Paper No.: 13-2185

A Next-Generation Intersection Control Algorithm for Autonomous Vehicles

A Paper Submitted to
the Transportation Research Board
for Review for Presentation & Publication
at the TRB 92nd Annual Meeting in Washington, D.C., January 13-17, 2013

Zhixia Li, Ph.D.
Research Associate
1249A Engineering Hall, 1415 Engineering Drive, Madison WI 53706
Tel: 513-484-2991; Fax: (608)262-5199
Email: zli262@wisc.edu

Madhav V. Chitturi, Ph.D.
Assistant Researcher
B243 Engineering Hall, 1415 Engineering Drive, Madison, WI 53706
Phone: (608)890-2439, Fax: (608)262-5199
Email: mchitturi@wisc.edu

Dongxi Zheng, M.S.
Research Assistant
1249A Engineering Hall, 1415 Engineering Drive, Madison WI 53706
Phone: (608)335-0889
Email: dzheng3@wisc.edu

Andrea R. Bill
Associate Researcher
B243 Engineering Hall, 1415 Engineering Drive, Madison, WI 53706
Phone: (608)890-3425, Fax: (608)262-5199
Email: bill@wisc.edu

David A. Noyce, Ph.D. PE
Professor
Director, Traffic Operations and Safety (TOPS) Laboratory
1204 Engineering Hall, 1415 Engineering Drive, Madison, WI53706
Phone: (608)265-1882, Fax: (608)262-5199
Email: noyce@engr.wisc.edu

Traffic Operations and Safety (TOPS) Laboratory
Department of Civil and Environment Engineering
University of Wisconsin-Madison

(5463 + 10 Figures and Table ×250 = 7963 words)

ABSTRACT

A reservation-based autonomous intersection control system, named Autonomous Control of Urban TrAffic (ACUTA) is presented in this paper. ACUTA manages autonomous vehicles in the vicinity of an intersection to allow them to pass the intersection without any conflict and few stops. To address the operational issues identified in previous studies on reservation-based autonomous intersection management, three operational enhancement strategies were introduced and incorporated in ACUTA. Along with operational enhancements offered by ACUTA, its implementation in the standard simulation platform VISSIM is significant. The enhancement strategies were evaluated and shown to be effective in reducing intersection delay. ACUTA was modeled as a single-tile and a multi-tile system and simulation experiments were conducted in VISSIM to evaluate operational performance of both. Performance of single and multi-tile ACUTA was compared with operational performance of an optimized signalized intersection, and a four-way stop intersection. Evaluation results demonstrated that compared with the optimized signal control, Multi-Tile ACUTA increased left turn, right turn and through capacities by 37%, 32%, and 31%, respectively. As a result, the Multi-Tile ACUTA intersection caused considerably less delay than the optimized signalized intersection. Single-Tile ACUTA also resulted in significantly less delay than four-way stop control, when the approach traffic demand was less than 300 veh/hr. Finally, sensitivity analyses were conducted on ACUTA's configurable parameters, identifying the parameters that the intersection delay is sensitive to, along with their trends in impacting intersection delay. Results of the sensitivity analyses can be used to optimize the operational performance of ACUTA in future research.

INTRODUCTION

Traffic congestion is a global issue with increasing traffic demand every year. Federal Highway Administration (FHWA) estimates that by 2020, 29% of urban National Highway System (NHS) routes will be congested for much of the day, and 42 percent of NHS routes will be congested during peak periods (*1*). A key solution to alleviate future traffic congestion lies in better management of the existing network to process traffic more efficiently. One of the key bottlenecks in the transportation system is the signalized intersection.

The application of autonomous vehicles makes it possible to eliminate traditional traffic signals from the intersection, and hence has the potential to maximize intersection capacity, significantly enhancing intersection mobility. From a safety perspective, considering that 90% of road crashes are attributed to driver errors (*2*), use of autonomous vehicles, is potentially effective in reducing intersection related crashes. Therefore, autonomous vehicles (vehicles without human intervention) offer an unprecedented opportunity to address the twin issues of traffic operations and safety dodging the society today. Autonomous vehicles are under development by many automotive manufacturers and their wide usage on highway systems is expected to become reality in the near future. Although potential benefits are expected, how to take full advantage of autonomous vehicles, and maximize operational performance of autonomous vehicles at intersections is not fully understood.

Previous studies have investigated both centralized and decentralized strategies for managing autonomous vehicles at intersections (*3-17, 19-20*). In fact, the research on the autonomous vehicles can be dated back to 1990s (*21-24*). An evaluation study indicated that among all possible solutions to autonomous intersection control, the reservation-based centralized control had the best performance in terms of maximizing the intersection capacity and reducing the delay (*17*). The mechanism of the reservation-based system is introduced in the following section of Background and Literature. Another study found that starvation issues may occur in the reservation-based system when traffic demands on the mainline and side road were unbalanced (*8*). Starvation here reflects the scenario that approaching vehicles on the side street cannot get reservations and form a queue at the entrance of the intersection.

According to a different comparison research, the reservation-based system was outperformed by the traffic signal when the traffic demand was higher than a certain threshold and indicated a further investigation on the robustness of reservation-based system is needed (*20*). All these facts indicate that issues still exist in the reservation-based system although it has potential to maximize intersection capacity among all possible solutions. It has to be noted that none of the exiting studies on autonomous intersection control used standard commercial microscopic simulation software, such as VISSIM or CORSIM. Customized simulation tools were used in those studies, which cause that the results from different studies can not be comparable to each other due to the ununiformed simulation platform.

Therefore, the objective of this research is three-fold: (1) develop an enhanced reservation-based autonomous intersection control algorithm, named as Autonomous Control of Urban TrAffic (ACUTA), with potential enhancements that address existing operational issues and make the system more realistic; (2) develop a VISSIM-based simulation platform to evaluate ACUTA; and (3) compare ACUTA with 4-way stop control and signal control, as well as conduct sensitivity analysis to investigate avenues to maximize the performance of ACUTA.

BACKGROUND AND LITERATURE REVIEW

Many researchers have explored ideas and algorithms for effective management of autonomous vehicles at intersections. Both centralized and decentralized control strategies were investigated in previous studies.

Centralized control features an intersection controller that regulates the entire intersection. Vehicles only communicate with the central controller to get passing instructions. Dresnser and Stone were the first to introduce a reservation-based multi-agent system, named as Autonomous Intersection Management (AIM) (*3*). In reservation-based system, intersection is divided into a grid of n by n tiles. When a vehicle approaches an intersection, the driver agent that represents the vehicle communicates with the intersection manager. Basic mechanism of AIM is that driver agent sends requests to intersection manager to reserve the intersection for certain time-spaces needed for traversing the intersection based on vehicle's estimated arrival and departure time. Intersection manager checks what and how much resource (tiles) will be occupied by arequesting vehicle, and identifies whether these requested tiles have already been reserved by other vehicles. If the tiles are already reserved,, the request will be rejected. Otherwise a reservation will be made. Vehicle agent is notified by intersection manager whether the request is approved or rejected. The instruction of travel will be sent to vehicle agent by intersection manager with approval notice.

In the prototype version of Dresner and Stone's system, left and right turns were not allowed and all vehicles traveled at the same speed (*3*). Dresner and Stone validated their algorithm using a simulation that they developed, in which they defined certain lane-change and car following behaviors, signal and stop control operations for comparison purpose, and methods for estimating throughput volume and delay. The second version of their system was much more comprehensive by allowing turns and acceleration in the intersection (*4, 5*). The improved system was evaluated in their own simulation environment with comparison to stop-control and signal-control scenarios. The impact of restricting left and right turns being made from designated lanes rather than from any lanes was also analyzed. Theoretically, in a reservation-based system, the restriction was not necessary. Relaxing the restriction was supposed to provide more flexibility to drivers. However, results showed that restricted turn conditions resulted in lower delay than allowing turns from any lane. Dresner and Stone further stated that the results might be misleading, because the delay incurred by vehicles from lane change maneuvers can cause longer delay (*6*).

