Automated Intersection Control: Performance of a Future Innovation Versus Current Traffic Signal Control

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ABSTRACT

Congestion is one of the biggest challenges faced by the transportation community, accounting for an estimated 87.2 billion dollars in losses in 2007 alone. As such, transportation professionals need to go beyond capacity expansion projects and explore novel strategies to mitigate traffic congestion. One such novel strategy, automated intersection management, has been identified with the potential to greatly reduce intersection delay and improve safety. While the implementation of such a system is contingent on the development of automated vehicles, competitions such as DARPA's Grand and Urban Challenges have shown that this technology is feasible and will be available in the future. As such, it becomes critical to develop the infrastructure and associated control methods required to fully exploit the benefits of such technology at the system level. This research explores one such innovative strategy, an Automated Intersection Control protocol based on a First Come First Serve (FCFS) reservation system. In particular, it's shown that the FCFS reservation system can significantly reduce intersection delay by exploiting the features of autonomous vehicles. We present microscopic simulation experimental results and show that the FCFS reservation system significantly outperforms a traditional traffic signal in reducing delay.

1. INTRODUCTION

As population growth has been unmatched by transportation systems' ability to handle increased levels of demand, congestion has become one of the most challenging engineering issues today. The roadway system is not only a source of mobility to drivers, but also to goods and services, and as such, the ability for this system to handle vehicle demand is paramount to the economic development of the country. Traffic congestion accounted for an estimated 87.2 billion dollars in 2007 (*1*), and as the ability to build excess capacity has decreased, transportation professionals have been forced to look beyond capacity expansion-based approaches to address the issue of congestion.

Federal Highway Administration's (FHWA's) Exploratory Advanced Research (EAR) Program was established by the Safe, Accountable, Flexible, Efficient Transportation Equity Act – A Legacy for Users (SAFETEA-LU). The program focuses on long-term, high-risk research "*with the potential for transformational improvements to plan, build, renew, and operate safe, congestion free, and environmentally sound transportation systems*." The EAR Program addresses underlying gaps faced by applied highway research programs (www.fhwa.dot.gov/advancedresearch), anticipates emerging issues with national implications, and reflects broad transportation industry goals and objectives.

One of the EAR projects being conducted is examining the feasibility of autonomous vehicles and intersections for the future. Research in the field of artificial intelligence and robotics in recent years has made the feasibility of automated vehicles a much more tangible reality than in the past. Although the technology may not be at a stage warranting mass deployment of such vehicles in the present, it is clear that this technology has the potential to eventually become the standard. As such, it becomes important to begin to examine the consequences of what could amount to be a major overhaul of traditional operational systems as the component of automation is introduced. As congestion mitigation is an important societal problem, the operational efficiency derived from implementations aimed at exploiting the technological advantages of these automated vehicles warrants serious consideration.

Human error accounts for a majority of vehicle crashes, and prevention of these crashes through automated driving is achievable but requires new systems to coordinate the movement of autonomous vehicles in complex traffic situations. This paper evaluates an automated intersection control mechanism called First Come First Serve (FCFS) protocol developed by Dresner and Stone (*2*). FCFS promises to process traffic much more efficiently than traffic signals without compromising safety. Its development is guided by a set of criteria that includes the use of sensor technologies, the adoption of a standardized communication protocol, and the ability to deploy incrementally, allowing expansion to other intersections and adaptation to increasing numbers of autonomous vehicles. Absolute collision prevention, even under conditions of communications failure, is the primary goal for the system.

While that previous work introduced the FCFS protocol and demonstrated its promise as a future intersection control mechanism, all of the testing was done against ad-hoc signal timing and phasing plans. In addition to describing some refinements to the simulator and protocol, the main contribution of this paper is to validate it against traffic signals that were optimized using a software package called SYNCHRO, which is generally accepted by the transportation community. Results further confirm the promise of the FCFS protocol.

2. BACKGROUND

This section provides an overview of information relevant to this research: autonomous vehicles and their technological feasibility, and the current state of technology; current practices in traditional traffic signal design and optimization; automated intersection control and its potential benefits as an operational strategy; and microscopic simulation software and its role in numerical testing of operational strategies.

2.1 Autonomous Vehicles

The engineering challenges regarding reliable computerized control of vehicles are well understood and mostly solved for perceptually "simple" situations. Vehicles can already be equipped with features of autonomy such as adaptive cruise control, GPS-based route planning (*3*,*4*) and autonomous steering (*5*,*6*). Since the late 90s, adaptive cruise control systems have become widely available as optional equipment on luxury production vehicles of most of the major car manufacturers. Early adaptive cruise control systems can only slow down the vehicle when it is too close to the vehicle in front of it. But the capability of adaptive cruise control systems has greatly improved since then: for instance, the adaptive cruise control systems on Mercedes-Benz S-Class and GM's Cadillac SLR can automatically maintain a safe following distance. Automatic parking is another autonomous feature that have already been commercialized. Today's automatic parking systems such as those in Toyota Prius and BMW can perform autonomous parallel parking with little or no human intervention. Other new autonomous features currently offered by some car manufacturers are traffic sign recognition and lane departure warning systems.

