Semi-Autonomous Intersection Management

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***Abstract*— Autonomous Intersection Management [3] (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. However, 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 multiagent protocol called *Semi-Autonomous Intersection Management* (SemiAIM), which allows vehicles with partially-autonomous features such as adaptive cruise control to make reservations in AIM. Our results show that the delay of semi-autonomous vehicles in SemiAIM can be greatly reduced compared to human-driven vehicles.**

I. Introduction

Recent robotic car competitions and demonstrations have convincingly shown that autonomous vehicles are feasible with the current generation of hardware [1]. 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 [3]. 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 [4].

AIM is designed for the time when vehicles are autonomous. We, however, 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. The National Highway Traffic Safety Administration acknowledges that fully autonomous vehicles represent just the top level in five levels of vehicle automation [8]. Indeed, they define a level below this top level with vehicles that have limited self-driving automation. The main motivation of this paper is to propose a new intersection control system called *Semi-Autonomous Intersection Management (SemiAIM)* that can accomodate both fully autonomous vehicles and *semi-autonomous* vehicles with limited self-driving automation. 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.

The main contributions of this paper are 1) the introduction of the concept of SemiAIM; 2) a full specification of the reservation requests for SemiAIM; 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 II outlines the architecture of AIM which forms the basis of SemiAIM. Section III categorizes semi-autonomous vehicles that work with SemiAIM. Section IV discusses the design of the user interface for drivers on semi-autonomous vehicles to interact with SemiAIM. Section V describes the constraint-based reservation system, a generalization of AIM for semi-autonomous vehicles. Section VI presents the results of the simulation experiments we used to evaluates SemiAIM. The related work and the conclusion are given in Section VII and VIII, respectively.

II. Autonomous Intersection Management

The AIM protocol is based on a *reservation* paradigm, in which vehicles "call ahead" to reserve space-time in the intersection [3]. 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.

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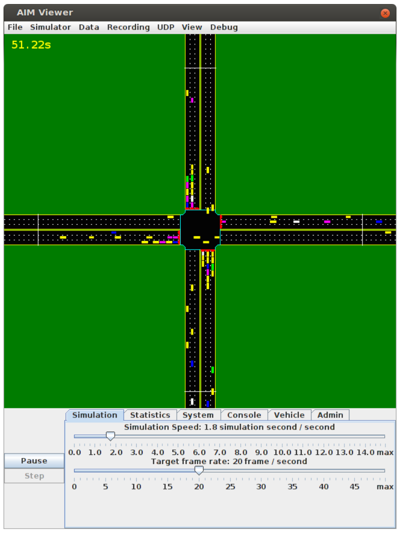

Fig. 1. A screenshot of the simulator we developed for the experiments on SemiAIM.

- 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 request will be rejected. Empirical results in simulation demonstrated that the reservation system with FCFS can dramatically improve the intersection efficiency when compared to traditional intersection control mechanisms [3].

III. Semi-Autonomous Vehicles

An apparent drawback of FCFS is that it is designed for fully autonomous vehicles only—it does not work with any vehicles that require human operations. Dresner and Stone proposed the FCFS-signal (a.k.a. FCFS-Light) policy which makes AIM compatible with human drivers [2]. 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. However, FCFS-signal only allows fully autonomous vehicles to enter intersections during red signal phases. SemiAIM sets out to overcome these issues by allowing *semi-autonomous vehicles* to use the reservation system to enter an intersection during red signal phases.

To facilitate our discussion, we will focus on semi-autonomous vehicles which use the following set of equipment that is readily available today.

- **Communication device (Com)**: a component in a vehicle's on-board electronic system that enables the vehicle to wirelessly communicate with the transportation infrastructure including the IM. The communication is bidirectional.

TABLE I
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		

- **Simple Cruise control (CC)**: An optional speed control subsystem in vehicles' drivetrain that automatically controls the vehicle speed by taking over the throttle of the vehicles.
- **Adaptive cruise control (ACC)**: an advanced cruise control system that automatically adjusts the speed of a vehicle in order to maintain a certain distance from vehicles ahead.

