Semi-Autonomous Intersection Management (Extended Abstract)

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ABSTRACT

Autonomous Intersection Management (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. 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.

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 [4]. 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 [6]. 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 [7].

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. 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. While AIM provides a significant efficiency improvement at intersections when all cars are autonomous, the benefits are minimal even when as few as 10% of the vehicles are driven by humans (Figure 16 in [6]). The requirement that most, if not all, vehicles are fully autonomous is a key obstacle to the adoption of AIM-like intersection control when most vehicles are not fully autonomous.

The National Highway Traffic Safety Administration acknowledges that fully autonomous vehicles represent just the top level in five levels of vehicle automation [11]. 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.

2. SEMI-AUTONOMOUS VEHICLES

In this paper, we use the term *semi-autonomous vehicles* to refer to vehicles with limited autonomous driving and wireless communication capabilities. While these vehicles are not fully autonomous, they are assumed to be able to follow a *limited* number of predictable trajectories at intersections more precisely than human drivers. This ability allows them to utilize our constraint-based reservation system to make reservations in the same manner as fully autonomous vehicles.

Our proposed reservation system is general enough to accept

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reservation requests from *any* semi-autonomous vehicles that are capable of following some trajectories and communicating with the IM. 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: the messages sent from the IM is presented to the human driver on the LCD screen of an on-board navigation system or on a smartphone, and the human driver makes decisions on the user interface of the device. The device is also hooked up with the odometer, GPS, and other sensors such that it can send these sensing information along with the request messages to the IM.
- **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. With the help of cruise control systems, vehicles can maintain a steady constant velocity more precisely than human drivers can manually.
- **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. To achieve this car-following maneuver, ACC uses on-board distance sensors coupled with cruise control in a feedback loop.

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**: Utilizing adaptive cruise control to enter an intersection by either moving straight through the intersection or following another vehicle.
- **Type SA-CC Vehicles**: Using simple cruise control only to enter an intersection at a constant velocity in a straight line.
- **Type SA-Com Vehicles**: Reserve an entire lane in an intersection such that the human driver can get through the intersection without the help of any autonomous control device; thus only the communication device is needed.

3. 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. 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. Therefore, we need a new kind of reservation requests, which we call it as *maneuverability profile* that do not rely on this assumption. 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. The maneuverability profile for adaptive cruise control is

```
(acc-profile (vin d derror angle)
  (is-auto-speed-control)
  (not is-auto-steering)
  (< (dist-from vin) (+ d derror))
  (> (dist-from vin) (- d derror))
  (< steer-angle angle) (> steer-angle -angle))
```

where `vin` is the vehicle id of the vehicle ahead, `d` is the target distance from the vehicle ahead, `derror` is the maximum error for acc to maintain the target distance from `vin`, and `angle` is the maximum feasible steering angle for the human driver.

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.

4. EXPERIMENTAL EVALUATION

The 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 2 as well as Type 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 1. 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 1, 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. Previous studies showed that FCFS-Signal needs at least 90% of fully autonomous vehicles

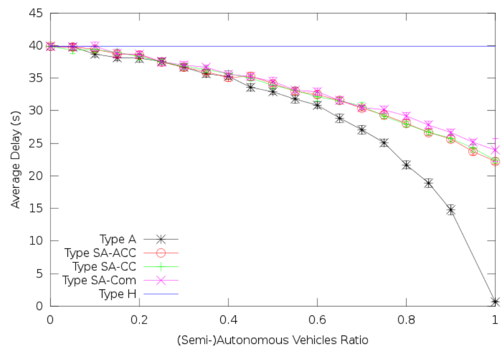

Figure 1: (Semi-)Autonomous vehicles vs. Human-Driven vehicles. Traffic level = 360 vehicles/lane/hour.

in the traffic in order to be fully effective [5]. We successfully replicate the result, observing that the average delay drops rapidly when the traffic has more than 90% fully autonomous vehicles, and approaches zero when all vehicles are fully autonomous. Semi-autonomous vehicles cannot achieve the same dramatic decrease in traffic delay, but they, 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.

5. 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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