Building a *fully* autonomous vehicle, however, is a challenging engineering task---much more difficult than adding individual features of autonomy. But there are signs that fully autonomous vehicles are on the horizon. For example, in the DARPA Grand and Urban Challenges (*7*) in 2007, 6 autonomous vehicles completed the 60 mile course of suburban-type roadways with light traffic (*8*). In doing so, they demonstrated that it is currently possible to encode and act upon traffic laws and precisely control an autonomous vehicle. In 2008, GM was experimenting with a nearly autonomous vehicle under its European "Opel" brand (*9*). The prototype of this autonomous vehicle is called the Opel Vectra, which uses a video camera, lasers, and substantial processing power to identify traffic signs, curves in the street, lane markings, and other vehicles. Early this year GM demonstrated a concept vehicle EN-V that has the ability to operate autonomously (*10*).

The use of autonomous vehicles has the potential to: improve safety and mobility; reduce driving related stress; increase freeway capacity; reduce emissions and improve fuel efficiency. Furthermore, higher expected compliance levels with traffic instructions could improve system performance.

2.2 Traditional Traffic Signals

Signal optimization methods aim to choose signal timing and phasing plans that achieve optimal values for specific intersection performance metrics such as delay, throughput, queue length, etc. Intersection delay, defined as the amount of time the vehicle added to a vehicle's travel time due to the presence of the intersection, is the most commonly used metric for evaluating the performance of intersections. (*11*)

The operations of an intersection amount to what is a very complex system. As such, predicting intersection delay exactly is often infeasible. As a result, intersection delay is usually seen as a random variable. Traditional methods for estimating delay have relied on the use of analytical equations that provide with point-estimates of delay, such as the expected value or specific percentiles (*11*). Further work has been done in determining signal plans that are optimal at the network level by combining the assignment and signal optimization process. A review of the area can be found in (*12*).

While signal optimization implementations have resulted in substantial operational improvements, there are fundamental limitations to the operational performance of a traditional intersection that stem from the need to address the safety issues arising from driving behavior, namely the limited ability of drivers to process information and make subsequent decisions during the driving activity.

As such, intersections and their associated control devices have been limited to have a simple design and to minimize the number of simultaneous conflicting movements. The rules for navigating an intersection consist of few elements of information, with many standard conventions limiting the number of decisions the driver has to make. For example, drivers are only allowed to make left/right turns from designated lanes, and are never allowed to interfere with a lane containing through traffic. Another example is the use of protected left turns, which removes the need for drivers to evaluate whether gaps in oncoming traffic are appropriate for make a left turn.

Although some measures, such as turning lane conventions, do not significantly affect intersection performance, others, such as protected left turns, do significantly reduce the fraction of available intersection capacity that is actually used. Like many other transportation design problems, a balance must be reached between safety and operational efficiency.

We do make the distinction between traditional fixed time signals, which can change according to the time of day, and actuated signals, in which the presence or absence of vehicles on intersection approaches can affect the amount of green time for each approach in real time. This research did not consider actuated signals as part of the numerical testing for this research, but will be considered as part of future numerical testing.

2.3 Autonomous Intersection Management

In parallel with the development of autonomous vehicles, we consider infrastructure that is able to interact with these autonomous vehicles. Among all elements in modern transportation infrastructure, intersection is the most critical one that needs to be improved. Automobiles in modern urban settings spend a lot of time idling at intersections, due to traffic congestion caused by inefficiency of traffic light systems and stop signs, generating harmful emissions and causing an increase in fuel usage for no significant purpose. According to a 2006 National Highway Traffic Safety Administration (NHTSA) report on Traffic Safety Facts, intersection crashes account for about 40% of the total crashes in the US (*13*). In 2008, 7,772 out of 37,261 fatalities on US roadways were intersection or intersection related (*14*). As intersections make up a very small portion of the roadway, this is a wildly disproportionate amount. Furthermore, collisions at intersections include significant number of side impact crashes, thus they frequently result in great injury and damage.

Therefore, a better intersection management will be a major step towards an infrastructure for fully autonomous vehicles that will revolutionize transportation of people and goods. Our research is to propose a new form of intersection control can dramatically increase vehicle throughput on roads by taking advantages of the capacity of autonomous vehicles.

The advantages of autonomous vehicle traffic are two-fold. First, the introduction of autonomous drivers into intersection control allows for a greater degree of efficiency by removing the need for some of the safety-oriented features of traditional intersections. The operational efficiency that can be gained will be strongly influenced by the ability of the autonomous vehicle's driving mechanism to process information and navigate the vehicle. As technology continues to develop, we can expect that eventually autonomous vehicles will be vastly superior to human drivers in their ability to perform driving operations.

Second, autonomous vehicles can eliminate the uncertain nature of driver behavior that influences the design of intersections. In traditional intersection control, an individual driver knows what the trajectory of his vehicle will be, but other drivers do not possess this information. As such drivers must not only account for what they *expect* other drivers to do, but must also make decisions that are robust across all potential decisions other drivers may make. For example, a driver attempting to make a non-protected left turn will decide whether a gap in oncoming traffic is acceptable based not only on the oncoming vehicles' current speed, but also on how the gap will change if the vehicles begin to suddenly accelerate or decelerate. In the autonomous vehicle traffic, computerized drivers' decisions can be communicated directly to other vehicles, or to intersection-based infrastructure. That allows for less conservative driving behavior as each vehicle can more accurately predict the trajectory of other vehicles in the intersection, and can in turn better predict the viability of specific movements, thus improving intersection efficiency.

