Semi-Autonomous Intersection Management

Paper XXX

ABSTRACT

Autonomous Intersection Management [7] (AIM) is a reservation-based intersection control protocol that leverages the capacities of autonomous vehicles to dramatically reduce traffic delay at intersections. AIM was designed for the time when all, or most, of the vehicles on the road are *fully* autonomous. In this paper, we anticipate that there will be a long transition period during which many cars are still driven by human drivers and/or most vehicles have some but not all capabilities of fully autonomous vehicles.In order to accommodate this transition, this paper introduces a new multi-agent protocol called *Semi-Autonomous Intersection Management* (SemiAIM), which allows vehicles with partially-autonomous features such as adaptive cruise control to make reservations in AIM. We propose a method for vehicles with limited autonomy to make reservations to enter an intersection in an AIM-like style and conduct extensive experiments in simulation to evaluate its effectiveness. Our results show that the delay of semi-autonomous vehicles in SemiAIM can be greatly reduced compared to human-driven vehicles, and can be close to the delay of fully autonomous vehicles.

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—Multiagent systems

General Terms

Algorithms, Performance, Economics, Experimentation, Theory

Keywords

Autonomous vehicles, multiagent systems, coordination

1. INTRODUCTION

Recent robotic car competitions and demonstrations have convincingly shown that autonomous vehicles are feasible with the current generation of hardware [5]. Looking ahead to the time when autonomous cars will be common, Dresner and Stone proposed a new intersection control protocol called *Autonomous Intersection Management* (AIM) and showed that by leveraging the control and network capabilities of autonomous vehicles it is possible to design an intersection control protocol that is much more efficient than traffic signals [7]. By removing human factors from control loops, autonomous vehicles, with the help of advanced sensing devices, can be safer and more reliable than human drivers. The AIM protocol exploits the fine control of autonomous vehicles to allow more vehicles simultaneously to cross an intersection, thus effectively reducing the delay of vehicles by orders of magnitude compared to traffic signals [9].

The main motivation for SemiAim is that we anticipate that there will be a long transition period during which most vehicles have some but not all capabilities of fully autonomous vehicles. In fact, this transition period has already begun. Since the late 1990s, adaptive cruise control systems and lane departure warning systems have become widely available as optional equipment on luxury production vehicles. Today's automatic parking systems such as those in the Toyota Prius and various BMW models can perform parallel parking with little or no human intervention. The National Highway Traffic Safety Administration defines five levels of vehicle automation [2]. In this paper, semi-autonomous vehicles meet the criteria of limited self-driving automation (Level 3). Fully autonomous vehicles are equivalent with full self-driving automation (Level 4). Hence, there is an opportunity to develop an intersection control protocol that works with these semi-autonomous vehicles. More importantly, there is a high likelihood that human-driven vehicles, semi-autonomous vehicles, and fully autonomous vehicles will *coexist* on the road in the future. SemiAIM takes advantages of this trend and allows autonomous intersections to handle a traffic mixture with different types of vehicles.

Another motivation for SemiAim is the drawback of AIM. The AIM policy has a significant improvement on the efficiency of intersection, but that requires the ratio of fully autonomous vehicles exceed 95% of all type of vehicles. Even if the ratio of fully autonomous vehicles exceeds 90%, there is no significant difference from traffic signal policy (Figure 16 in [7]).

The main contributions of this paper are 1) the introduction of the concept of Semi-Autonomous Intersection Management (SemiAIM); 2) a full specification of the first SemiAIM multiagent protocol; and 3) detailed empirical results demonstrating the effectiveness of this protocol, especially in moderate traffic levels with a mix of human-driven, semi-autonomous, and fully autonomous vehicles. The remainder of the paper is organized as follows. Section 2 outlines the architecture of AIM which forms the basis of SemiAIM. Section 3 categorizes semi-autonomous vehicles that work with SemiAIM. Section 4 discusses the design of the user interface for drivers on semi-autonomous vehicles to interact with SemiAIM. Section 5 describes the constraint-based reservation systems, a generalization of AIM for semi-autonomous vehicles. Section 6

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presents the results of the simulation experiments we used to evaluates SemiAIM. The related work and the conclusion are given in Section 7 and 8, respectively.

2. AUTONOMOUS INTERSECTION MANAGEMENT

The AIM protocol is based on a *reservation* paradigm, in which vehicles "call ahead" to reserve space-time in the intersection [7]. The system assumes that computer programs called *driver agents* control the vehicles, while an arbiter agent called an *intersection manager* (IM) is placed at each intersection. The driver agents attempt to reserve a block of space-time in the intersection. The intersection manager decides whether to grant or reject requested reservations according to an *intersection control policy*. In brief, the paradigm proceeds as follows.