In later versions of AIM, safety issues were addressed by adding a safety net in the system (*7*). Batch processing of reservation requests were also realized to address the starvation issue due to unbalanced traffic demands on mainline and side road (*8, 9*). AIM was finally tested in a mixed reality platform (*10*). Most of Stone's studies resulted in an exceptionally low delay (< 5 s/veh) at even extremely high traffic demand (i.e. 2100 veh/hr/ln) which even exceeds the typical saturation flow rate (*10*). All these results indicate their algorithm performed very well under high demand. However, these results were obtained using their own simulation tool, rather than standard commercial simulation packages like VISSIM or CORSIM.

In addition to Stone et al., centralized control system was also investigated by researchers from France. Wu et al. (*12*) and Yan et al. (*13*) studied a theoretical approach to control autonomous vehicles at an isolated intersection through V2I communications. In their system, the intersection has only two directions. Yan et al. (*14*) improved the system by generalizing the intersection into a common four-way intersection. Approaching vehicles inform the intersection controller of their position and routing information. The intersection controller decides the passing sequence of vehicles. The decision by the controller was optimized. The objective of the optimization was to minimize total time of clearing all autonomous vehicles at the intersection. The key point was to decide an optimal vehicle passing sequence. A dynamic programming algorithm was used to solve this problem. Vehicle passing sequence could dynamically change when new vehicles enter the control range. No simulation or validation was performed in their research.

Wu et al. compared both of their centralized control strategies based on dynamic programing and their negotiation-based decentralized control strategy to an adaptive traffic controller and reservation-based traffic system developed by Dresner and Stone (*3*) in terms of operational performance (*19*). Results indicated that the reservation-based system performed best while their centralized and decentralized systems had similar operational performance. They concluded that despite the fact that reservation-based system maximizes use of space of the intersection, it lacks considerations of safe distance between two vehicles in both non-conflicting and conflicting movements.

Vasirani and Ossowski evaluated reservation-based system and compared it to signal control system (*20*). They found that reservation-based system only outperformed traffic signal when traffic demand is below a certain threshold of about 555 veh/hr/ln. Reservation-based approach performed worse than traffic signal when traffic volume was higher than a certain threshold. They concluded that this was because a reservation-based intersection is less robust than a signal-controlled intersection and performance is very sensitive to traffic demand.

In summary, centralized control can achieve better efficiency by maximizing the use of all available resources, and is more reliable and safer. However, it will also cost more to deploy in the field. Decentralized control has lower cost to implement when compared with centralized control. Therefore, centralized control is more suitable for urban intersections with heavy traffic, while the decentralized control works better for rural intersections with light traffic. Among all centralized control strategies, reservation-based system is the simplest one with the highest efficiency, although it has some potential issues like starvation and lower performance under high traffic demand.

THE ENHANCED RESERVATION-BASED ALGORITHM

Working Mechanism of ACUTA

Considering the superiority of reservation-based system in terms of maximizing intersection capacity, the next-generation intersection control system developed in this project was based on First-Come-First-Serve (FCFS) reservation-based protocol (*2*), with enhancements to improve some operational issues identified in previous studies (*2, 9*). The system was named Autonomous Control of Urban TrAffic (ACUTA). Note that ACUTA only applies to the condition that 100% of the vehicles on the road are autonomous vehicles.

ACUTA utilizes a centralized control strategy for managing fully-autonomous vehicles at an intersection. All vehicles in ACUTA are autonomous and communicate only to an intersection controller, namely, intersection manager (IM). An IM regulates the intersection by determining the passing sequence of all approaching vehicles. Specifically, intersection is divided into a mesh of n by n tiles, as shown in Figure 1, where “n” is termed as granularity, which is tile density of the intersection mesh.

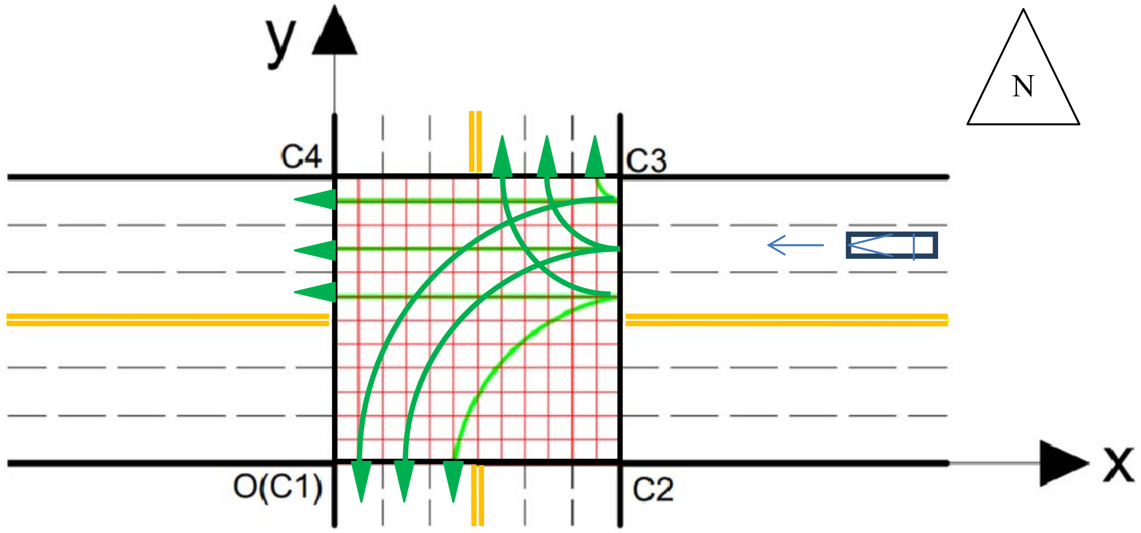


FIGURE 1 Intersection mesh of tiles and example of vehicle's possible routing decisions.

In ACUTA, each approaching vehicle sets up a communication connection with the IM after it enters -IM's communication range (i.e., 600 ft, which reflects a reasonable communication range based on existing communication technology). When connected, a vehicle immediately starts to send IM a reservation request along with its location, speed and routing information (i.e., making a left/right turn or going straight), indicating its intention to traverse the intersection. IM processes the reservation request by computing the required time-spaces for the vehicle to get through the intersection (i.e., intersection tiles that will be occupied by the requesting vehicle for all simulation steps when it traverses the intersection) based on location, speed, maximum acceleration rate, and routing information provided by the requesting vehicle. Acceleration from the requesting vehicle's current location to the entrance boundary of the intersection is considered when computing required time-spaces. Using different acceleration rates can change the required time-spaces significantly. Alternative acceleration rate is between zero and maximum acceleration rate of the specific vehicle, and is calculated using the following equation:

$$
\begin{aligned}
a_i &= 0 && (i=1) \\
a_i &= a_{\max} - (i-1)\frac{1}{m}a_{\max} && (i>1)
\end{aligned}
\qquad (1)
$$

Where, α_i = ith alternative acceleration rate (ft/s^2);
α_{max} = maximum acceleration rate (ft/s^2); and,
m = maximum number of internal simulations.