The central hypothesis of our research is that these advantages of autonomous vehicles can be explored to develop an autonomous intersection control can be far superior to the traditional intersection control mechanisms such as traffic signals and stop signs. In Section 2.5, we will describe our proposed autonomous intersection control.

2.4 Microscopic Simulation

In order to test the performance of automated intersection control protocols, the use of microscopic simulation models becomes indispensible. As the technology for autonomous vehicles is currently not at the level needed for real world testing of intersections with any meaningful amount of traffic flow, microscopic simulation software is necessary to obtain any estimate of the performance of systems of such vehicles.

Microscopic simulation software packages are commonly used in the transportation field to evaluate operational strategies at a very high level of resolution. Software packages such as VISSIM (*15*), CORSIM (*16*) and SIMTraffic (*17*) can realistically simulate the vehicle-to-vehicle interactions in a roadway system, and allow transportation planners to generate estimates of performance metrics such as delay, throughput and travel time.

Despite the great value that such software packages provide, the options offered within the programs are usually limited to existing transportation road elements and strategies. Furthermore, while some of these software packages do provide the user with some level of access to the internal data structures used for the simulation, this access is not enough to give the user the ability to incorporate the intersection control system presented in this paper. For these reasons, we implemented a microsimulator from scratch so as to allow the research team to model the intersection control system developed, and evaluate its performance.

2.5 The FCFS Intersection Control Protocol

Current intersection control mechanisms were designed to work with human-driven vehicles only. When vehicles are controlled by computers, there are opportunities to alleviate or resolve these issues by taking advantage of the capabilities of autonomous vehicles, wireless communication, and smart intersection management protocols. As laid out in detail in (*2*), an ideal autonomous intersection management protocol must satisfy seven desiderata: 1) allow for fully distributed and autonomous control by the driving agent, 2) have low communication complexity, 3) assume non-expensive vehicle sensors found in production, 4) use a standardized communication protocol, 5) be incrementally deployable, 6) be safe, and 7) be efficient. Modern-day traffic signals completely satisfy all but the last one of these properties. Traffic signals are very inefficient—not only do vehicles traversing intersections equipped with these mechanisms experience large intersection delays, but also the intersections themselves can only manage a limited traffic capacity—much less than that of the roads that feed into them. Therefore, we have investigated a solution that exceeds the efficiency of traffic signals without sacrificing any of the other properties.

2.5.1 The Reservation Idea

The aforementioned desiderata led to the development of an efficient intersection management system developed by Dresner and Stone (*2*) that is a radical departure from existing traffic signal optimization schemes. The solution is based on a *reservation* paradigm, in which vehicles “call ahead” to reserve space-time in the intersection. The earlier a vehicle places a request, the earlier it will be granted, but there is no inherent minimum or maximum lead time required for a request. In the approach, computer programs denoted as *driver agents* control the vehicles, while an arbiter agent called an *intersection manager* is assigned to each intersection. The role of the intersection manager is to grant or reject driver agent requests to reserve blocks of space-time in the intersection. In brief, the paradigm proceeds as follows (*2*):

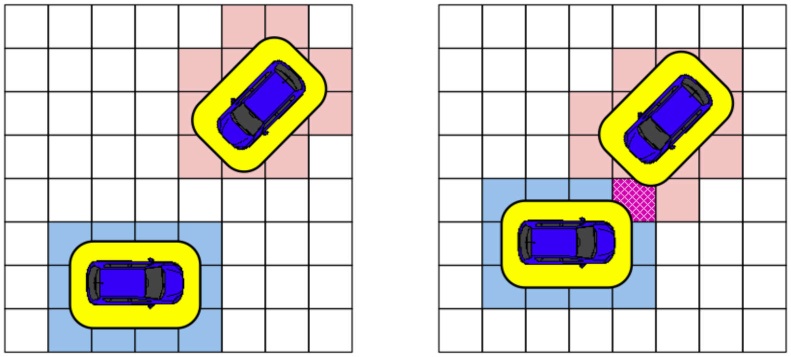
- An approaching vehicle announces its impending arrival to the intersection manager. The vehicle indicates its predicted arrival time, arrival velocity, arrival lane and departure lanes.
- The intersection manager simulates the vehicle's path through the intersection, checking for conflicts with the paths of any previously processed vehicles.
- If there are no conflicts, the intersection manager issues a reservation. It becomes the vehicle's responsibility to arrive at, and travel through, the intersection as specified (within a range of error tolerance).
- In the case of a conflict, the intersection manager suggests an alternate later reservation.
- The car may only enter the intersection once it has successfully obtained a reservation.

- Upon leaving the intersection, the car informs the intersection manager that its passage through the intersection was successful.

A key feature of this paradigm is that it relies only on vehicle-to-infrastructure (V2I) communication. In particular, the vehicles need not know anything about each other beyond what is needed for local autonomous control (e.g., to avoid running into the car in front). While real-world implementations may be subject to additional sources of error and risk, the paradigm is itself completely robust to communication disruptions: if a message is dropped, either by the intersection manager or by the vehicle, delays may increase, but safety is not compromised. Safety can also be guaranteed in mixed mode scenarios when both autonomous and manual vehicles operate at intersections.

2.5.2 Intersection Control Policy

Our prototype intersection control policy divides the intersection into a grid of *reservation tiles*, as shown in Figure 1. (This notation can be generalized for rectangular and irregularly shaped intersections.) 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.