- An approaching vehicle announces its impending arrival to the IM. The vehicle indicates its predicted arrival time, velocity, acceleration, and arrival and departure lanes.
- The IM simulates the vehicle's path through the intersection, checking for conflicts with the paths of any previously processed vehicles.
- If there are no conflicts, the IM issues a reservation. It then becomes the vehicle's responsibility to arrive at, and travel through, the intersection as specified.
- The car may only enter the intersection once it has successfully obtained a reservation.

The prototype intersection control policy called *First Come, First Served* (FCFS) operates by dividing the intersection into a grid of *reservation tiles*. When a vehicle approaches the intersection, the intersection manager uses the data in the reservation request regarding the time and velocity of arrival, vehicle size, etc. to simulate the intended journey across the intersection. At each simulated time step, the policy determines which reservation tiles will be occupied by the vehicle. If the vehicle's space-time request has no conflict, the reservation is successful; otherwise, the reservation request will be rejected.

A drawback of FCFS is that it is designed for fully autonomous vehicles only—it does not work with any vehicles that require human operations. If any human-driven vehicle appears. Dresner and Stone did propose a hybrid protocol called FCFS-Signal[1] which allows human-driven vehicles to share the road with autonomous vehicles at intersections in AIM [6]. However, their approach has two major drawbacks. First, the benefits of FCFS-Signal over conventional traffic signals are relatively small until 90-95% of the vehicles on the road are autonomous. Second, and most important for this paper, FCFS-Signal cannot take advantage of the limited autonomous capabilities of semi-autonomous vehicles. There are useful features that human-driven vehicles could have, that AIM managers have overlooked. To remedy these issues, this paper introduces a new autonomous intersection system called *SemiAIM* that works not only with autonomous vehicles but also with human-driven vehicles and semi-autonomous vehicles. Figure 1 shows a screenshot of the SemiAIM simulator we developed.

Empirical results in simulation demonstrated that the reservation system with FCFS can dramatically improve the intersection efficiency when compared to traditional intersection control mechanisms [7]. Overall, by allowing for much finer-grained coordination, the simulation-based reservation system can dramatically reduce per-car delay by two orders of magnitude in comparison to traffic signals and stop signs. This reduction of delays can translate into less traffic congestion [3, 14], which in turn leads to better fuel efficiency and lower emissions.

[1] It was originally called "FCFS-Light."

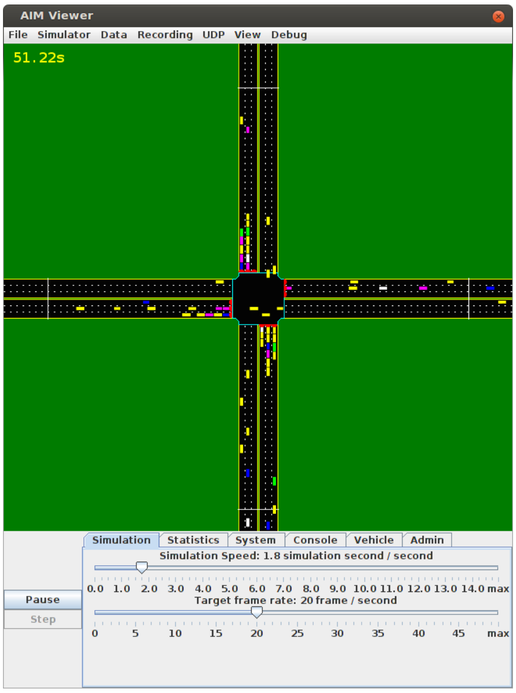

Figure 1: A screenshot of the simulator we developed for the experiments on SemiAIM.

3. SEMI-AUTONOMOUS VEHICLES

Dresner and Stone proposed the FCFS-signal policy, which makes AIM compatible with human drivers [6]. According to their study, when more than 5-10% of traffic is comprised of human-driven vehicles, the average delay time of all vehicles increases significantly. For one thing, the human-driven vehicles themselves may not enter the intersection during red signal phases. But more importantly, they prevent the autonomous vehicles from obtaining reservations when they are behind such stalled vehicles. To allow more efficient management of traffic at intersections, we consider human-driven vehicles with additional communication features to facilitate interaction with the IM and other vehicles. In this paper, we use the term *semi-autonomous vehicles* to refer to both the vehicles with simple/adaptive cruise control and human-driven vehicles with additional communication capabilities. We consider the following categories of vehicles.

- **Autonomous vehicles (Type A).** These are fully autonomous vehicles that can be totally controlled by computers.
- **Semi-autonomous vehicles (Type SA).** Although they are driven by humans, they have some devices that can assist human drivers and can communicate with the IM. In this paper, we consider three concrete types of SA vehicles, as specified in this section.
- **Human-driven vehicles (Type H).** These vehicles are exactly the same as the ones on today's roads. They are completely controlled by humans and have no communication with the IM.

Table 1: Features of semi-autonomous vehicles.

Vehicle Type	Communication device	Cruise control	Adaptive cruise control
SA-ACC	X	X	X
SA-CC	X	X	
SA-Com	X		

Moreover, we classify semi-autonomous vehicles according to the equipment on the vehicles. We consider the following set of equipment that can be put on a semi-autonomous vehicle. This equipment is based on technology that is readily available today.

