crosses an active green trajectory. Currently, the lane on which vehicle 1 approaches the intersection allows continuing straight or turning right. If the turning policy on that lane is changed to “right only”, the dashed straight green trajectory will no longer exist allowing vehicle 3 to obtain a reservation.
Figure 3: Three turning assignment policies for a three lane road approaching a four way intersection.

4.1 Turning Assignment Policy

As was shown in the previous section, the performance of a managed intersection is affected by the allowed turning options in each lane. When considering a four-way intersection, each incoming lane has between one and three turning options from the set \{left, straight, right\}. The turning assignment policy assigns each incoming lane with allowed turns.

Assuming three incoming lanes, this study considers three representative turning assignment policies that are depicted in Figure 3. The policies are ordered and labeled according to degrees of freedom.

**Definition 4 (Turning policy degree of freedom).** Define degree of freedom for a lane as the number of turning options minus one. Define degree of freedom for a turning assignment policy as the sum of degrees of freedom over all lanes.

A restrictive turning policy is one that has a low degree of freedom which, in turn, translates to fewer green trajectories. Policy 0 is an extreme case, representing the most restrictive turning policy (0 degrees of freedom). On the other hand, policy 4 is an extreme case of a liberal turning policy.

**Definition 5 (Consistent turning policy).** A turning assignment policy is said to be consistent if trajectories originating from the same road never cross each other.

In our representative policy set, turning policy 4 is not consistent while 0 and 2 are. When considering more than one type of vehicle, different turning policy combinations might be considered. For instance, we might choose to assign one turning policy for HVs and a different one to CAVs.

**Definition 6 (Consistent turning policy combination).** A set of turning assignment policies are said to be a consistent combination if no trajectory from one policy crosses any trajectory from any other policy when both originate from the same road.

In our representative policy set, \{0, 4\} is a consistent turning policy combination (even though 4 is not a consistent policy on its own). \{2, 4\} is not a consistent turning policy combination.

For safety reasons we don’t consider assigning an inconsistent policy to HVs. On the other hand, assigning such a policy to CAVs is reasonable since conflicting reservations are automatically denied by the intersection manager. During our empirical study, we observed that assigning inconsistent policy combinations for CAVs and HVs is counterproductive from an efficiency standpoint and should be avoided. Figure 4 demonstrates the inefficiency that stems from an inconsistent turning policy combination. The figure presents a single road approaching a four-way intersection. CAVs are assigned the turning policy shown on the top level (checkerboard texture) while HVs are assigned the bottom turning policy (plain texture). Vehicle 1 is autonomous. It is located in the middle lane and would like to turn right. Assuming a green signal for this incoming road and that HVs are arriving on the rightmost lane, vehicle 1 will not be able to obtain a
reservation as it crosses an active green trajectory. Vehicle 1 will thus be stuck and will jam all the vehicles behind it despite having a green signal.

5 Empirical Study

This section presents results from a comprehensive empirical study. The goals of these experiments are two-fold:

1. Study the effectiveness of H-AIM for mixed traffic with an emphasis on low CAV ratios.
2. Indicate which turning policy should be assigned to HVs and CAVs in different traffic and CAV penetration levels.

Similar to the experiments presented by Dresner and Stone (2008), our experiments assume that a CAV may communicate with the intersection manager starting at a distance of 200 meters. Following Dresner and Stone, results are presented as averages over 20 instances per setting where each instance simulates one hour of traffic. Unlike Dresner and Stone, our experiments assume a speed limit of 15 meters/second and a safety distance of 0.5 second between CAVs’ trajectories. Dresner and Stone considered a speed limit of 25 meters/second which is uncommonly high for signaled intersections, and a safety distance of 0.1 second, which might cause discomfort among passengers.

In line with our desiderata (presented in Section 3.1), we present average results for the following measurements:

- **Average delay** - see Definition 2
- **Maximal queue length** - the maximal number of vehicles that simultaneously occupy a single incoming lane. Note that 29 vehicles is the maximal queue length for any lane in the simulator, no new vehicles will be generated on a lane as long as this limit is reached. When high traffic volumes are
Figure 5: A screenshot from the modified AIM simulator. HVs (in purple) may not enter the intersection on a red signal. CAVs (in yellow) may enter the intersection on a red signal when following an approved reservation.

considered, the maximal queue length is often reached and queue spillbacks occur. In such cases it is hard to compare different policies as they all return similar results making the maximal queue length measurement less valuable. Hence, we also report throughput.