All of this equipment gives semi-autonomous vehicles *some* of the functionality of autonomous vehicles, though human drivers still retain some control of the vehicles. We can equip a semi-autonomous vehicle with more than one of these devices. Next, we introduce three types of semi-autonomous vehicles that we envision utilizing this equipment: *Type SA-ACC Vehicles*, *Type SA-CC Vehicles* and *Type SA-Com Vehicles*. Table I summarizes the equipment being used on different types of these semi-autonomous vehicles.

Figure 1 shows a screenshot of the SemiAIM simulator we developed to simulate semi-autonomous vehicles at intersections.[1]. In this figure, the yellow vehicles are fully autonomous, the green vehicles are Type SA-ACC, the blue vehicles are Type SA-CC, the white vehicles are Type SA-Com, and the magenta vehicles are human-driven vehicles.

IV. Interaction Model

Safety is a main concern when involving human drivers in the control loop of semi-autonomous vehicles. For the semi-autonomous vehicles defined above to be able to go through an intersection safely, we need to define a simple and clean interface for negotiating with the IM and passing control between the human driver and the driver agent. In this section, we describe how our proposed protocol can be realized safely by having an *interaction model* between human drivers and driver agents that simplifies the task of the human drivers.

Figure 2 summarizes the interaction model between human drivers, driver agents, and the IM. We require the inclusion in the vehicle of a single button that signals the driver agent to ask for a reservation. After pressing the button, the driver agent will automatically send a request message to the IM on behalf of the human driver. It is also important that there is a clear "Okay" indicator (such as a green light) installed in the car which indicates when the request has been confirmed. After seeing the okay signal, the driver would have to actively pass control to the driver agent, again by

[1] Modified from the open-source AIM4 simulator: `http://www.cs.utexas.edu/~aim`

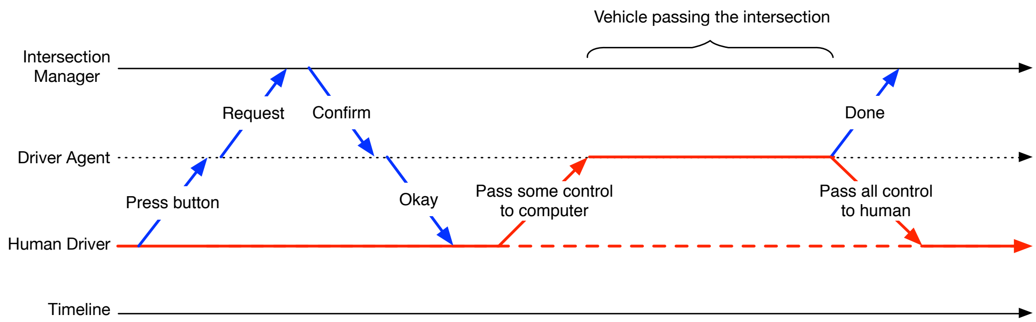

Fig. 2. The interaction between human drivers, driver agents, and the IM. The blue lines are message passing, and the red lines are transfer of control. Note that human drivers retain some control of the vehicle inside the intersection (the dashed red line).

pressing a single button. This way the driver will not be surprised by any sudden autonomous actions of the vehicle.

This interaction model only requires the human driver to perform relatively simple driving maneuvers such as holding the steering wheel at a certain angle (for Types SA-ACC and SA-CC vehicles) or driving as if under a traffic signal (for Type SA-Com vehicles). These tasks are much simpler than other maneuvers such as lane changing and passing other vehicles, and thus should not be taxing to experienced human drivers.

V. Constraint-based Reservation Systems

SemiAIM extends AIM by allowing human-driven vehicles and semi-autonomous vehicles to make reservations in the same way as fully 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 profiles 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 IM to compute the exact trajectory of the vehicle and reserve tiles for the vehicle on the trajectory. In our system, we use a *maneuverability profile* to encode the limitations of the control of human drivers when the automation devices are activated. For simple cruise control, the maneuverability profile is written in Lisp syntax as follows:

```
(cc-profile (v verror angle)
  (is-auto-speed-control)
  (not is-auto-steering)
  (< velocity (+ v verror))
  (> velocity (- v verror))
  (< steer-angle angle) (> steer-angle -angle))
```

where `v` is the target velocity, `verror` is the maximum error of the target velocity, and `angle` is the maximum feasible steering angle for the human driver when the cruise control is turned on.