- **Adaptive cruise control** A vehicle can be set to follow another vehicle in front of it. This feature is currently available as an option in some high-end vehicles. A vehicle with this feature can propose an *anchor request* that will be discussed in Section 5.1. The IM considers whether it can safely traverse the intersection by following the vehicle in front of it.
- **Simple Cruise control** A vehicle can be set to maintain a constant velocity by turning on cruise control. This is a technology that is widely available today. A vehicle with this feature can propose a *constant-velocity request*. The IM considers whether it can traverse the intersection by keeping a constant velocity.
- **Communication device** This is a device, which can be a smart-phone or on-board navigation system, that can communicate with the Intersection Manager. It can gather data from the vehicle, and communicate instructions to the driver when necessary. For example, at a red signal, the IM could inform the driver that it is now safe to enter the intersection. A vehicle with such a feature could propose a *whole-row request* to reserve an entire lane in the intersection for the vehicle. This is a very strong request and is only likely to be confirmed in very light traffic in which an entire "row" is available.

All of this equipment gives semi-autonomous vehicles *some* of the functionality of autonomous vehicles, even though human drivers still retain some control of the vehicles. Next, we introduce several types of semi-autonomous vehicles that we envision utilizing this equipment. For each, we summarize how the semi-autonomous vehicle can interact with the IM when authorized to do so by the driver. In general, having additional equipment provides additional potential advantages over manually driven cars. But we emphasize that in all cases, the human driver can always opt to simply follow the traffic signals if engaging the equipment is too distracting at any given time. Table 1 summarizes the equipment being used on different types of the semi-autonomous vehicles that we consider.

Type SA-ACC Vehicles can utilize all of the above equipment to make a reservation:

1. Such a vehicle can propose an anchor request. If the vehicle in front of it is (semi-)autonomous and is going in the same direction, then if they can both get reservations, the request is confirmed. The vehicle can follow the front vehicle and enter the intersection.
2. If the anchor request is denied, it can propose a constant-velocity request. If keeping the current velocity it can safely traverse the intersection, the request is confirmed.
3. If the constant-velocity request is denied, it can propose a whole-row request. If there is no conflict and the vehicle can enter the intersection directly, the request is confirmed.
4. If denied again, the car must decelerate enough to be able to stop before the intersection. It can retry step 3 or pass control to the human.

Type SA-CC Vehicles mainly utilize simple cruise control as follows.

1. Such a vehicle can propose a constant-velocity request. If it can enter the intersection by keeping the current velocity, the request is confirmed.
2. If the constant-velocity request is denied, it can propose a whole-row request. If the entire lane is available, the request is confirmed.
3. If denied again, the car must decelerate enough to be able to stop before the intersection. It can retry step 2 or pass control to the human.

Type SA-Com Vehicles utilize only communication devices to make reservations:

1. Such a vehicle can propose a whole-row request. If the entire lane is available, the request is confirmed.
2. If denied again, the car must decelerate enough to be able to stop before the intersection. It can retry step 1 or pass control to the human.

In Figure 1, we color Type A with yellow, Type SA-ACC with green, Type SA-CC with blue, Type SA-Com with white and Type H with magenta. This is a red phase for all lanes, Some Type A vehicles are permitted to enter the intersection.

4. USER INTERFACES

For the semi-autonomous vehicles defined above to be able to interact with the IM, we need to define interfaces for passing control from the human to the driver agent and back. Safety is a common (and quite reasonable) concern when involving human drivers in the control loop of autonomous vehicles. In the semi-autonomous vehicles we introduced in the previous section, a human driver can always intervene and simply follow the traffic signal. In this section, we describe how our proposed protocol can be realized safely, as long as no driver runs a red light (without a reservation granted).

For drivers of vehicle types SA-ACC, SA-CC, and SA-Com, we assume inclusion in the vehicle of a single button that signals the driver agent to ask for a reservation. We define such an active "opt-in" interface so as to allow drivers to drive as they do today if they do not signal their intention for a semi-autonomous reservation. It is also important that there is a clear indicator (such as a green light) installed in the car which indicates when the request has been confirmed. The driver must then actively pass control to the computer, again by pressing the single button. In this way, the driver will not be surprised by any sudden autonomous actions of the vehicle. Figure 2 shows the interactions between human drivers, driver agents, and the Intersection Manager. Since vehicles are semi-autonomous, only some control will be passed to the driver agent when the vehicle is passing the intersection.