The maximum acceleration rate is one of the characteristics of the requesting vehicle. Considering that a high acceleration rate may cause passenger discomfort, maximum acceleration rate is designed as a configurable parameter in ACUTA and can be simply set as maximum comfortable acceleration rate. The number can be defined, and simply changed in VISSIM simulation environment by adjusting VISSM's maximum acceleration rate curve. Vehicles must maintain a constant speed when traversing the intersection. In other words, after a vehicle's center point enters the intersection, the vehicle's speed does not change until it completely clears the intersection. IM checks whether the required intersection tiles have already been reserved by other vehicles at every simulation step. If a conflict is detected, another alternative acceleration rate will be used to compute the required time-spaces, and conflicts will be checked again based on the updated required time-spaces. This iteration process is called internal simulation. The maximum number of trials of the alternative acceleration rates is termed as the maximum number of internal simulations (MAXNIS). Note that for approaching vehicles with slow speed, the alternative acceleration rate cannot be zero. In other words, slow vehicles must accelerate to proceed through the intersection and fixed-speed reservation is not allowed for slow vehicles. This strategy prevents vehicles with slow speeds from occupying too much time-space within the intersection. The "slow" is determined by incorporating the concept of "Minimum Speed to Allow Fixed-Speed Reservation (MINSAFSR)" in ACUTA system. The MINSAFSR defines a speed threshold to allow IM to use a zero acceleration rate in internal simulation. If speed of an approaching vehicle falls below MINSAFSR, zero cannot be used as an alternative acceleration rate in internal simulation. If all alternative acceleration rates are tried out in internal simulation and conflicts in reservation still exist, the reservation request will be rejected; otherwise the reservation request will be approved by the IM. IM automatically rejects requests from a vehicle that is following a vehicle without a reservation.

After making a decision to reject the reservation request, IM sends a rejection message to the requesting vehicle with a designated deceleration rate, which is calculated using the following equation:

$$a_{Dec} = \frac{{v_0}^2}{2(s_0 - d_0 - v_0\delta)} \tag{2}$$

Where, α_{Dec} = designated deceleration rate (ft/s^2);
v_0 = vehicle's speed at the time when submitting the request (ft/s);
S_0 = vehicle's distance from intersection at the time when submitting request (ft);
δ = vehicle response time (s); and,
d_0 = distance from the intersection to the advance stop location (ft).

Vehicle response time (δ) in Equation (2) is the time interval between the instant when the vehicle receives the rejection message from the IM and the instant the vehicle applies the deceleration rate. Variable 'δ' is analog to the driver's perception reaction time in human-operating vehicles. In ACUTA, the default δ is zero, which assumes an ideal condition with negligible response time. The advance stop location (ASL) (d_0) is a special parameter in ACUTA, which designates a predefined advance stop location other than stop line for vehicles with rejected reservations. The detailed features of ASL are discussed in the following section. A vehicle with a rejected reservation request will apply the designated deceleration rate and start to decelerate as soon as the rejection message is received. The vehicle keeps sending reservation requests until the request is finally approved by the IM.

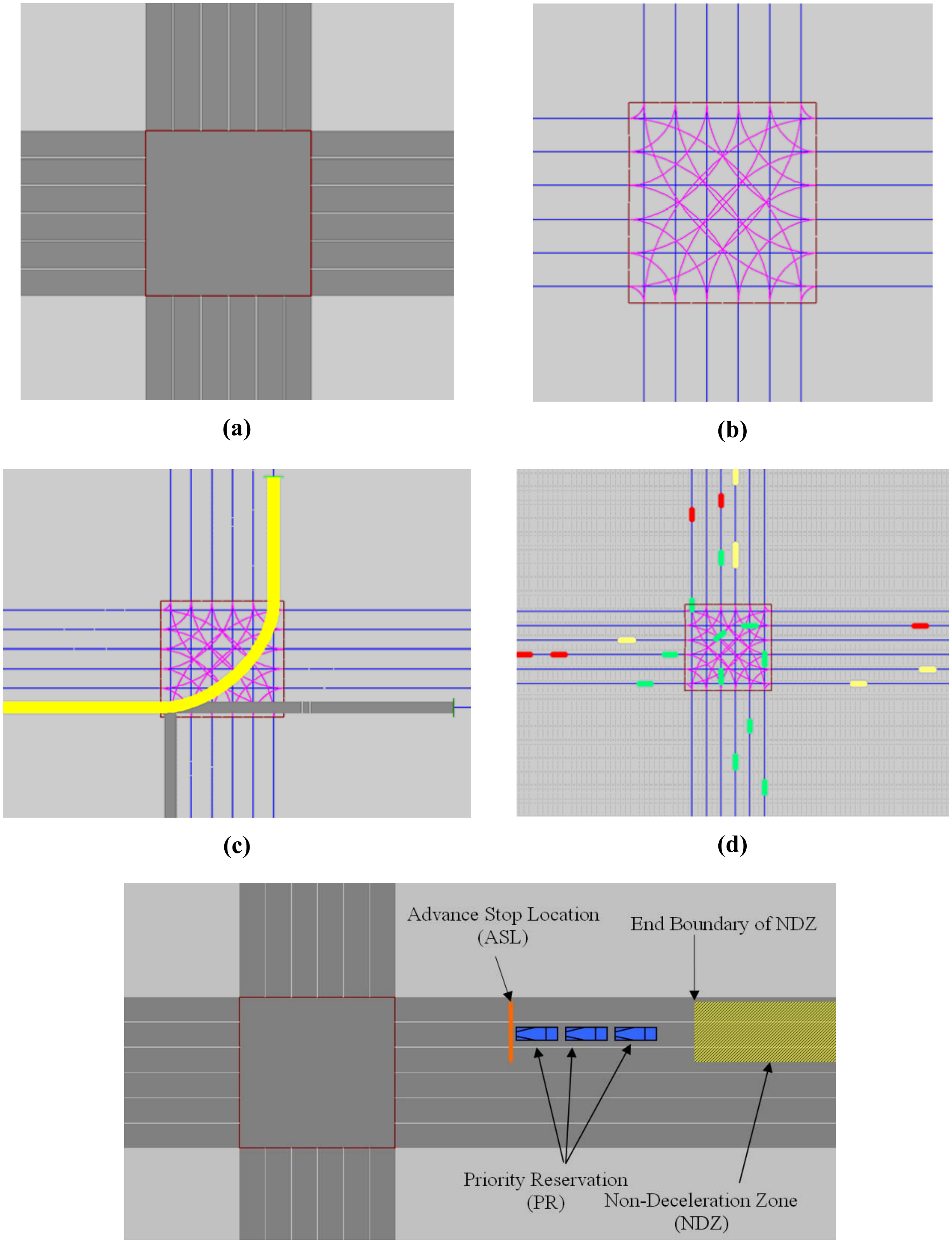
If IM approves a reservation request, it sends an approval message to the requesting vehicle along with a designated acceleration rate that will result in no conflicts with existing reservations. Timestamps indicating when to end the acceleration and when to completely clear the intersection are also sent to the vehicle in the approval message. The approved vehicle will follow the acceleration instruction as soon as it receives the approval message until the vehicle completely clears the intersection.

Modeling the ACUTA Intersection in VISSIM

ACUTA was implemented in VISSIM by using the VISSIM External Driver Model (EDM). Through EDM, VISSIM provides an option to bypass and replace VISSIM's internal driving behavior. During a simulation run, VISSIM calls the EDM DLL at every simulation step to pass the current state of each vehicle to the DLL. Therefore, in this research, an intersection manager class was built in the EDM DLL to collect each vehicle's speed, location, vehicle class, maximum acceleration rate, length, width, and many other parameters pertaining to the vehicle at each simulation step. IM processes all reservation requests at the beginning of each simulation step, and passes its decision and suggested acceleration/deceleration rate to vehicles in the same simulation step. Vehicles then pass their acceleration/deceleration rates back to VISSIM in the same simulation step, thus real-time control of each vehicle's acceleration rate is realized.

ACUTA was modeled at a four-legged intersection with three lanes per direction, as shown in Figure 2.a. Different from traditional signalized intersections, vehicles can turn from any lanes in an ACUTA intersection, (shown in Figure 2.b) to eliminate en-route lane changes required for turning vehicles, which are a significant contributing factor to vehicle delays due to conflicts caused by vehicle lane change maneuvers. Each lane in the simulation model was built as a separate link to simplify the simulation model.