A. Constraint-Based Requests

Different maneuverability profiles can have different sets of constraints. To facilitate communication with all kinds of semi-autonomous vehicles, SemiAIM uses a *unified* language for vehicles to express their constraints in the same format in their requests. 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 vehicle.
3) **Entry Condition**: The condition under which the vehicle will enter the intersection.
4) **Acceleration Profile List**: The list of possible acceleration schedules from among which the vehicle will choose one to follow during the traversal of the 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 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.

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: an arrival lane condition, an arrival time constraint, and an 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 during which the vehicle will arrive at the intersection. An *arrival velocity constraint* $[v_1,\ v_2]$ states that the arrival velocity of a vehicle will be between v_1 and v_2. An entry statement is a 3-tuple $\langle(l_1 \vee l_2 \vee \ldots \vee$

[2]An 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.

$l_n), [t_1,\ t_2], [v_1,\ v_2]\rangle$.

An *acceleration profile* is the acceleration schedule 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, and a_i is the acceleration the vehicle will use from time t_i until time t_{t+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 and the entry condition.

Each vehicle may have its own algorithm to generate constraint-based requests that satisfy its maneuverability profile. In this paper, we do not fully explore the space of how vehicles could generate such requests. However, we define the following two requests that will be used by Type SA-CC and Type SA-Com vehicles, respectively:

- A **constant-velocity request** is $\langle \mathsf{Intent}, \mathsf{Type}, \mathsf{Entry}, \mathsf{AP}\rangle$, where $\mathsf{Intent} = (l_1 \vee l_2 \vee \ldots \vee l_n)$ in which l_i is a possible lane from which the vehicle exits the intersection; Type is the vehicle type; $\mathsf{Entry} = ((l'_1 \vee l'_2 \vee \ldots \vee l'_n), [t_1,\ t_2], [v_1,\ v_2])$ is the entry statement; and $\mathsf{AP} = (\langle(t_1, 0)\rangle)$ is the acceleration profile list. Since the acceleration in AP is always zero, the vehicle will move at a constant velocity.
- A **whole-row request** is $\langle \mathsf{Intent}, \mathsf{Type}, \mathsf{Entry}, \mathsf{AP}\rangle$, where $\mathsf{Intent} = (l_1 \vee l_2 \vee \ldots \vee l_n)$ in which l_i is a possible lane from which the vehicle exits the intersection; Type is the vehicle type; $\mathsf{Entry} = ((l'_1 \vee l'_2 \vee \ldots \vee l'_n), [t_1,\ t_2], [v_1,\ v_2])$ is the entry statement; and AP is the acceleration profile list. In order to reserve the entire row in an intersection, the difference between t_1 and t_2 as well as the difference between v_1 and v_2 must be large enough to cover the entire row, regardless of the acceleration profiles.

B. Anchor Requests

Semi-autonomous vehicles with adaptive cruise control can use a special constraint-based request called *anchor requests* to make reservations. An anchor request is $\langle \mathsf{Type}, \mathtt{vin}, d\rangle$, where Type is the vehicle type, `vin` is the vehicle id of the vehicle ahead, and d is the following distance from the vehicle of `vin`. Currently anchor requests are designed specifically for semi-autonomous vehicles with adaptive cruise control. However, this formulation is general enough to enable some sophisticated cooperative maneuvers such as platooning [10].

VI. Experimental Evaluation

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 conducted a series of experiments with the modified AIM4 simulator that simulates the behavior of vehicles using the constraint-based reservation system. The implementations of fully autonomous vehicles (Type A) and human-driven vehicles (Type H) are as provided with the simulator and described in [3]. The concrete implementations of the semi-autonomous vehicles, as described in Section III, are as follows.

- **Type SA-ACC Vehicles**: If there exists a vehicle ahead which is either autonomous or semi-autonomous and is going in the same direction, it sends an anchor request to the IM. If the request is confirmed, the vehicle follows the vehicle ahead and enters the intersection. If the request is denied or there is no such vehicle ahead, the vehicle follows rules for Type SA-CC Vehicles, shown below.
- **Type SA-CC Vehicles**: Sends a constant-velocity request to the IM when it is close enough to the intersection. If it can enter the intersections by keeping the current velocity, the request is confirmed; otherwise, the vehicle follows rules for Type SA-C-om Vehicles, shown below.
- **Type SA-Com Vehicles**: Sends a whole-row request to the IM. If the entire lane is available, the request is confirmed; otherwise, the vehicle resends the request after a few seconds, and at the same time decelerates enough to be able to stop before the intersection. If it keeps failing to obtain a reservation it stops at the intersection and returns control to the human driver, who must then obey the traffic signal.