In Type SA-Com vehicles, the driver can safely enter the intersection when the request is confirmed. If the request is confirmed and the driver decides not to enter, it still does no harm (even though

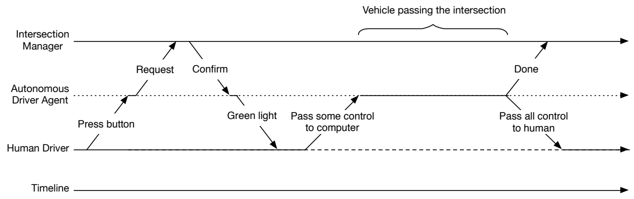

Figure 2: The interactions between human drivers, driver agents, and the Intersection Manager.

the tiles it requested are wasted). When the reservation is granted to Types SA-ACC and SA-CC vehicles, the vehicle starts controlling the speed. If the person touches the brakes or accelerator, the person regains control, and the reservation is cancelled.

There is a point near the entry of the intersection where it is no longer possible to brake before entering the intersection. Beyond this point, the person must lose the ability to take back control of the speed until leaving the intersection (presumably with an emergency override option for extreme situations). This constraint is based on the fact that if the driver were to change its velocity, its reservation would need to be modified. The IM cannot guarantee that the modified reservation will be confirmed.

Drivers can must always steer in type SA-CC vehicles. For type SA-ACC, the vehicle might follow a vehicle in front of it to make a turn. The driver would cede control over the steering wheel in this case.

Two points are important to keep in mind about all the cases above:

- The only actions a human driver needs to take is to press a single button to request a reservation, and press a single button to accept it (possibly the same button). All of the negotiation involving arrival times and trajectories is completed automatically by the driver agent and IM in a manner similar to how it is done in AIM.

- No equipment is *required* on any car. Like FCFS-Signal in AIM, Semi-AIM is fully compatible with "classic" human-driven cars that have no communications equipment.

5. CONSTRAINT-BASED RESERVATION SYSTEMS

SemiAIM extends AIM by allowing human-driven vehicles and semi-autonomous vehicles to make reservations in the same way as autonomous vehicles. The key idea of SemiAIM is to turn AIM into a *constraint-based reservation system*, which allows vehicles to make reservations in terms of constraints over (1) their driving profile such as their arrival time and arrival velocity, and (2) the relationships with other vehicles. In AIM, a reservation request is a 5-tuple $\langle l_1, l_2, t_0, v_0, p \rangle$, where l_1 is the entry lane, l_2 is the exit lane, t_0 is the arrival time, v_0 is the arrival velocity, and p is the physical characteristics of the vehicle. This information allows the Intersection Manager (IM) to compute the exact trajectory of the vehicle in the intersection and reserve tiles for the vehicle on the trajectory. However, this computation assumes the vehicle can be controlled *precisely* in the intersection so that it can meet the reservation constraints exactly.

Human drivers cannot control their vehicles as precisely, and semi-autonomous vehicles may only be able to control certain aspects of their trajectories. However, even partial control can be sufficient for interfacing with AIM. For example, vehicles with cruise control are capable of precisely controlling their speed, even if a human is steering. Thus reservations for moving straight through the intersection may be able to be followed precisely. Similarly, vehicles with adaptive cruise control can maintain a certain distance from the vehicle in front, so they could be able to meet reservations that are specified relative to the traversal times of other vehicles. These examples motivate the need for a new reservation system that relaxes the assumption of exact trajectories so as to allow semi-autonomous vehicles to make reservations.

To this end, we propose a constraint language to facilitate communications between vehicles and IMs, which is specified in Section 5.1. If a vehicle expresses its reservation request in this language, the IM will be able to interpret the request and determine whether it is possible to reserve a matching set of tiles. For example, a semi-autonomous vehicle with simple cruise control can make a reservation stating that it is approaching the intersection at 30mph and will arrive at the intersection between 10:15:05am and 10:15:10am, and it will go straight through the intersection. Upon receiving this reservation request, the IM will determine the set of tiles along *all* possible trajectories of the vehicle and check whether any of these tiles have been reserved by other vehicles. If none of these tiles is reserved, the IM sends a confirmation message to the vehicle and the human driver can then turn on the cruise control accordingly. dangerous when there are other vehicles in the practice, the human driver can propose a request with constraints that are relaxed enough such that he/she can enter the intersection comfortably and safely, and the IM can guarantee there is no collision. If the human driver is unable to enter the intersection according to the proposed reservation, or if the driver does not have any equipment to make reservations, the human driver must follow the traffic signals at the intersection. Thus any possible use of SemiAIM will be an advantage to the driver.

For semi-autonomous vehicles with *adaptive* cruise control, a reservation request, called an anchor request, proposes that it will follow the vehicle with a vehicle tag GXC345 in front of it and maintains a following distance of $5m$. To determine the set of tiles for this vehicle, the IM in SemiAIM has to derive the trajectories from the reservation request of the vehicle GXC345. Hence, the IM in SemiAIM will retain all reservation requests in symbolic forms. If the vehicle GXC345 is also a semi-autonomous vehicle whose request depends on other requests, the IM has to deduce the trajectories by constraint propagation. Anchor reservation requests are described in more detail, along with constraint-based requests in general, in Section 5.1.