Each approach of the intersection is more than 2000 feet long with a fixed lane width of 12 feet. The volume input of each lane is identical, trying to create balanced traffic demands from all lanes of the intersection. Each lane has three routing decisions: left turn, straight, and right turn. The volume assignments to each routing decisions are the same for all lanes, namely 25% for left turn, 60% for through, and 15% for right turn. Figure 2.c illustrates the routing decisions of a particular lane. The vehicle composition is 93% passenger cars and 7% heavy vehicles. The speed distribution of traffic is also fixed at a setting equivalent to the 30 mph speed limit. No priority rules, conflict areas, desired speed decisions, reduced speed areas, traffic signals, or stop signs are used in the simulation model, because the traffic control of the entire intersection is governed by the intersection manager only. Figure 2.d illustrates the screenshot of a simulation run; red vehicles are vehicles that do not have a reservation; green vehicles are vehicles that have a reservation and are in the process of passing the intersection; and, yellow vehicles are those that have already cleared the intersection.



(a) **(b)**

(c) **(d)**

(e)

FIGURE 2 Simulation model of ACUTA intersection.

Strategies for Operational Enhancement

Previous research identified that unbalance traffic demands could cause a starvation issue where approaching vehicles on a side street could not get reservations and form a queue at the entrance of the intersection (*8, 9*). Slow-speed reservations which can unnecessarily occupy many intersection resources were also observed in a previous study (*5*). To address these issues, three enhancement strategies have been incorporated into ACUTA, to maximize operational performance of the reservation-based autonomous intersection, as shown by Figure 2.e.

The three enhancement strategies are realized by incorporating the following concepts into ACUTA:

(1) Advance Stop Location (ASL): ASL designates a predefined advance stop location other than stop line for vehicles with rejected reservations. ASL is introduced in ACUTA as a major enhancement strategy to address the slow-reservation-speed issue pertaining to vehicles stopping at a traditional stop line. By using ASL, vehicles with rejected reservations can stop at an upstream distance from entrance of the intersection, hence are capable of gaining a higher speed when reaching the entrance point of the intersection. A higher entrance speed can increase the chances of a vehicle to get reservation, meanwhile saving the intersection time-space resources by reducing the vehicle's total traverse time within the intersection. In ACUTA, the ASL is configured by the parameter "ASL," which is in terms of distance from the intersection.

(2) Non-Deceleration Zone (NDZ): NDZ defines a zone in which vehicles do not need to decelerate if their reservation requests are rejected. There is no upstream boundary for NDZ. The downstream boundary of NDZ is typically at a location that can ensure that a vehicle can stop at ASL with a reasonably high deceleration rate (e.g. 15 ft/s^2). The downstream boundary of NDZ is a configurable parameter, which can be set as a specific location which can assure a comfortable deceleration rate. NDZ can help a vehicle continue to maintain a high traveling speed even though its reservation request is rejected. This gives the vehicle a better chance of obtaining a reservation with a later request. On the other hand, a vehicle located downstream of the boundary of the NDZ needs to decelerate to stop at the ASL. In ACUTA, NDZ is configured by the parameter "End Boundary of NDZ (EBNDZ)", which specifies the location of downstream boundary of NDZ in terms of distance from the intersection.

(3) Priority Reservation (PR) for Queuing Vehicles: the PR gives queuing vehicles a better chance to get their reservation requests approved by prioritizing processing of their reservation requests by the intersection manager. PR takes effect only when a certain queue length is detected by the intersection manager. In ACUTA, two parameters are used to configure PR, namely, Maximum Speed to be Considered as a Queuing Vehicle (MSQV), and Minimum Queue Length (MINQL) to activate priority reservation. Once PR is activated, vehicles in queue have priority for placing reservation requests.

ANALYSIS AND RESULTS

Analyses were conducted to evaluate the enhancement strategies and overall operational performance of ACUTA. Specifically, operational performance was assessed by delay. Results for left-turn (LT) vehicles, right-turn (RT) vehicles, and through (Thru) vehicles as well as overall intersection delay are measured. All experiments discussed in this section were performed using five simulation runs with different random seeds. Each simulation run lasted 2,100 seconds, with the first 300 warm-up seconds dropped from the evaluation. The highest simulation resolution of 10 simulation steps per second was used. A high simulation resolution can achieve a more detailed modeling of the real-world operation of autonomous vehicles which react much faster than human drivers due to the elimination of human perception reaction time.

Operational performance was compared between multi-tile ACUTA and a signalized intersection and between single-tile ACUTA and a four-way stop intersection. Additionally, sensitivity analyses were conducted to investigate the impact of eight configurable parameters of ACUTA on operational performance. .

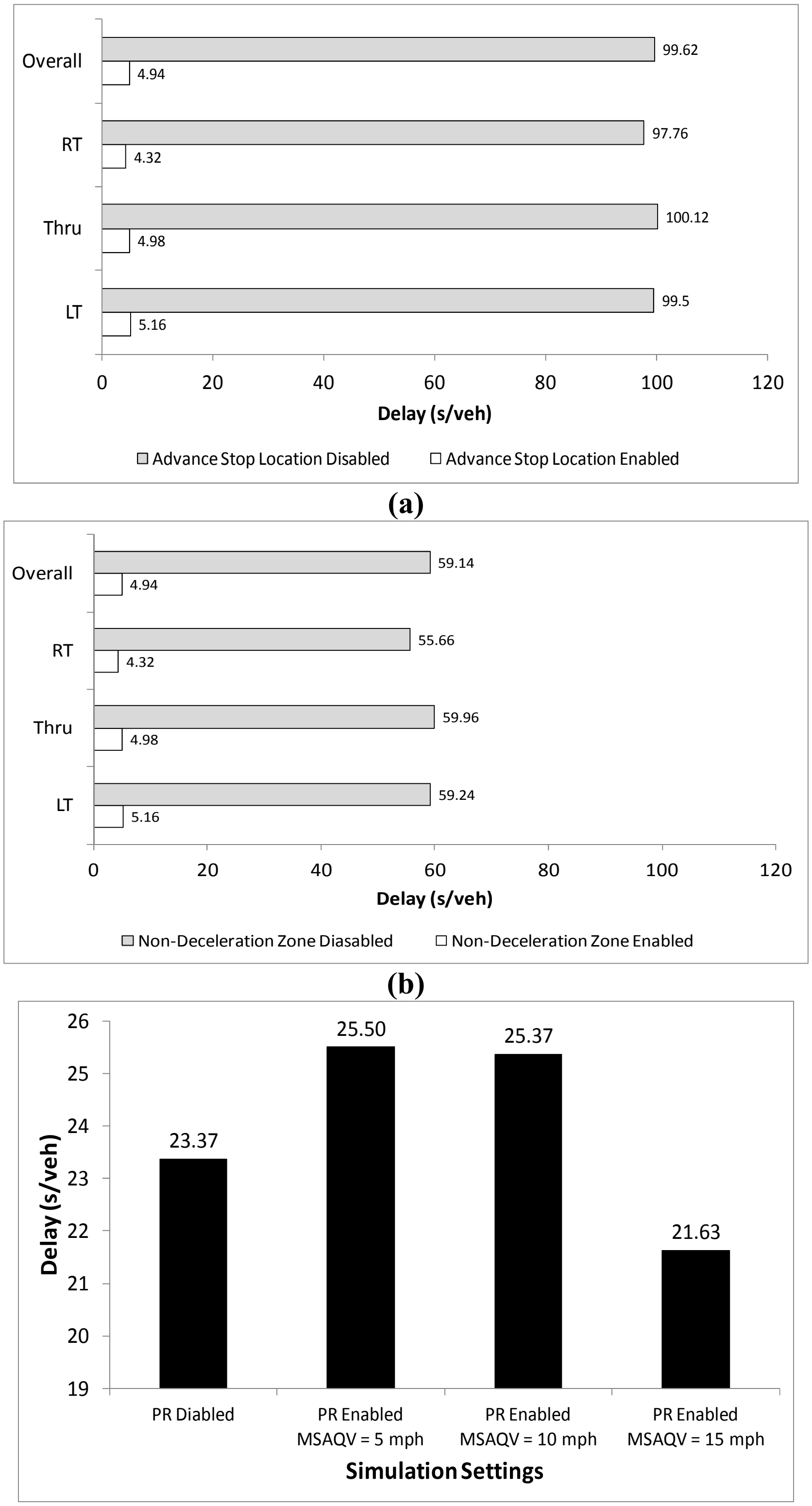
Evaluation of Operational Enhancement Strategies

In this subsection, effectiveness of the three operational enhancement strategies is examined. Figures 3.a through 3.c summarize the impact of enabling ASL, NDZ, and PR, respectively on delay. Simulations experiments were performed under a high approach demand of 1650 veh/hr.