(a) Successful (b) Rejected

FIGURE 1 (a) The vehicle's space-time request has no conflicts at time *t*. (b) The vehicle's request is rejected because at time *t* of its simulated trajectory, the vehicle requires a tile already reserved by another vehicle (*15*)

If at any time during the trajectory simulation the requesting vehicle occupies a reservation tile that is already reserved by another vehicle, the policy rejects the driver's reservation request, and the intersection manager communicates this to the driver agent. Otherwise, the policy accepts the reservation and reserves the appropriate tiles. The intersection manager then sends a confirmation to the driver. If the reservation is denied, it is the vehicle's responsibility to maintain a speed such that it can stop before the intersection. Meanwhile, it can request a different reservation.

3. NUMERICAL TESTING: THE AIM4 SIMULATOR

There are many traffic simulators available for traffic purposes. Some of these simulators are designed to model vehicle kinematics with extremely high fidelity, including tire friction, engine power output, and even aerodynamics. Others deal with very large networks of roads or freeways, or model traffic flow instead of individual vehicles (*18*,*19*). Many simulators are designed to model true human behavior, rather than testing custom agent algorithms (*20*). When this research began, however, none gave us the ability to easily replace the mechanism by which intersections are governed. Since this is the main focus of this work, we need a custom simulator.

This section focuses on the features of the AIM4 simulator, with emphasis on its ability to model autonomous vehicles and automated intersections.

3.1 Vehicle Representation

Each vehicle, while represented visually in the simulator as a rectangle with a fixed length and width, also possesses a vector of fixed properties and a vector of state variables.

At a bare minimum, vehicles in the simulator have the following fixed properties: vehicle identification number (VIN), length, width, front axle displacement, rear axle displacement, maximum velocity, maximum acceleration, minimum acceleration, maximum steering angle, maximum steering rate, sensor range, transmission range. The front and back axle displacement, which represent the distance from the front of the vehicles to the front and back axle respectively, and the maximum steering rate allow for more realistic limitations placed on the simulated vehicles during turning maneuvers.

Each vehicle also has the following state variables: position, velocity, direction, acceleration, steering angle. Position is represented in a Cartesian coordinate, where the positive X-axis represents the East, and the positive Y-axis represents the North. The direction in which a vehicle is facing is represented as an angle, where zero radians would represent a vehicle driving east, and a vehicle with a positive steering angle would be turning to the left.

3.2 Vehicle Sensor Data

As in real life, a simulated vehicle would be equipped with gauges that are designed to provide information from simulated sensors that the vehicle could have. While an actual autonomous vehicle would have a multitude of outward-facing sensors, including laser range finders, short-wave radar, lidar, and video cameras, many of these technologies are either very difficult to simulate or do not make sense in our simulated environment. We have determined that a vehicle in our simulated environment really only needs to sense one thing: how far away the next vehicle in front of it is. It may not be well-defined as to which vehicle is the next vehicle in front, and so we created two different sensors that try to accomplish this: a simplified simulated laser range finder that can be used in any situation, and an interval sensor that is much cheaper to use computationally, but can only be used when the vehicle is traveling within a lane.

3.2.1 Simulated Laser Range Finder

Simulating the complex workings of a full laser-range finder is not only computationally expensive, but also more detailed than necessary for simulation purposes. Therefore, the laser range finder is implemented in the simulator using a method introduced by Dresner and Stone (*2*). While a single sensor aimed in the direction that the vehicle is moving can provide sufficient information when the vehicle is driving in a straight line, it is not enough to gather enough information during a turning movement. To address this, a flexible sensor is implemented in the simulator: when the vehicle is turning, the sensor's range increases in the direction of the turn, while it decreases from the opposite side. This treatment of sensors allows vehicles to avoid many collisions even in the absence of intersection control measures (*2*). The main drawback of this approach is that, unamortized, it requires $O(n^2)$ distance calculations just to determine which vehicles are in range of the sensor, where n is the number of vehicles.

3.2.2 Interval Sensor

The simulated laser finder is necessary in some complex driving scenarios. But in the most of the time, vehicles need only know the distance the next vehicle in front of them. This can be accomplished in the simulator by generating a list of vehicles and the distance from the start of the lane. While it is possible for a vehicle to be in more than one lane, for example during a lane changing procedure, this can still be accommodated within this system. Once each of these lists of vehicles is sorted, the distances between the successive vehicles are calculated and recorded in the vehicles' interval sensor gauges. This process takes only *O(n log n)* of computational time. Instead of only being able to simulate tens of vehicles in real time using simulated laser range finders, we can simulate hundreds using interval sensors.

3.2.3 Safety Buffers

The AIM4 simulator makes use of three types of buffers to protect vehicles from moving too close to each other: (i) a *static buffer* represents a constant sized space around the vehicle (e.g., 0.5m from each side of the vehicle) in which no other vehicle should present at any point in time during the traversal of the intersection; (ii) the *internal time buffer* adds additional space in the direction of travel that extends for *t* seconds of driving distance, thus allowing the vehicle to arrive t seconds early or late at the intersection; and (iii) the *edge time buffer* creates a time gap of *t* seconds at the edge of the intersection such that exiting vehicles have at least t seconds of driving distance between them, thus preventing the vehicles from exiting too close to the previous vehicle.