5.1 Constraint-Based Request Messages

We define constraint-based reservation requests as follows. A request message consists of four components:

1. **Intention**. The direction in which the vehicle intends to move.

2. **Vehicle Type**. The type of the vehicle.

3. **Entry Condition**. The condition under which the vehicle will enter the intersection.

4. **Acceleration Profile List**. The schedule of acceleration the vehicle plans to use to enter an intersection.

The intention of a vehicle is the direction in which the vehicle wants to exit from an intersection. The intention is expressed as an *intention statement*, which is formally a disjunction of lane and road identifiers: $(l_1 \vee l_2 \ldots \vee r_1 \vee r_2)$, where l_i is an exit lane and r_i is an exit road. For every lane l_i, there exists only one r_j such that $l_i \in r_j$. Examples of legal intentions are $(l_1 \vee l_3)$ or (r_1).[2] This feasibility facilitates different path planning strategies the vehicle might use.

The vehicle type of a vehicle is the information with which the IM can determine how the vehicle will move inside an intersection. Different types of vehicles have different sizes, shapes, and kinematics. For example, the motion of a bus is very different from the motion of a passenger car. By knowing the type of the vehicle, the IM will be able to compute the trajectories of the vehicle under various conditions such as the arrival times and velocities. We assume the IM maintains a database of vehicle types.

The entry condition is the condition under which a vehicle enters an intersection. An *entry statement* is used to describe the entry condition. An entry statement consists of three parts: the arrival lane condition, the arrival time constraint and the arrival velocity constraint. An *arrival lane condition* states the possible lanes from which the vehicle will enter the intersection. It is a disjunction of labels: $(l_1 \vee l_2 \vee \ldots \vee l_n)$ where l_i is a possible lane from which the vehicle enters the intersection. An *arrival time constraint* $[t_1, t_2]$ states the time interval the vehicle will arrive at the intersection. An *arrival velocity constraint* $[v_1, v_2]$ states that the arrival velocity of a vehicle is between v_1 and v_2. An entry statement is a 3-tuple $\langle (l_1 \vee l_2 \vee \ldots \vee l_n), [t_1, t_2], [v_1, v_2] \rangle$.

An *acceleration profile* is the schedule of accelerations the vehicle will use to accelerate through the intersection on a trajectory. An acceleration profile is a list of pairs $\langle (t_1, a_1), (t_2, a_2), \ldots, (t_n, a_n) \rangle \in A$, where A denotes the set of possible acceleration profiles, a_i is the acceleration the vehicle will use from time t_i until time t_{i+1}. Note that the vehicle may or may not provide the acceleration profile of all possible trajectories in a request message. If the acceleration profile is missing, the IM will generate an acceleration profile based on a simulation of the movement of the vehicle given the vehicle type. The most trivial acceleration profile is one that gives the vehicle zero acceleration, forcing the vehicle to maintain a constant speed. Another acceleration profile the IM considers is a constant acceleration profile. The IM will consider these acceleration profiles one by one in order to find one that leads to a successful reservation. Ultimately, the reservation includes a required acceleration profile to be followed by the vehicle once it enters the intersection.

Anchor Requests We also introduce a new type of reservation requests called anchor requests, which is used for vehicles whose entry conditions and trajectories depend on other vehicles. For example, a vehicle v with adaptive cruise control can make an anchor request such as $Anchor(\mathsf{id}, d, T)$, which means that v will start following another vehicle with the VIN number id at time T, and then maintain a following distance less than or equal to d. The following distance constraint causes the IM to consider the two vehicles as being a single, longer vehicle, with no free space between them.

In their current form, anchor requests are designed specifically for semi-autonomous vehicles with adaptive cruise control. However, our formulation is general enough to include other kinds of cooperative maneuver such as platooning [16].

6. SIMULATION RESULTS

To demonstrate the feasibility of SemiAIM as well as evaluate the hypothesis that SemiAIM can offer substantial improvements over traffic signals and FCFS-Signal, we modified the AIM4 simulator at `http://www.cs.utexas.edu/~aim` to simulate the behavior of vehicles in the constraint-based reservation system and measured the average delays of vehicles under (1) AIM, (2) SemiAIM, and (3) traffic signals with optimized signal timing. In all experiments, we spawn vehicles in each lane according to a Poisson distribution with the expectation of 360 vehicles per hour. We denote this setting as traffic level = 360 vehicles/hour/lane.[3] We assume the intersection is fully observable to the intersection manager.

We expect that in the presence of semi-autonomous vehicles, SemiAIM will provide significant advantages over FCFS-Signal if we assume that semi-autonomous vehicles have to act as fully human-driven vehicles in FCFS-Signal. However, we do not expect that semi-autonomous traffic under SemiAIM will perform as well as fully autonomous traffic in AIM. The goal of SemiAIM is not to replace AIM, but rather to provide many of its benefits prior in the time period between today, when most cars are driven fully manually, and the time when all cars are fully autonomous. To do so, it leverages features of semi-autonomy, that we expect will be widespread much sooner than full autonomy.