- **Throughput** - the number of vehicles that passed the intersection in one hour. When low traffic volumes are considered the maximal throughput is often reached since all approaching vehicles eventually cross the intersection. At high traffic volumes, when queue spillbacks occur, throughput can give evidence on the severity of spillbacks i.e., the degree to which the spillbacks block new vehicles from entering the system.

The experiments presented in this section were obtained using the AIM4 simulator [http://cs.utexas.edu/~aim/](http://cs.utexas.edu/~aim/). Several adaptations were required in order to run these experiments.

### 5.1 Modifications to the AIM simulator

Below is a list of changes introduced to the AIM simulator In order to simulate H-AIM. The reader is encouraged to view a video presenting the modified simulator at: [http://youtube.com/watch?v=79UwpfD0u6s](http://youtube.com/watch?v=79UwpfD0u6s)

- Vehicles are spawned with equal probability on all roads, and are generated via a Poisson process governed by the probability that a vehicle will be generated at each time step. Each vehicle is randomly assigned a type (HV or CAV) and destination. Given the assigned destination a vehicle is placed on an incoming lane from which it can continue to its destination (the incoming lane must allow turning to the vehicle’s destination). If several such lanes exist it will be placed on the lane with the least number of vehicles currently on it. For instance, consider Figure 1, a vehicle arriving at the intersection from...
Phase | Direction   | Green | Yellow
--- | ----------- | ----- | ----
1   | East-west  | 30    | 0    
*2  | Westbound  | 15    | 3    
*3  | Southbound | 15    | 0    
4   | North-south| 30    | 0    
*5  | Northbound | 15    | 3    
*6  | Eastbound  | 15    | 0    

Table 1: Six-phase traffic signal timing. Green and yellow durations are given in seconds. An asterisk next to a phase number means that left turns are allowed during that phase.

Figure 5 presents a snapshot from the modified AIM simulator. HVs (in purple) wait at the entrance of the intersection for a green signal while CAVs (in yellow) are allowed to enter the intersection as long as they are following an approved reservation.

5.2 Four-way Intersection

Following Dresner and Stone (2008) we start by presenting results from simulating a four way intersection with three lanes on each of the incoming roads (similar to the intersection presented in Figure 5). 30% of the vehicles turn right at the intersection, 20% turn left and 50% continue straight regardless of the incoming road and vehicle type. 2 A fixed six-phase traffic signal timing was used (the signal timing is presented in Table 1).

Recall that under our assumption that HVs can turn right on red, the FCFS+Signals protocol has no advantage over traditional traffic signals (unless using the one-lane signal policy, see Section 2.1.2 for more details). Since FCFS+Signals using the one-lane signal policy was found to be helpful when considering 90% CAVs or more, it is not relevant to our current study which focuses on early CAV adoption stages.

Results are presented for low, medium, and heavy traffic demand scenarios where 300, 900, and 1500 vehicles are spawned per incoming road per hour. The top part of Figure 6 presents three graphs for the four-way intersection scenario with low traffic demand. Each graph presents average delay for CAVs and HVs in seconds (y-axis) versus CAV penetration rates (x-axis). Each graph refers to a different consistent turning policy combinations based on the policies presented in Figure 3.

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2Dresner and Stone (2008) do not report the turning ratios for their mixed traffic experiment. Our turning ratio was chosen since it results in a good balance between the incoming queues when 100% of the vehicles are HVs.
Figure 6: Average delays (y-axis) for different CAV penetration rates (x-axis) according to vehicle type in a four-way intersection scenario with low, medium, and heavy traffic demands (100, 900, 1500 vehicles/road/hour). 95% confidence intervals are provided for each data point.

For low traffic demand, assigning a restrictive turning policy to HVs (policy 0) combined with a liberal turning policy (policy 4) for CAVs results in reduced delay for CAVs (especially at the early adoption stages) while having no significant negative effect on HVs’ delay. The average delay over all vehicles (the “Average” line) is lower than the base case (where all vehicles yield to traffic signals, i.e., 100% HVs) and is decreasing as the CAV ratio increases.

The second row in Figure 6 presents results for a similar scenario with medium traffic demand. The trends are somewhat similar to those observed in the low traffic demand scenario in the sense that policy combination {HV-0, CAV-4} is most beneficial for CAVs while not hurting the performance of HVs. Unlike the low traffic demand scenario, we see that other policy combinations (HV-0, CAV-0) and (HV-2, CAV-2) present no advantage for CAVs over HVs. Nonetheless, the total delay is still clearly decreasing which gives evidence that H-AIM is effectively improving the intersection’s performance wrt delays.