3.3 Communication

Each agent (a driver agent or an intersection manager) has two queues of messages: an *inbox* and an *outbox*. Whenever an agent wants to send a message, it places the message in its outbox. At the end of each simulation cycle, the simulator examines all agents' outboxes, takes any messages in them, and then conditionally delivers them to their destinations' inboxes. The next time the destination agents are able to act, they can examine their inboxes and take actions based on the messages present. Whether or not an individual message is delivered is a function of two things: the transmission strength of the sending agent, and the distance between the sending agent and the receiving agent. The location of an intersection, for these purposes, is the centroid of the intersection's area. For all of our experiments, we use a very simple function: the message is delivered if and only if the message strength is greater than or equal to the distance between the agents, though a stochastic model could easily be implemented.

One nice result of explicitly modeling communication (instead of using simple function calls, as in previous versions of the simulator) is that it allows us to do a *mixed simulation*. In a mixed simulation, one or more of the vehicles in the simulator is an actual physical vehicle. Each real vehicle corresponds to a proxy vehicle in the simulator whose state—position, velocity, and so forth—are continuously updated using data from the real vehicle. The real vehicle's sensors are fed information from the simulator to make it appear to the real vehicle that the simulated vehicles are real. This enables us to run experiments involving real vehicles without risking expensive damage to the real vehicles should something go awry (*21*,*22*).

3.4 Vehicle Controller

In every time step in a simulation, the AIM4 simulator updates the position, the direction, and the speed of every vehicle according to an approximate law of physics as follows. Based on some simplifying assumptions such as only planar motion is allowed and vehicles do not skid on a road, the state of a vehicle is updated using the following differential equations for non-holonomic motion:

$$\frac{\partial x}{\partial t} = v \cdot \cos(\phi)$$

$$\frac{\partial y}{\partial t} = v \cdot \sin(\phi)$$

$$\frac{\partial \phi}{\partial t} = v \cdot \frac{\tan\psi}{L}$$

where x, y, and ϕ is the coordinate and the direction of the vehicle, v is the vehicle's velocity, ψ is the steering angle, and L is the vehicle's wheelbase (i.e., the length between the front wheels and the rear wheels). Given x, y, ϕ, v, and ψ, in the previous time step, the AIM4 simulator solves these equations and computes x, y, and ϕ in the next time step, assuming ψ remains constant in the time step and v changes according to the acceleration a which remains constant in the time step.

Vehicles' controllers controls the motion of vehicles by setting the acceleration a and the steering angle ψ at every time step, in the same way as drivers in the real world control vehicles by gas pedal/brake and steering wheels. In the previous version of the simulator, a vehicle controller computes the acceleration and the steering angle in every time step without planning ahead the entire course of actions for the traversal. This can cause some difficulties in meeting the arrival time and the arrival velocity requirement of the FCFS protocol (*22*,*23*). In AIM4, vehicle controllers can optionally be given *acceleration schedule* and/or *track* to aide the control. An acceleration schedule is a time series of accelerations: $\langle(a_1,t_1), (a_1,t_2), \ldots , (a_n,t_n)\rangle$, which means that the controller should set the acceleration to a_i at time t_i, for $1 \leq i \leq n$. In AIM4, when a vehicle sends a request to the intersection manager to make a reservation, the vehicle controller computes an acceleration schedule such that, if follows correctly, the vehicle can arrive at the intersection at the arrival time and the arrival velocity as stated in the request message. The use of acceleration schedule can prevent vehicles from making reservations that are impossible to keep (*22*,*23*). Likewise, a vehicle controller can control the steering angle by a given track, which is usually the middle of a lane or a trajectory inside the intersection. The controller would then set the steering angle so as to stay as close to the track as possible.

3.5 The Simulation

The input of the simulator consists of a map, a detailed layout of the roads and intersections, and a specification of the vehicle generation at the vehicle spawn points. The simulation proceeds with a sequence of time steps, each of them represents a fixed amount of time t (usually 0.02 second) in the simulation. At the beginning of each time step, the simulator performs a sequence of tasks as follows:

*Task 1. Spawn Vehicles***:** Vehicles are spawned according to an approximate Poisson process, except when there is no room for more vehicles in the lane.

Task 2. Provide Sensor Input: For each vehicle, that vehicle's velocity, acceleration, direction, and position are recorded to the speedometer, accelerometer, compass, and position gauges, respectively. Additionally, the interval gauge and/or simplified laser range finder are simulated, and the results are recorded to the corresponding gauges in the vehicle.

Task 3. Control vehicles: Vehicle controllers and intersection managers are given a chance to act after the vehicles' sensing inputs are updated.

Task 4. Deliver messages: Any messages in the vehicles' and the intersections' outgoing messages queues are delivered to their destinations.

Task 5. Move Vehicles: The positions, directions and velocities of all vehicles are updated based on the physical model of the vehicles.

Task 6. Clean up: Any vehicle that has traveled outside the simulated area or has arrived at its intended destination is removed from the simulation.

Figure 2 shows a screenshot of the simulator's graphical display.