The implementation of autonomous vehicles (Type A) and human-driven vehicles (Type H) can be referenced from [7]. The semi-autonomous vehicles can be implemented according to their description in Section 3. The concrete implementation is as follows.

1. Type SA-ACC: IM tries to reserve the tiles the vehicle needs to occupy directly following the vehicle in front of it, if they are heading for same destination lane. If tiles successfully reserved, IM grants confirmation, otherwise rejects.

2. Type SA-CC: IM tries to reserve the tiles the vehicle needs to occupy if it moves in constant velocity and not making a turn. If tiles successfully reserved, IM grants confirmation, otherwise rejects.

3. Type SA-Com: IM tries to reserve ALL the tiles in the trajectory that a vehicle would occupy. If tiles successfully reserved, IM grants confirmation, otherwise rejects.

Table 2: The traffic signal phase plan.

Direction	Green Phase	Yellow Phase	Red Phase
East-West	30s	3s	5s
South	8s	3s	5s
East	10s	1s	5s
North-South	40s	3s	5s
West	10s	1s	5s
North	8s	3s	5s

We experimentally generated the *optimized* traffic signal phase plan in Table 2 by using randomized greedy search in the parameters space with random restart. According to this plan, there is a 30 second green phase for traffic coming from East and West, followed by a 3 second yellow phase and a 5 second red phase. Then, there is a 8 second green phase for traffic from South direction only, followed by a 3 second yellow phase and a 5 second red phase, etc.

[2] A intention in the form of $r_i \vee r_j$ is also possible, especially for multiple-intersection management, which involves path planning. In this case, the vehicle is proposing two directions to go and the IM will respond with a confirmation message for either one. We will leave this case for future work.

[3] We choose this traffic level as being high enough to cause significant delays at signals, but light enough to allow for benefits even if cars are not precisely controlled. Figure 7 examines higher traffic levels.

The experiments were conducted in a 3×3 intersection (3 lanes in each direction) as shown in Figure 1. In all cases, we measure the average vehicle delay, where delay is computed as the increase in travel time compared to traversing the intersection without slowing down at all, as if no other vehicles were on the road. Thus, lower delays correspond to better performance. This measure is the same one used in [7]. For all the vehicles, both the static buffer and the edge time buffer are 0.25 meters (see [7] for details), when auto-controlled.

In the first experiment, the traffic consisted of all five types of vehicles we defined in Section 3. The results are in Figure 3. The experiments only compare two types of vehicles at the same time—human-driven vehicles (Type H) and the type of vehicles specified in the legends. We gradually increased the percentage of (semi-)autonomous vehicles while keeping the traffic level at 360 vehicles/hour/lane.

For example, for the line of Type SA-ACC vehicles, at origin point, there are 0% SA-ACC vehicles and 100% human-driven vehicles. At the point of ratio = 1, there are 100% SA-ACC vehicles and 0% human-driven vehicles. At the point of ratio = 0.4, there are 40% SA-ACC vehicles and 60% human-driven vehicles. As described in the legend, the traffic level is 360 vehicles/hour/lane, so it can be easily calculated how many vehicles of a certain type are spawned at each lane.

It can be observed that semi-autonomous with more features have better performance—this is shown in Table 1. For example, SA-ACC vehicles have three features, while SA-CC only have two of them. Now we want to examine how semi-autonomous vehicles attribute their performance to each feature they have. Therefore, in Figure 4, we isolate the features for different types of semi-autonomous vehicles and only consider one at a time. From this perspective, Figure 3 make comparison between sets of features, while Figure 4 compares features themselves.

The setup of this experiment is same as Figure 3, but we only allow a certain vehicle have one feature. For example, the line of Adaptive Cruise Control Only, we simulate a vehicle that only has Adaptive Cruise Control. As can be seen, the feature of communication device is more important than other features in terms of reducing delay time. It implies that being able to communicate is fundamental to the efficiency of intersections.

In addition, we compared the performance in traffic with a mixture of different types of vehicles. We conducted two experiments to test 1) the effect of gradually shifting from human-driven vehicles to autonomous and semi-autonomous vehicles, and 2) the effect of shifting from semi-autonomous vehicles to fully autonomous vehicles. The schedule for shifting is indicated in Tables 3 and 4, which can be used to interpret the mix of vehicles along the x-axes of Figures 5 and 6 respectively.

1. Gradually replace human-driven vehicles with semi-autonomous vehicles. The result shows that with appearance of more autonomous and semi-autonomous vehicles (i.e. fewer human-driven vehicles), the delay time decreases. The result is shown in Figure 5.

2. Gradually replace semi-autonomous vehicles with fully autonomous vehicles. The result shows that when the percentage of human vehicles is fixed, the delay time decreases with appearance of more autonomous vehicles (i.e. fewer semi-autonomous vehicles). The result is shown in Figure 6.