Finally, the bottom part of Figure 6 presents results for heavy traffic demand. Similar to the low and medium traffic demand cases, policy combination {HV-0, CAV-4} is most beneficial for CAVs at early adoption stages
(until 0.2). However, as CAVs ratio increases we observer an anomaly in the behavior of policy combination {HV-0, CAV-4}; the delay imposed on both HVs and CAVs increases with the CAVs ratio. We explain this anomaly through the example depicted in Figure 7. In this example HVs are assigned a strict turning policy (policy 0) while CAVs are assigned a liberal policy (policy 4). Vehicle 1 is a CAV and would like to turn left from the middle lane. Assuming that a green signal is assigned to the east and westbound roads (phase 1 in Table 1), vehicle 1 is blocked from obtaining a reservation due to an active green trajectory. This active green trajectory is caused by continually arriving eastbound HVs (vehicle 2 for instance). Vehicle 1, being unable to obtain a reservation, blocks all vehicles behind it from entering the intersection. Imagine vehicle 3 is a HV and would like to continue straight. As long as vehicle 1 blocks the way it is unable to cross the intersection despite having the right of passage (green signal).

![Figure 7: An example where a combination of strict turning policy for HVs and liberal policy CAVs is counterproductive. Vehicle 1 (CAV) blocks vehicle 3 (HV) from passing the intersection.](image)

Table 2 presents average results for maximal queue length and throughput for the four-way intersection scenario. Results are presented for different CAV penetration and traffic demand levels. An asterisk in front of a value indicates that it is significantly better (lower queue or higher throughput) compared to the values of the other two policies. There is no turning policy combination that is globally better for avoiding congestion (minimizing queue length or maximizing throughput). The best performing turning policy combination is a function of the traffic demand levels and CAV penetration levels. For most cases, policy {HV-0, CAV-4} performs best. A significant exceptions is observed at high traffic levels (500 vehicles/road/hour) with medium and high CAV ratios (> 0.1 but lower than 1). This result is consistent with the anomaly that is discussed above which prevents policy {HV-0, CAV-4} from performing well in such cases.

5.3 Three-way Intersection

Next we present results from simulating a three way intersection with two lanes in each of the incoming roads (similar to the intersection presented in Figure 8). 60% of the eastbound or westbound vehicles continue straight while the rest (40%) turn (either right or left depending on the incoming road). 50% of the northbound vehicles turn right and the rest (50%) left. We used a three-phase fixed traffic signal timing that is presented in Table 3.

Figure 8 also depicts three representative turning policies (with 0, 3 and 6 degrees of freedom). Since a
Table 2: Results for a four-way intersection scenario using different turning policy combinations and different CAV penetration levels (CAV ratio). Values represent maximal queue length and throughput. An asterisk represents a significant advantage for one policy over the two others using a single tail unpaired t-test with 95% confidence.

<table>
<thead>
<tr>
<th>CAV ratio</th>
<th>Maximal Queue</th>
<th>Throughput</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>HV-0, CAV-4</td>
<td>HV-0, CAV-0</td>
</tr>
<tr>
<td>0</td>
<td>9.33</td>
<td>8.80</td>
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<tr>
<td>0.05</td>
<td>8.85</td>
<td>8.90</td>
</tr>
<tr>
<td>0.1</td>
<td>8.75</td>
<td>8.93</td>
</tr>
<tr>
<td>0.3</td>
<td>* 7.10</td>
<td>8.50</td>
</tr>
<tr>
<td>0.5</td>
<td>* 6.15</td>
<td>8.30</td>
</tr>
<tr>
<td>0.7</td>
<td>* 4.60</td>
<td>8.00</td>
</tr>
<tr>
<td>1</td>
<td>* 2.00</td>
<td>3.75</td>
</tr>
</tbody>
</table>

Table 3: Results for a three-way intersection scenario using different turning policy combinations and different CAV penetration levels (CAV ratio). Values represent maximal queue length and throughput. An asterisk represents a significant advantage for one policy over the two others using a single tail unpaired t-test with 95% confidence.

Figure 9 presents nine graphs for the three-way intersection case. The layout of these graphs is similar to those presented for the four-way case (Figure 6). Each graph is affiliated with one of the three consistent turning policies combinations shown in Figure 8. Results show a general trend that is similar to the one observed in the four-way intersection scenario. For low and medium traffic demand, assigning a restrictive policy to HVs (policy 0) and a liberal one to CAVs (policy 6) is most beneficial for reducing delays as well as giving CAVs the biggest relative advantage over HVs. At high traffic demand, on the other hand, policy combination \{HV-0, CAV-6\} is counter productive, similar to the anomaly observed in the four-way case (Figure 7 can be easily adapted to apply for a three-way intersection).