Figure 3.a compares intersection delays under two scenarios: (1) ASL disabled, and (2) ASL enabled and set as 35 ft from the intersection. For both scenarios, NDZ is enabled with its end boundary set to 200 ft from the intersection, and PR was enabled as well, with the MSQV and MINQL set as 0 mph and 3 veh, respectively. The results indicate that, by enabling ASL, intersection delay was substantially reduced by approximately 95 s/veh, a 95% reduction in overall intersection delay.

Figure 3.b compares delay when NDZ was disabled and enabled. When NDZ was enabled, EBNDZ was set as 200 ft from the intersection. For both scenarios, ASL was enabled and set as 35 ft from the intersection, and PR was enabled, with MSQV and MINQL set as 0 mph and 3 veh, respectively. The results show that using NDZ resulted in a substantial 50 – 55 s/veh reduction in overall intersection delay, a higher than 90% reduction.

Figure 3.c shows effectiveness of PR. Four simulation scenarios were tested under a near capacity approach demand of 1800 veh/hr. ASL and EBNDZ were set as 35 ft and 200 ft, respectively. Other ACUTA parameters of granularity, communication range, number of internal simulations and MINSAFSR were set as 24, 600 ft, 10, and 30 mph, respectively. The first scenario was the benchmark scenario in which PR was disabled. In the second, third, and fourth scenarios, PR was enabled with the maximum speed as queuing vehicle (MSQV) set to 5 mph, 10 mph, and 15 mph, respectively, and MINQL set as 3 veh. Results indicate that when MSQV was below 15 mph, enabling PR resulted in no improvement in intersection delay; instead, intersection delay increased by about 2 s/veh. When MSQV was set to 15 mph, the reduction in delay compared to the benchmark scenario was around 2 s/veh, a 7% reduction in delay. In summary, PR can reduce delay only when MSQV is set to a large value of 15 mph or perhaps higher. These results are due to the fact that PR only offers priority for placing the reservation requests through bypassing the FCFS protocol. PR does not assure the approval of the reservation requests. The combined benefits from PR and higher traveling speed jointly worked to get the reservation requests from those queuing vehicles approved.



(a)

(b)

(c)

FIGURE 3 Operational enhancements: (a) enhancements with advance stop location enabled, (b) non-deceleration zone enabled, (c) priority reservation enabled.

Multi-Tile ACUTA vs. Signal Control

The granularity of the intersection mesh is one of the most important parameters in ACUTA. If the granularity is set to one, the entire intersection is undivided and only one vehicle can occupy the entire intersection at one time. The system in this case is termed as Single-Tile ACUTA. When the granularity is greater than one, the system is termed as Multi-Tile ACUTA.

In this section, the operational performance of Multi-Tile ACUTA under various traffic demand conditions was evaluated using the simulation results, and was further compared with performance of a comparable signalized intersection. The signalized intersection modeled in VISSIM has a left-turn lane, a through lane, and a shared through and right-turn lane designated to each approach. Traffic demands for each movement were identical between the Multi-Tile ACUTA model and the signalized intersection model. Other parameters except lane configurations are all identical between the two models.

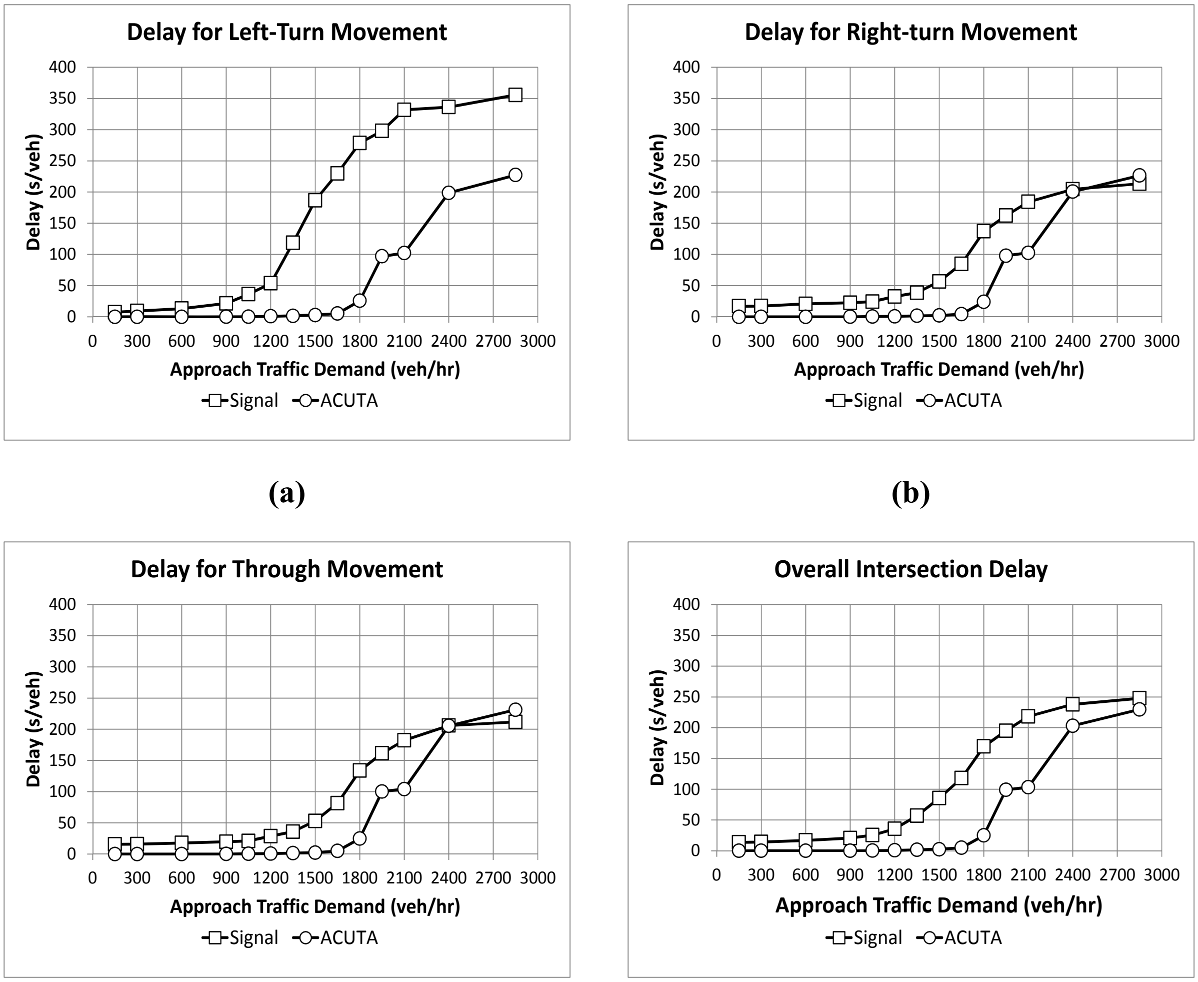
For each traffic demand condition, five simulation runs with different random seeds were performed. Each simulation run lasted 2,100 seconds, with the first 300 warm-up seconds dropped from the evaluation. Specifically, the demand for each approach increased from 150 to 2850 veh/hr to cover the possible range of traffic demands. Proportions of traffic demands for left turn, through and right turn movements were fixed as 25%, 60%, and 15%, respectively for all the simulation runs. Specific demands by movement are summarized in Table 1. For the signalized intersection model, signal timing was optimized using Highway Capacity Software (*25*). Optimization was conducted for each tested traffic demand. Table 1 lists phasing and optimized timings for the signalized intersection along with the corresponding optimized cycle lengths.