The performance of semi-autonomous vehicles can be significantly better than human-driven vehicles in small traffic levels.

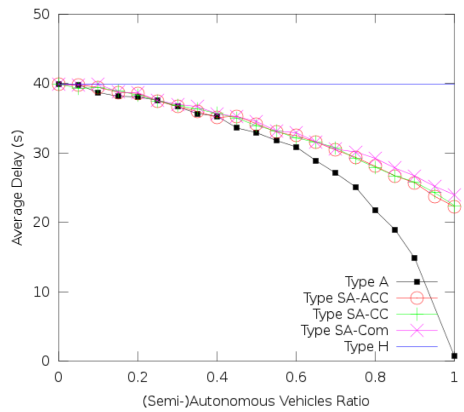

Figure 3: (Semi-)Autonomous vehicles vs. Human-Driven vehicles, traffic level = 360 vehicles/lane/hour. The simulation time is 1800 seconds. Each data point is an average of the delay times over 30 runs.

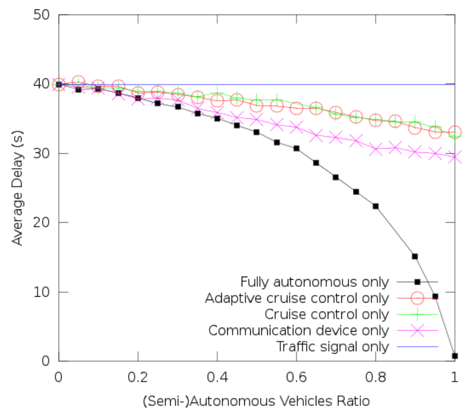

Figure 4: Comparison on different features of semi-autonomous vehicles , traffic level = 360 vehicles/lane/hour. The simulation time is 1800 seconds. Each data point is an average of the delay times over 30 runs.

Table 3: **The distribution of semi-autonomous vehicles in Figure 5.**

Type H	Type SA-* (x-axis)	Type A
90	9	1
87	11	2
84	13	3
...	...	...
0	69	31

Table 4: The distribution of semi-autonomous vehicles in Figure 6.

Type H	Type SA-* (x-axis)	Type A
10	85	5
10	80	10
10	75	15
...	...	...
10	5	85

However, the benefits decrease significantly at higher traffic levels. In Figure 7, we increase the traffic level to 540 vehicles/hour/lane. At this traffic level, congestion appears. It is true that semi-autonomy would not "harm" normal traffic which follows traffic signals, but they have almost no chance to enter the intersection in phases other than when the signal is green. This condition leads to little or no improvement over traditional traffic light policy.

This result confirms our hypothesis that while semi-autonomous vehicles can significantly bridge the gap between the time when all vehicles are human-driven to that when most are autonomous, there will likely always remain strong benefits of full autonomy, especially at high traffic levels. Nevertheless, for lower levels of traffic, the benefits of semi-autonomy can be large.

7. RELATED WORK

The main context of our work is an extension to the FCFS policy proposed by Dresner and Stone [7]. Their experimental results indicated that a mixture of human-driven vehicles and autonomous vehicles is possible, and leads to better performance than having all human-driven vehicles, which is the current status quo. However, their experiments indicated that the impact of autonomous vehicles was relatively small until almost all (90-95%) of the vehicles on the road are autonomous. Our extension to embrace semi-autonomous vehicles shows significant performance benefits all along the technology presentation curve.

Our work is similar to the analysis of adaptive cruise control performance by Jerath and Brennan, who showed that by introducing adaptive cruise control vehicles into traffic, the vehicles would have a more *condense* performance, thus increasing the efficiency of traffic [11]. When compared to our work, there are two key differences. First, we are focusing on the intersection—a place more critical both from the points of view of congestion and safety, while the analysis of Jerath and Brennan is focused on highways. Second, we study five types of vehicles, compared to the three types considered by Jerath and Brennan.

Although we are not aware of any other work that is directly concerned with the interaction of semi-autonomous and autonomous vehicles, research on vehicular autonomy in general has made significant progress in recent years. This was in part due to a series of robotic car competitions such as the *DARPA Grand Challenges* [1]. These competitions accelerated the development of

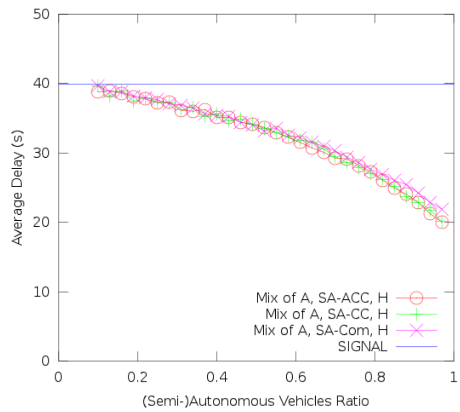

Figure 5: The average delay time in different percentage of semi-autonomous vehicles and autonomous vehicles. The combination of each point is specified in Table 3. Traffic level = 360 vehicles/lane/hour. Simulation time is 1800 seconds.