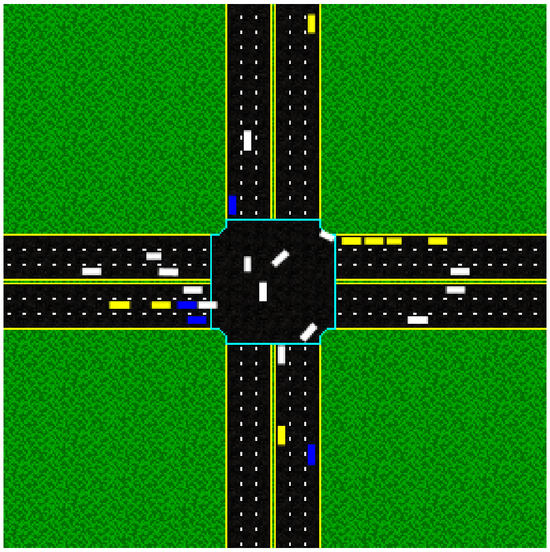


FIGURE 2 A screenshot of the simulator in action.

4. DESCRIPTION OF THE TESTING PROCEDURE

The objective of this paper is to compare the performance of the FCFS Intersection protocol to the performance of an optimized signal timing plan as generated by a standard signal optimization software package. While several signal optimization software packages exist in the market, SYNCHRO (*24*) was chosen due to the fact that it is commonly used by state agencies and private consulting agencies alike.

Our hypothesis is that, by significantly decreasing the amount of lost time in the intersection, the intersection protocol presented in this paper will allow for much more efficient use of the time-space capacity of an intersection. We will focus on the performance of both an optimized signal plan and the automated intersection manager on a single, three-lane, four-approach intersection. While we realize that a more varied set of scenarios is desirable, it is important to note that a validation of the model is impossible for 100% of scenarios.

As such, we wish to establish, at least for a common intersection configuration, whether or not the intersection manager outperforms a traditional intersection. Furthermore, we wish to identify what are the factors that affect the potential for improvement. In particular, we will look at how performance varies with changes in the total volume per approach.

Two general sets of scenarios will be considered:

i. Two Phase Intersection: 3 levels of flow for the through movement at each of the 4 approaches of the intersection are considered: Low (200 v/h), Medium (600 v/h), and High (1000 v/h). The objective of this set of testing scenarios is to determine the effect that different combinations of overall level of congestion have on the performance of the intersection. Left turn volume is kept at 100 v/h, and right turn volume is kept at 200 v/h.

ii. Three Phase Intersection with single protected Left Turn: We consider 5 levels of flow for a single approach's left turning volume (200, 400, 600, 800, 1000 v/h), and 4 levels of flow for the opposing approach's through movement level of flow (400, 600, 800, 1000 v/h). All other approaches are kept at 500 v/h for the through movement, and 100 v/h for right and left turn movements. The objective of this set of testing scenarios is to determine how the conditions of the left turning movement affect the performance of the intersection.

For each set of testing scenarios, 4 different intersection control strategies will be tested:

i. Traditional Traffic Signal, optimized using SYNCHRO

ii. FCFS manager with 0.25 meter static buffer, 0.1 second internal time buffer, and 0.25 second edge time buffer.

iii. FCFS manager with 0.50 meter static buffer, 0.2 second internal time buffer, and 0.50 second edge time buffer.

iv. FCFS manager with 0.75 meter static buffer, 0.3 second internal time buffer, and 0.75 second edge time buffer.

5. RESULTS AND DISCUSSION

The FCFS protocol significantly outperformed traditional signals in both sets of experiments conducted, regardless of the traffic pattern, or selected set of safety buffers for the autonomous vehicles. Table 1 shows the results for the two-phase intersection experiment, and Table 2 shows the results for the Three-phase intersection experiment. In each case the null hypothesis that the average from the traditional signal (Y) was less than or equal to the delays of the FCFS control (X) was rejected, which allows us to conclude with great confidence that the FCFS reservation system significantly outperforms a traditional traffic signal in minimizing delay.