TABLE 1 Traffic Demand Inputs and Optimized Timing Plan

Approach Traffic Demand (veh/hr)	**Approach Demand by Movement (veh/hr)**			**Signal Timing Plan**				
					Phase Timing (s)			
	LT	*Thru*	*RT*	*Cycle Length (s)*	↗ ↙	⇉ ⇇	↘ ↖	⇊ ⇈
150	38	90	23	40	6	6	6	6
300	75	180	45	40	6	6	6	6
600	150	360	90	60	6	16	6	16
900	225	540	135	60	6	16	6	16
1050	263	630	158	60	6	16	6	16
1200	300	720	180	90	10	28	9	27
1350	338	810	203	90	10	28	9	27
1500	375	900	225	110	12	35	12	35
1650	413	990	248	110	12	35	12	35
1800	450	1080	270	110	12	35	12	35
1950	488	1170	293	110	12	35	12	35
2100	525	1260	315	110	12	35	12	35
2400	600	1440	360	120	12	39	13	40
2850	713	1710	428	120	12	39	13	40

Operational performances of Multi-Tile ACUTA and optimized signal control were assessed by delays, which were obtained directly from VISSIM's output. Volume-to-capacity (v/c) ratios for left turn, right turn and through movements as well as the overall intersection v/c ratio were also computed for both Multi-Tile ACUTA and optimized signal control. When computing v/c ratios, capacity (c) was measured as the maximum throughput among all demand conditions, while volume (v) was directly obtained from VISSIM's output for that specific demand condition.

Based on simulation results, capacities for different movements at the signalized intersection were identified to be 366 veh/hr, 218 veh/hr, and 908 veh/hr for left turn, right turn, and through movements, respectively. Capacity for an entire approach of the signalized intersection was 1480 veh/hr. Capacities for left turn, right turn, and through movements of an approach of the Multi-Tile ACUTA intersection were measured to be 501 veh/hr, 288 veh/hr, and 1185 veh/hr, respectively. Capacity for an entire approach of the Multi-Tile ACUTA intersection was 1974 veh/hr. Comparing Multi-Tile ACUTA with signalized control, Multi-Tile ACUTA successfully increased left turn, right turn and through capacities by 37%, 32%, and 31%, respectively. The overall approach capacity was increased by 33% by implementing Multi-Tile ACUTA.



(a) **(b)**

(c) **(d)**

FIGURE 4 Operational performance of Multi-Tile ACUTA with comparison with optimized signalized intersection: (a) left-turn delay, (b) right-turn delay, (c) through delay, and (d) overall intersection delay

TABLE 2 Comparison of Operational Performances between Multi-Tile ACUTA and Optimized Signal Intersection

Approach Traffic Demand (veh/hr)	Optimized Signalized Control								Multi-Tile ACUTA (default setting)							
	v/c ratio				Delay (s/veh)				v/c ratio				Delay (s/veh)			
	LT	*Thru*	*RT*	*Overall*	*LT*	*Thru*	*RT*	*Overall*	*LT*	*Thru*	*RT*	*Overall*	*LT*	*Thru*	*RT*	*Overall*
150	0.10	0.10	0.10	0.10	7.36	15.54	17.06	13.70	0.07	0.07	0.07	0.07	0.00	0.00	0.00	0.00
300	0.22	0.19	0.20	0.20	9.26	15.90	17.26	14.34	0.12	0.12	0.12	0.12	0.00	0.00	0.00	0.00
600	0.45	0.39	0.39	0.40	13.12	17.72	20.74	16.90	0.31	0.28	0.31	0.29	0.00	0.00	0.00	0.00
900	0.65	0.59	0.59	0.61	21.52	19.74	22.48	20.62	0.49	0.43	0.45	0.45	0.04	0.04	0.06	0.02
1050	0.75	0.69	0.69	0.71	36.24	21.04	24.38	25.48	0.55	0.51	0.53	0.52	0.26	0.42	0.44	0.38
1200	0.84	0.79	0.79	0.81	53.62	28.70	32.56	35.66	0.62	0.59	0.61	0.60	0.98	0.70	0.76	0.78
1350	0.90	0.88	0.89	0.89	118.72	35.82	38.68	56.86	0.70	0.67	0.67	0.68	1.46	1.48	1.64	1.50
1500	0.92	0.96	0.95	0.96	186.70	53.02	56.64	85.44	0.77	0.76	0.74	0.76	2.82	2.30	2.14	2.42
1650	0.97	0.98	0.99	0.99	230.04	81.46	84.82	117.90	0.84	0.83	0.83	0.83	5.16	4.98	4.32	4.94
1800	0.98	0.98	0.98	0.99	278.72	133.74	137.08	169.42	0.90	0.90	0.87	0.89	25.70	24.78	24.12	24.90
1950	0.98	0.99	0.98	0.99	298.04	161.54	162.30	194.98	0.91	0.91	0.89	0.91	97.00	100.20	97.86	99.04
2100	0.97	1.00	1.00	1.00	331.78	182.34	184.22	218.32	0.99	0.99	0.98	0.99	102.20	104.04	102.52	103.34
2400	0.99	0.98	0.98	0.99	336.26	206.02	204.48	237.88	0.97	0.96	0.96	0.96	198.72	205.50	200.64	203.06
2850	1.00	0.98	0.98	0.99	355.66	211.78	213.28	247.86	1.00	1.00	1.00	1.00	227.24	231.28	226.52	229.58

All evaluation results including the v/c ratios and delays are summarized in Table 2. The signalized intersection reached the 0.99 overall v/c ratio when the approach traffic demand was around 1650 veh/hr, while Multi-Tile ACUTA did not reach the 0.99 overall v/c ratio until the approach traffic demand reached 2100 veh/hr. These facts indicate that the Multi-Tile ACUTA intersection can process 450 extra vehicles per hour per approach without being oversaturated when compared with the optimized signalized intersection.

Figure 4 depicts the relationships between the delays and traffic demands. Figures 4.a through 4.c illustrate the delays for left turn, right turn, and through movements, respectively. These figures indicate that operational performance of different traffic movements in Multi-Tile ACUTA was very balanced as delays for left-turn, right-turn, and through movements were similar under all traffic demand conditions. Overall intersection delay shown in Figure 4.d was computed by taking weighted average of delays for all the movements. According to Figure 4.d, overall intersection delay for Multi-Tile ACUTA remained at an extremely low level (under 5 s/veh) when approach traffic demand was less than 1650 veh/hr, while signalized intersection already started to operate at near capacity conditions when approach traffic demand reached 1350 veh/hr. Delay for Multi-Tile ACUTA started to increase rapidly when traffic demand reached 1800 veh/hr. However, delays were still significantly less than delays for signalized intersection for approach traffic demands greater than 1800 veh/hr and less than 2100 veh/hr. The superiority of Multi-Tile ACUTA became marginal at extremely high approach traffic demands of 2400 and 2850 veh/hr.

Single-Tile ACUTA vs. Four-way Stop Control

The single-tile ACUTA system has an undivided intersection mesh, and only one vehicle can occupy the entire intersection at a specific instant. From the perspective of field implementation, the single-tile ACUTA system is relatively easier to implement than the multi-tile ACUTA system. The single-tile ACUTA system is hence a promising replacement for the four-way stop intersection, considering that the operational characteristics of both the single-tile ACUTA and the four-way stop control are analogous.