Similar to Table 2, Table 3 presents maximal queue length and throughput but for the three-way intersection scenario. For this scenario we observe that policy \{HV-0, CAV-0\} is never significantly superior to the two other policies. This result seems to be in contradiction to the results presented in Figure 9 where, for the
Table 3: Three-phase traffic signal timing. Green and yellow duration are given in seconds. An asterisk next to a phase number means that left turns are allowed during that phase.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Bound</th>
<th>Green</th>
<th>Yellow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>East-west</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>*2</td>
<td>Westbound</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>*3</td>
<td>Northbound</td>
<td>15</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 8: Three different turning assignment policies for a two lane road approaching a three way intersection.

In case of heavy traffic demand, policy \{HV-0, CAV-0\} seems to outperform the others. This discrepancy is due to the fact that north and westbound vehicles that request to turn left can do so only from the leftmost lane under policy \{HV-0, CAV-0\}. As such, the left most lane becomes congested and, once the queue reaches 29 vehicles, no more left turning vehicles are spawned. In such cases the throughput and queue length decrease and increase respectively while the average delay decreases since left turning vehicles that suffer from more delays are less abundant. The same explains the fact that policy \{HV-3, CAV-3\} produces shorter queues in many cases, allowing left turning vehicles to use both lanes alleviates the congestion formed on the left most lane.

6 Conclusion and Future Work

Though previous intersection management protocols were shown to be extremely efficient in coordinating connected and autonomous vehicles (CAVs) through an intersection, they were shown to provide no or little improvement until 90% of the processed vehicles are CAVs. This paper presents Hybrid-AIM (H-AIM), an efficient intersection management protocol for early CAV penetration stages. H-AIM builds on top of the Autonomous Intersection Management (AIM) protocol (Dresner and Stone, 2008) and is applicable under the assumption that vehicles approaching the intersection can be sensed (on top of the assumptions required by AIM).

When an approaching HV is sensed by H-AIM the protocol examines whether the current traffic signal assignment allows the HV right of passage. If this is the case, H-AIM reserves the relevant trajectory through the intersection and denies any conflicting reservation requests.

Results obtained from a comprehensive empirical study support the following general conclusions:
At non-extreme CAV penetration levels (between 0 and 0.9) H-AIM is superior to previous approaches (AIM, traffic signals).

At low and medium traffic demands a turning policy that restricts HVs while allowing maximal flexibility to CAVs is recommended for reduced average delay, reduced congestion, and encouraging CAV adoption (since CAVs suffer from lower delays compared to HVs).

At high traffic demand, restricting HVs while allowing CAVs maximal flexibility is beneficial only at early CAVs adoption stages ($\leq 0.1$). Beyond early adoption stages, such a policy combination is counter-productive and other policies should be considered.

Future work will study the effects of H-AIM when semi-autonomous vehicles are considered and are assigned different turning policies. Future work will also examine how different traffic conditions affect the performance of H-AIM. Where traffic conditions relate to: the number of lanes on different incoming roads, turning ratios, traffic signal timing, imbalanced traffic (different volume of vehicles arrive
<table>
<thead>
<tr>
<th>CAV ratio</th>
<th>Maximal Queue</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HV-0, CAV-6</td>
<td>HV-0, CAV-0</td>
</tr>
<tr>
<td>0</td>
<td>6.00</td>
<td>6.10</td>
</tr>
<tr>
<td>0.01</td>
<td>5.90</td>
<td>5.85</td>
</tr>
<tr>
<td>0.05</td>
<td>5.70</td>
<td>6.10</td>
</tr>
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<td>0.1</td>
<td>5.88</td>
<td>6.25</td>
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<td>0.3</td>
<td>5.15</td>
<td>5.65</td>
</tr>
<tr>
<td>0.5</td>
<td>* 4.00</td>
<td>5.30</td>
</tr>
<tr>
<td>0.7</td>
<td>* 3.60</td>
<td>5.65</td>
</tr>
<tr>
<td>1</td>
<td>* 2.15</td>
<td>3.20</td>
</tr>
</tbody>
</table>

Table 4: Results for a three-way intersection scenario using different turning policy combinations and different CAV penetration levels (CAV ratio). Values represent maximal queue length and throughput. An asterisk represents a significant advantage for one policy over the two others using a single tale unpaired t-test with 95% confidence.

on different incoming roads, safety buffer size, and speed limit. Ultimately, our goal is to test H-AIM on real intersections with real vehicles.

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References