TABLE 1 Delay for Two-phase experiment

Flow by Approach (v/h)				Traffic Signals (Y)		FCFS (0.25,0.1,0.25) (X_{25})			FCFS (0.50,0.2,0.50) (X_{50})			FCFS (0.75,0.3,0.75) (X_{75})		
EB	NB	SB	WB	average delay (s)	std dev (s)	average delay (s)	std dev (s)	H_0:Y-X_{25}?0 H_A:Y-X_{25}>0	average delay (s)	std dev (s)	H_0:Y-X_{50}?0 H_A:Y-X_{50}>0	average delay (s)	std dev (s)	H_0:Y-X_{75}?0 H_A:Y-X_{75}>0
200	200	200	200	3.98	0.12	0.12	0.01	Reject H0	0.23	0.02	Reject H0	0.37	0.03	Reject H0
200	200	200	600	4.89	0.17	0.13	0.01	Reject H0	0.28	0.02	Reject H0	0.46	0.04	Reject H0
200	200	600	600	4.18	0.11	0.16	0.01	Reject H0	0.30	0.02	Reject H0	0.57	0.03	Reject H0
200	200	600	1000	5.86	0.18	0.29	0.02	Reject H0	0.59	0.03	Reject H0	1.24	0.12	Reject H0
200	200	1000	600	5.83	0.17	0.25	0.02	Reject H0	0.52	0.04	Reject H0	1.03	0.07	Reject H0
200	200	1000	1000	7.33	0.25	0.40	0.03	Reject H0	0.89	0.07	Reject H0	2.03	0.20	Reject H0
200	600	200	1000	5.72	0.17	0.25	0.02	Reject H0	0.53	0.04	Reject H0	1.05	0.08	Reject H0
200	600	600	200	4.66	0.20	0.15	0.01	Reject H0	0.30	0.02	Reject H0	0.53	0.04	Reject H0
200	600	600	600	4.24	0.09	0.17	0.02	Reject H0	0.35	0.02	Reject H0	0.66	0.05	Reject H0
200	600	600	1000	5.80	0.16	0.30	0.02	Reject H0	0.66	0.05	Reject H0	1.35	0.10	Reject H0
200	600	1000	200	6.15	0.18	0.23	0.02	Reject H0	0.47	0.04	Reject H0	0.91	0.07	Reject H0
200	600	1000	600	5.70	0.11	0.25	0.01	Reject H0	0.54	0.03	Reject H0	1.07	0.11	Reject H0
200	600	1000	1000	7.64	0.15	0.39	0.02	Reject H0	0.94	0.05	Reject H0	2.20	0.29	Reject H0
200	1000	200	200	6.59	0.22	0.24	0.02	Reject H0	0.46	0.04	Reject H0	0.88	0.08	Reject H0
200	1000	200	600	5.80	0.17	0.29	0.02	Reject H0	0.61	0.05	Reject H0	1.26	0.11	Reject H0
200	1000	600	200	6.06	0.14	0.23	0.02	Reject H0	0.48	0.03	Reject H0	0.88	0.07	Reject H0
200	1000	600	600	5.77	0.17	0.29	0.02	Reject H0	0.61	0.04	Reject H0	1.22	0.08	Reject H0
200	1000	600	1000	7.60	0.21	0.42	0.02	Reject H0	1.04	0.07	Reject H0	2.52	0.30	Reject H0
200	1000	1000	200	6.55	0.17	0.30	0.01	Reject H0	0.61	0.03	Reject H0	1.23	0.10	Reject H0
200	1000	1000	600	6.60	0.15	0.34	0.01	Reject H0	0.78	0.05	Reject H0	1.59	0.14	Reject H0
200	1000	1000	1000	8.56	0.19	0.50	0.03	Reject H0	1.23	0.08	Reject H0	3.06	0.31	Reject H0
600	600	600	600	4.30	0.10	0.18	0.01	Reject H0	0.39	0.03	Reject H0	0.76	0.05	Reject H0
600	600	1000	1000	6.85	0.15	0.42	0.02	Reject H0	1.04	0.08	Reject H0	2.53	0.20	Reject H0
600	1000	600	600	5.80	0.14	0.30	0.02	Reject H0	0.71	0.04	Reject H0	1.40	0.11	Reject H0
600	1000	1000	600	6.63	0.13	0.40	0.02	Reject H0	0.93	0.05	Reject H0	2.03	0.15	Reject H0
600	1000	1000	1000	8.39	0.19	0.55	0.02	Reject H0	1.39	0.10	Reject H0	3.32	0.33	Reject H0
1000	1000	1000	1000	9.11	0.21	0.67	0.04	Reject H0	1.84	0.14	Reject H0	4.51	0.37	Reject H0

5.1 Two-Phase Experiment

While the FCFS protocol outperformed traditional signals in every scenario and for every set of buffers, it is important to note that the improvement in intersection performance was affected by the set of buffers used, especially as levels of congestion increased. For the scenario with the lowest level of congestion, the FCFS protocol outperformed the traffic signal by an order of magnitude, with the average delays for the FCFS being under 0.4 seconds for all 3 sets of buffers. In the scenario with the highest level of congestion, the FCFS implementation with the least conservative buffers outperformed the traffic signal by an order of magnitude (0.67 seconds vs. 9.11 seconds), yet the more conservative set of buffers was only able to reduce delay to an average of 4.51 seconds per vehicle. While this is still a significantly improvement over the traditional traffic signal, it is clear that it's affected by the ability of the automated vehicle to sense information, and accurately performing driving actions based on the information. It further shows that determining the appropriate set of buffer is pivotal in proper implementation of the FCFS protocol.