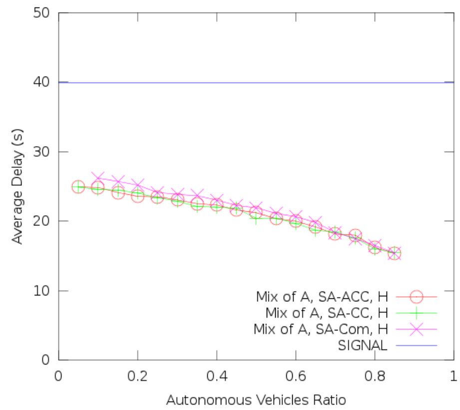

Figure 6: The average delay time in different percentage of human driven vehicles and semi-autonomous vehicles. The combination of each point is specified in Table 3. traffic level = 360 vehicles/lane/hour. Simulation time is 1800 seconds.

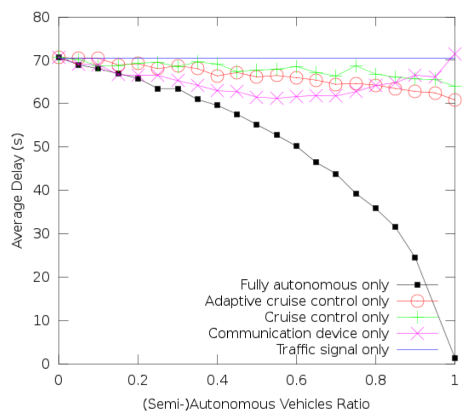

Figure 7: Comparison on different features of semi-autonomous vehicles, traffic level = 540 vehicles/lane/hour. Simulation time is 3600 seconds.

autonomous vehicles to the point where the technical problem of open-road autonomous driving is considered by some to be essentially solved [8]. When pushed to extremes, autonomous vehicles can even out-perform many human drivers in carrying out intricate maneuvers [18]. The non-technical barrier for the adaptation of autonomous vehicles are largely traffic laws and regulations, though this is also being overcome [4].

The vast majority of research on autonomous vehicles focuses on how to ensure they run on existing road infrastructure; there is limited literature on understanding changes to road infrastructure that can facilitate vehicular autonomy. One such project on jointly optimizing autonomous vehicles and road infrastructure is the PATH program, which relies on magnetic markers in the roadway for measuring steering angle and vehicle movements [17]. The Autonomous Intersection Management (AIM) protocol [8, 10, 15] is a vehicle-to-infrastructure (V2I) mechanism in which vehicles request space-time in the intersection for their trajectories prior to arriving at the intersection; a server at the intersection handles these requests, granting or rejecting reservations using a grid-based collision detection scheme. This protocol is enhanced to reduce network traffic and increase safety using spatial-temporal buffers surrounding the vehicles [10].

Vehicle-to-Vehicle (V2V) forms of autonomous intersection management have also been investigated [13, 19]. In this form, no centralized server is required (i.e., there is no single point of failure) and vehicles coordinate in a peer-to-peer fashion when crossing the intersection. Naumann *et al.* investigated a distributed policy that uses virtual "tokens" that a vehicle must possess to cross certain contested areas of the intersection [13] and formally evaluated it using petri-nets. VanMiddlesworth *et al.* developed an AIM-inspired protocol that enables vehicles to "call ahead" to reserve space-time in the intersection [19]. Their protocol outperformed the traditional stop sign in light traffic. Anchor requests we introduced in this paper can be implemented using V2V communications.

Other researchers have investigated autonomous intersections using real systems involving multiple mobile vehicles. For example, Kolodko and Vlacic used golf-cart-like Imara vehicles in evaluating an autonomous intersection [12]. In their study, all vehicles must come to a complete stop at the intersection irrespective of traffic conditions. Our work differs from this, and all other previous research by incorporating semi-autonomous vehicles into the mix, along with autonomous and human-driven cars.

8. CONCLUSIONS AND FUTURE WORK

This paper introduces SemiAIM, a new multiagent constraint-based autonomous intersection management system that includes human-driven vehicles and semi-autonomous vehicles, in addition to fully autonomous vehicles, to make reservations and enter an intersection within the AIM paradigm. To the best of our knowledge, SemiAIM is the first multiagent protocol to enable smooth interactions between human-driven, fully autonomous, and semi-autonomous vehicles. Our experimental results showed that our system can greatly decrease traffic delay when most vehicles are semi-autonomous, even when few (if any) are fully autonomous.

This study opens up several interesting directions for future work. For example, an open question is how the different types of constraint-based reservation requests affect the efficiency of SemiAIM. Some reservation requests are much less efficient than the others, and how to design efficient reservation requests is an important topic for the future. It will also be important to study in detail the performance of SemiAIM under a variety of different, or varying, traffic levels, and with different amounts of traffic traveling in different directions.

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