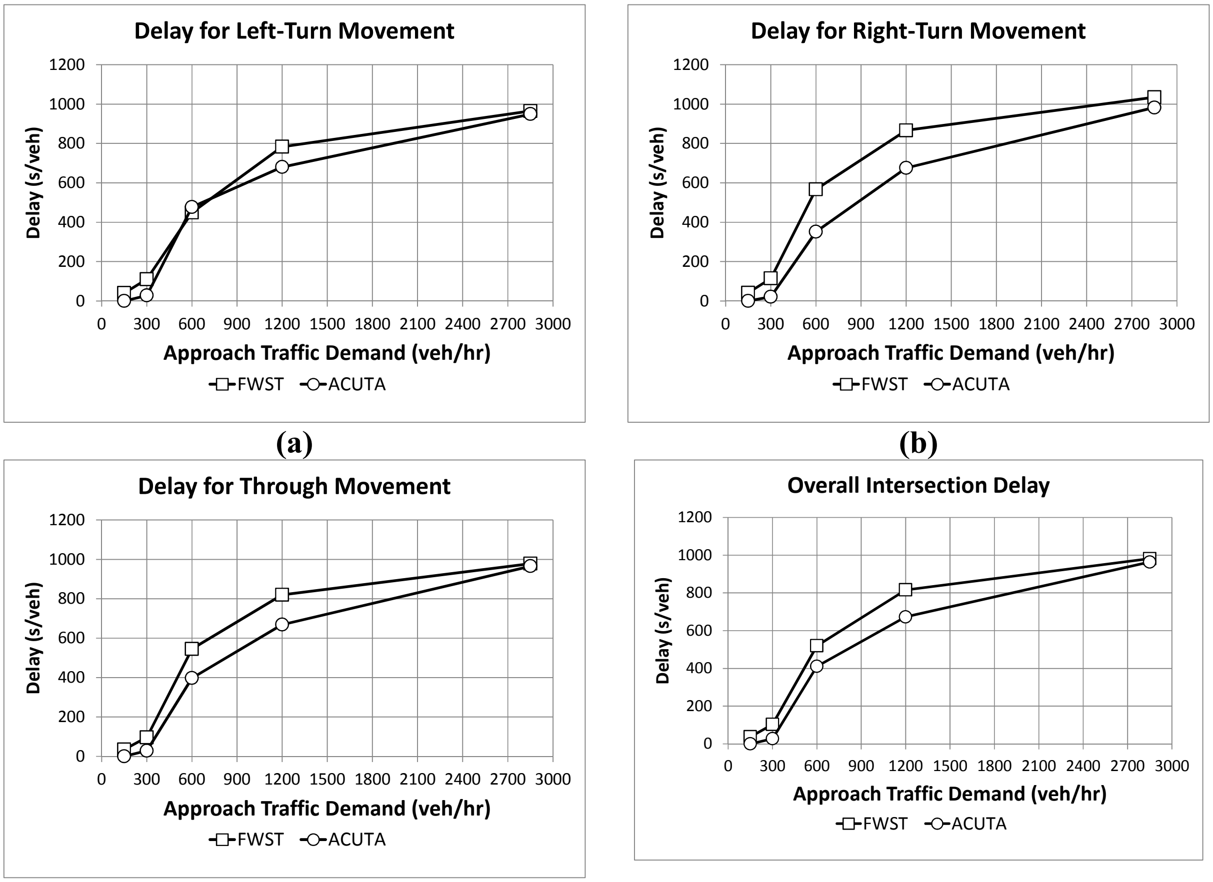
Similar to the comparison between signalized intersection and Multi-Tile ACUTA, a comparable four-way stop intersection was modeled in VISSIM to compare with single-tile ACUTA. The major difference between Single-Tile ACUTA and four-way stop control is that vehicles in ACUTA do not need to stop before their entry into the intersection. Additionally, at a four-way stop intersection, whoever gets to the stop line first goes first. This comparison aims at exploring the possibility of using Single-Tile ACUTA to replace four-way stop controlled intersections to accommodate autonomous vehicles in future. Results are summarized in Table 3. For better visualization, relationships between delays and traffic demands are depicted in Figure 5.

As shown in Figures 5.a through 5.d, delays of both single-tile ACUTA and four-way stop control increased as the approach traffic demand increased. Single-Tile ACUTA operated extremely well with a zero delay at an approach demand of 150 veh/hr, outperforming four-way stop control by 37.22 s/veh in terms of delay. Single-Tile ACUTA resulted in a reasonable delay of 27.16 s/veh at an approach demand of 300 veh/hr, while stop control had already reached its capacity with a large delay of 103 s/veh. When the approach traffic demand exceeded 300 veh/hr, delay started to increase dramatically for both. Overall, delays experienced under Single-Tile ACUTA were always less than delays at four-way stop control.

In summary, Single-Tile ACUTA performed more efficiently than four-way stop control. When the approach traffic demand exceeded 300 veh/hr, performance of Single-Tile ACUTA deteriorated and therefore, Multi-Tile ACUTA is recommended to replace Single-Tile ACUTA at those traffic demands.

TABLE 3 Comparison of Operational Performance between Single-Tile ACUTA and the Four-Way Stop Control

Approach Traffic Demand (veh/hr)	**Four-Way Stop**				**Single-Tile ACUTA**			
	Delay (s/veh)				**Delay (s/veh)**			
	LT	*Thru*	*RT*	*Overall*	*LT*	*Thru*	*RT*	*Overall*
150	40.54	34.62	41.80	37.22	0.00	0.00	0.00	0.00
300	110.44	96.30	114.48	103.00	27.88	28.32	20.92	27.16
600	449.50	545.16	567.22	520.02	477.50	397.40	351.50	410.80
800	783.56	820.18	866.56	816.32	680.50	668.80	675.80	673.20
2850	964.48	978.48	1034.90	981.98	949.30	965.80	982.40	964.00



(a) **(b)**

(c) **(d)**

FIGURE 5 Performance comparison between Single-Tile ACUTA and a four-way stop intersection: (a) left-turn delay, (b) right-turn delay, (c) thru delay, and (d) overall delay

Sensitivity Analysis of ACUTA Parameters

ACUTA has the following configurable parameters: (1) granularity, (2) ASL, (3) End location of NDZ, and (4) minimum speed to allow fixed-speed reservation (MINSAFSR).