Our experiments were conducted in a 3x3 intersection (3 lanes in each direction) as shown in Figure 1. Unless otherwise specified, the simulator spawns vehicles in each lane according to a Poisson distribution with an expectation of 360 vehicles per hour. We denote this setting as traffic level = 360 vehicles/hour/lane. We chose this traffic level as being heavy enough to cause significant delays at signals, but light enough to allow for benefits even if cars are not precisely controlled.

The performance of an intersection is measured by the *average 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 [3]. For all the vehicles, both the static buffer and the edge time buffer are 0.25 meters (see [3] for details), when auto-controlled.

Traffic signals are used as a fallback strategy when vehicles cannot get a reservation. We used an *optimized* 6-phase signal schedule that includes relatively long green times (roughly 35 seconds) for East-West and North-South phases, and shorter phases for each of the four single direction phases (roughly 9 seconds). It was optimized using SYNCHRO, a commercial traffic optimization package.

A. Experiment 1: Technology Penetration

Our first experiment studies the effect of an increasing penetration rate of vehicular automation technology. Suppose human-driven vehicles are gradually replaced by a particular type of semi-autonomous vehicle or fully autonomous vehicle until all vehicles become that type. We examine how much benefit SemiAIM provides during the transition period.

In this experiment, the traffic consisted of one of the three types of vehicles we defined in Section III as well as Type

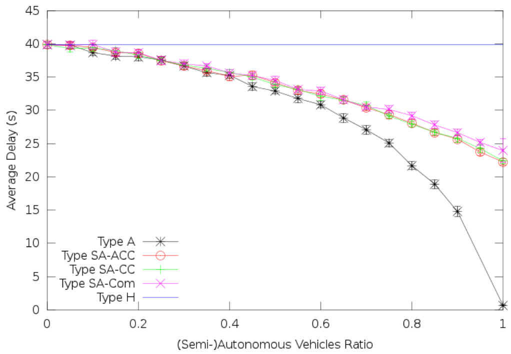

Fig. 3. (Semi-)Autonomous vehicles vs. Human-Driven vehicles. Traffic level = 360 vehicles/lane/hour.

A and Type H vehicles. We measured the traffic delay as we gradually increased the ratio of (semi-)autonomous vehicles to human-driven vehicles (Type H) while keeping the traffic level at 360 vehicles/hour/lane. As an example, consider the ratio of Type SA-ACC vehicles. At the beginning, there are 0% Type SA-ACC vehicles and 100% human-driven vehicles, and the ratio is 0. As the number of Type SA-ACC vehicles increases, the ratio increases and eventually becomes 1, which means there are 100% Type SA-ACC vehicles and 0% human-driven vehicles. We repeated the simulation 30 times for 1800s during each time. For each run, we measured the average delay of all vehicles. The average delays are shown in Figure 3. Each data point in the figure is an average of 30 values, and the error bar is the 95% confident interval of the average delay.

According to Figure 3, the performance of semi-autonomous vehicles is very similar to fully autonomous vehicles when the ratio to human-driven vehicles is below 40%. However, when the ratio increases beyond 40%, fully autonomous vehicles increasingly outperform semi-autonomous vehicles. We can also observe that with the help of SemiAIM, manage to reduce the delay by 46% (from 39.9s to 22.4s) compared to human-driven vehicles. As expected, in the presence of semi-autonomous vehicles, SemiAIM provides significant advantages even when there are no fully autonomous vehicles on the road.

Another observation is that both Type SA-ACC and Type SA-CC vehicles have a significantly lower average delay than Type SA-Com vehicles. The difference is consistent with our hypothesis that the use of more constrained requests can increase the performance of intersections since the footprints of the vehicles are smaller and more vehicles can enter the intersection at the same time. Nonetheless, the difference is small because the simulated human drivers in the simulator can control their vehicles quite well.