TABLE 2 Three-phase, protected left turn experiment

Traffic Pattern		Traffic Signals (Y)		FCFS (0.25,0.1,0.25) (X_{25})			FCFS (0.50,0.2,0.50) (X_{50})			FCFS (0.75,0.3,0.75) (X_{75})		
Left Turn Volume	Opposite Approach Volume	average delay (s)	sd	average delay (s)	sd	H_0:Y-X_{25}≤0 H_A:Y-X_{25}>0	average delay (s)	sd	H_0:Y-X_{50}≤0 H_A:Y-X_{50}>0	average delay (s)	sd	H_0:Y-X_{75}≤0 H_A:Y-X_{75}>0
200	400	6.59	0.15	0.28	0.02	Reject H_0	0.53	0.03	Reject H_0	0.92	0.06	Reject H_0
200	600	7.45	0.26	0.32	0.03	Reject H_0	0.63	0.03	Reject H_0	1.11	0.07	Reject H_0
200	800	8.84	0.23	0.37	0.02	Reject H_0	0.74	0.04	Reject H_0	1.42	0.07	Reject H_0
200	1000	10.60	0.22	0.41	0.03	Reject H_0	0.90	0.05	Reject H_0	1.77	0.10	Reject H_0
400	400	6.75	0.20	0.33	0.02	Reject H_0	0.61	0.04	Reject H_0	1.10	0.10	Reject H_0
400	600	7.62	0.21	0.36	0.02	Reject H_0	0.71	0.04	Reject H_0	1.35	0.07	Reject H_0
400	800	9.00	0.27	0.42	0.02	Reject H_0	0.90	0.06	Reject H_0	1.63	0.09	Reject H_0
400	1000	10.07	0.23	0.48	0.03	Reject H_0	1.05	0.06	Reject H_0	2.10	0.17	Reject H_0
600	400	7.60	0.34	0.37	0.03	Reject H_0	0.73	0.03	Reject H_0	1.44	0.15	Reject H_0
600	600	8.68	0.24	0.42	0.02	Reject H_0	0.85	0.05	Reject H_0	1.63	0.16	Reject H_0
600	800	10.14	0.45	0.47	0.03	Reject H_0	1.04	0.06	Reject H_0	2.02	0.13	Reject H_0
600	1000	11.00	0.46	0.54	0.03	Reject H_0	1.23	0.09	Reject H_0	2.59	0.14	Reject H_0
800	400	9.73	1.29	0.41	0.03	Reject H_0	0.87	0.06	Reject H_0	2.00	0.28	Reject H_0
800	600	9.88	0.31	0.46	0.03	Reject H_0	1.02	0.08	Reject H_0	2.51	0.60	Reject H_0
800	800	12.53	1.23	0.55	0.04	Reject H_0	1.26	0.10	Reject H_0	3.06	0.46	Reject H_0
800	1000	12.96	0.56	0.63	0.04	Reject H_0	1.50	0.13	Reject H_0	4.20	0.99	Reject H_0
1000	400	13.42	2.54	0.45	0.03	Reject H_0	1.14	0.10	Reject H_0	5.44	2.21	Reject H_0
1000	600	12.08	1.08	0.53	0.03	Reject H_0	1.40	0.14	Reject H_0	6.61	2.03	Reject H_0
1000	800	14.62	1.14	0.61	0.03	Reject H_0	1.63	0.17	Reject H_0	8.86	1.60	Reject H_0
1000	1000	16.06	0.73	0.69	0.04	Reject H_0	1.93	0.19	Reject H_0	9.50	1.95	Reject H_0

5.2 Three-Phase Experiment

While the FCFS implementations again outperform the traffic signal for all scenarios, we once again see that the improvements seen from the FCFS implementation with more conservative buffers deteriorate much quicker with increasing flow than with less conservative buffers. Another interesting observation is that the variation among simulations for the same scenario increased much more significantly in the presence of increasing left hand turns for the most conservative set of buffers, resulting in a standard deviation of 1.95 seconds, compared to a standard deviation of 0.37 seconds for the most congested case in the two-phase experiment.

As left turn movements increase the number of conflicts between opposing streams of traffic, it is expected that varying levels of left turn flows would significantly affect the performance of traditional signals. As such, it is not surprising to see that left turn volumes are also a significant factor for the performance of other intersection control systems such as FCFS.

An interesting corollary from the results of the 3-phase experiment is that the network flow distribution in the form of route choice can have a significant impact on the performance of the system simply by affecting the distribution of left turning movements per intersection: it may be beneficial to encourage vehicles to distribute left turning vehicles among several intersection when possible.

6. CONCLUSIONS AND FUTURE RESEARCH

In this paper, we presented the results of an experimental comparison between a reservation-based intersection control protocol and an optimized traditional traffic signal, in a population of autonomous vehicles. The results show that the FCFS protocol performs significantly better than a traditional traffic signal, reducing average vehicle delay by an order of magnitude in all cases. It was observed, however, that varying levels of flow affected the observed levels of improvement for different implementations of FCFS, especially as the safety buffers used by the intersection manager became more conservative. It was further observed that the volume of left turning vehicles would significantly affect the performance of both traditional signals and FCFS.

The results are encouraging, and show that further research must be conducted in order to enable deployment of such systems, as well as any other intelligent intersection control system, to exploit the benefits of automated vehicles. If the levels of performance observed in our numerical testing are achievable, the congestion mitigation impacts an intersection management system such as FCFS could have would be enormous. Even the improvements seen from the most conservative set of buffers tested could more than halve the current estimated delay at intersections.

While these results are promising, they provide only a starting point for what should be a thriving research field. Several research directions will be taken, not only to further validate the FCFS intersection control strategy, but also to develop more efficient intersection control systems:

- While we are confident that similar results will be observed regardless of the intersection configuration, a more thorough set of testing scenarios would not only provide validation, but would also allow for accurate prediction of expected delay reduction that could be achieved by replacing a traditional set of traffic signals with an automated intersection.
- While it is important to be able to estimate average vehicle delays at the intersection level, the network level effects of such vehicle reductions are much more significant: improved performance at a single intersection could potentially have a negative overall effect to the network if adjacent intersections are not prepared for the changes in traffic flow patterns and/or flow.
- The microsimulator used for testing procedures was custom developed for the testing of automated intersection management techniques. While we are confident that the simulator is realistic, further validation of the simulator results would be desirable using standard commercial packages. Because of the limitations of commercial microsimulation software, the process of validating the AIM4 simulator is a complex one, and to our knowledge, there is no trivial validation process.

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