B. Experiment 2: Incremental Deployment

Our second experiment considers realistic scenario of *incremental deployment* of autonomous vehicle technology. We believe that the adoption of semi-autonomous vehicles will be much faster than fully autonomous vehicles since the cost of ownership of semi-autonomous vehicles are lower.

TABLE II

THE DEPLOYMENT SCHEDULE IN FIGURE 4.

Type H	Type SA-ACC / SA-CC / SA-Com	Type A
90%	9%	1%
87%	11%	2%
84%	13%	3%
...	...	...
0%	69%	31%

TABLE III

THE DEPLOYMENT SCHEDULE IN FIGURE 5.

Type H	Type SA-ACC / SA-CC / SA-Com	Type A
10%	85%	5%
10%	80%	10%
10%	75%	15%
...	...	...
10%	5%	85%

We consider two plausible deployment schedules, one for the period of time before the domination of semi-autonomous vehicles, and the other for the subsequent period. In the first deployment schedule (Table II), Type H vehicles on the road are gradually displaced by (semi-)autonomous vehicles. Assume two out of three car buyers who abandoned their vehicles for newer technology will buy a semi-autonomous vehicles rather than a fully autonomous vehicle. Then eventually about two thirds of vehicles on the road will be semi-autonomous, and one third will be fully autonomous. Table III shows the second deployment schedule under which semi-autonomous vehicles are gradually replaced by fully autonomous vehicles. We assume that even when most vehicles are fully autonomous, a small number of drivers still prefer driving themselves.

Figures 4 and 5 show the results of the simulations according to these deployment schedules. The simulation setup is exactly the same as in Experiment 1. For each vehicle distribution, we ran the simulation 30 times for 1800s each run. Thus, each data point in the figures is an average of 30 delay times. The 95% CIs of the average are shown as the error bars in the figures. According to these figures, the average delay of the vehicles keeps decreasing as (semi-)autonomous vehicles are deployed, and the choice of the semi-autonomous vehicle technology does not matter much. Ultimately, the average delay depends on the number of drivers who insist on driving themselves.

VII. RELATED WORK

The main context of our work is an extension to the FCFS policy proposed by Dresner and Stone [3]. 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 is expected to be relatively small until almost all (90-95%) of the vehicles on the road are autonomous. Our extension to embrace semi-

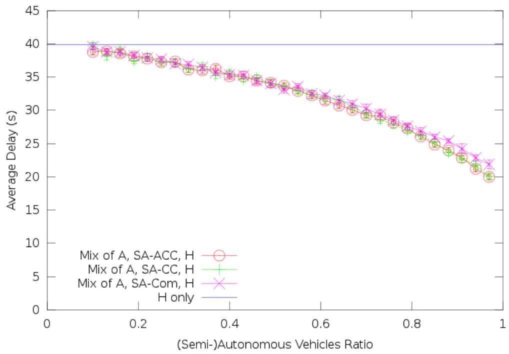

Fig. 4. The average delay according to the deployment schedule in Table II. Traffic level = 360 vehicles/lane/hour.

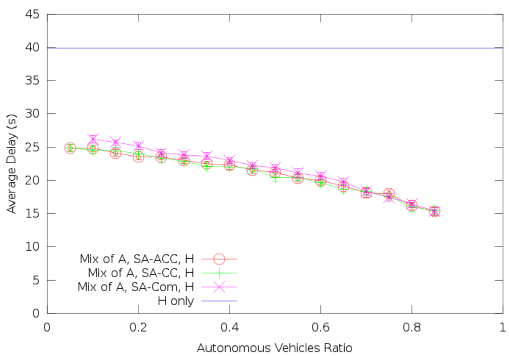

Fig. 5. The average delay according to the deployment schedule in Table III. Traffic level = 360 vehicles/lane/hour.

autonomous vehicles shows significant performance benefits all along the technology penetration 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 *condensed* formation, thus increasing the efficiency of traffic [5].

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 [11]. The AIM protocol [3], [4], [9] 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 [4]. Another popular form of autonomous intersection management is Vehicle-to-Vehicle (V2V), which has been investigated [7], [12]. 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.

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 [6].

VIII. Conclusions and Future Work

This paper introduces SemiAIM, a new multiagent constraint-based autonomous intersection management system that enables 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 to design better constraint-based reservation requests using more accurate profiling of the vehicles' physical behavior. 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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