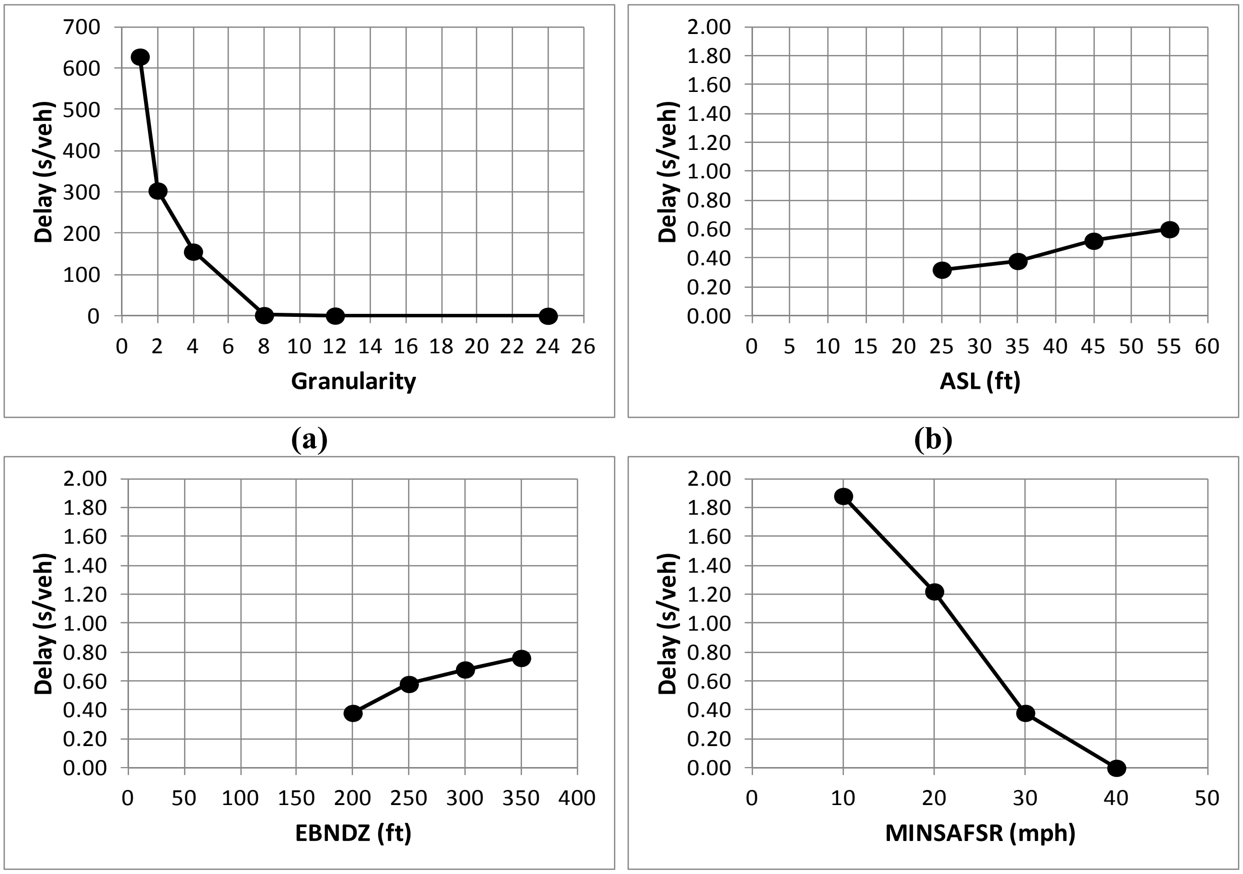
Sensitivity analyses were conducted on these four configurable parameters to investigate their impact on the operational performance of ACUTA. For each parameter, a series of intersection delays were observed by changing the value of the parameter and maintaining the other parameters at their default values. All simulations were performed under a medium approach demand of 1050 veh/hr, and PR's parameters MSQV and MINQL were set to 0 mph and 3 vehs, respectively. Results of sensitivity analysis are summarized in Table 4. To visualize the magnitudes of the sensitivities on different parameters, the results are also depicted in Figure 6.

TABLE 4 Results of the Sensitivity Analyses

		Delay (s/veh)			
Factor	**Value**	**LT Overall**	**Thru Overall**	**RT Overall**	**Overall**
Granularity	1	629.90	627.40	623.50	627.50
	2	282.00	309.30	321.50	303.40
	4	156.44	154.10	159.66	155.60
	8	2.16	1.98	1.60	1.98
	12	0.78	0.94	0.70	0.88
	*24	0.26	0.42	0.44	0.38
Advance Stop Location (ASL), ft	25	0.20	0.38	0.38	0.32
	*35	0.26	0.42	0.44	0.38
	45	0.34	0.60	0.52	0.52
	55	0.36	0.70	0.62	0.60
End Boundary of Non-Deceleration Zone (EBNDZ), ft	*200	0.26	0.42	0.44	0.38
	250	0.38	0.66	0.64	0.58
	300	0.46	0.76	0.72	0.68
	350	0.58	0.84	0.82	0.76
Min Speed to Allow Fixed-Speed Reservation (MINSAFSR), mph	10	1.62	2.00	1.86	1.88
	20	0.98	1.32	1.20	1.22
	*30	0.26	0.42	0.44	0.38
	40	0.00	0.00	0.00	0.00

* denotes the default value of the corresponding parameter, which is used in sensitivity analysis of other parameters.

According to Figure 6.a, intersection delay was extremely sensitive to model granularity. Intersection delay decreased rapidly as granularity increased from 1 to 8. After granularity reached 8, the reduction in the intersection delay became minor in magnitude. As shown in Table 3, intersection delay was roughly halved every time granularity doubled. The second sensitive parameter is MINSAFSR. Delay dropped from almost 2 s/veh to 0 s/veh as minimum speed threshold increased from 10 mph to 40 mph, requiring more high-speed vehicles to accelerate as needed. In addition to granularity and MINSAFSR, delay also showed modest sensitivity to ASL and EBNDZ. As ASL or EBNDZ increased, delay increased at a relatively constant rate.



(a) **(b)**

(c) **(d)**

FIGURE 6 sensitivity of delay about different parameters: (a) granularity, (b) advance stop location (ASL), (c) end boundary of non-deceleration zone (EBNDZ), (d) min speed to allow fixed-speed reservation (MINSAFSR)

CONCLUSIONS

A next-generation intersection control algorithm for autonomous vehicles, ACUTA, was developed to address operational issues identified in previous reservation-based intersection control algorithms. Three operational enhancement strategies: advance stop location (ASL), non-deceleration zone (NDZ) and priority reservation (PR) were introduced and incorporated in ACUTA. The evaluation results show that incorporating ASL or NDZ resulted in about 90% reduction in delays when compared to ACUTA without them. Incorporating PR had a limited 7% reduction in delay.

To evaluate ACUTA's operational benefits, comparisons were performed between the Single-Tile ACUTA and the four-way stop control, and between the Multi-Tile ACUTA and the optimized signal control. Evaluation results demonstrated that compared with the optimized signal control, Multi-Tile ACUTA increased left turn, right turn and through capacities by 37%, 32%, and 31%, respectively. The overall approach capacity was increased by 33%. Further analysis on the v/c ratios indicates that the Multi-Tile ACUTA intersection could process 450 more vehicles per hour per approach without being oversaturated than the optimized signalized intersection. As a result, the Multi-Tile ACUTA intersection caused considerably less delay than the optimized signalized intersection. The comparison between Single-Tile ACUTA and four-way stop control reveals that Single-Tile ACUTA caused significantly less delay than four-way stop control, when the approach traffic demand was less than 300 veh/hr. In summary, the results from both comparisons indicate the substantial advantage of ACUTA in terms of minimizing the delay and maximizing the intersection capacity.

For a comprehensive understanding of how ACUTA can be configured to reach its optimal performance, a series of sensitivity analyses were conducted for four configurable parameters in ACUTA. Delay was found to be very sensitive to granularity of the ACUTA model. Delay can be stably low when granularity was set to 8 and higher values. Also, as the minimum speed to allow fixed-speed reservation (MINSAFSR) increased, delay decreased. As advance stop location (ASL) or end boundary of non-deceleration zone (EBNDZ) increased, delay increased.

In conclusion, ACUTA proposed in this study has been evaluated to have excellent operational performance compared with optimized signal control and four-way stop control, and still has potential to be optimized by adjusting its configurable parameters.

ACKNOWLEDGEMENT

This project is funded by National Center for Freight & Infrastructure (CFIRE) at the University of Wisconsin-Madison.

REFERENCES

1. *An Initial Assessment of Freight Bottlenecks on Highways*, Federal Highway Administration, 2005.
2. National Highway Traffic Safety Administration, www.nhtsa.gov.
3. Dresner, K. and Stone, P. (2004) "Multiagent traffic management: A reservation-based intersection control mechanism." *The Third International Joint Conference on Autonomous Agents and Multiagent Systems*, New York, New York, USA, July 2004, pp. 530–537.
4. Dresner, K. and Stone, P. (2005). "Multiagent Traffic Management: An Improved Intersection Control Mechanism." *The Fourth International Joint Conference on Autonomous Agents and Multiagent Systems*, Utrecht, The Netherlands, July 2005, pp. 471-477.
5. Dresner, K. and Stone, P. (2005). "Turning the Corner: Improved Intersection Control for Autonomous Vehicles", *Proceedings of the 2005 IEEE Intelligent Vehicles Symposium*, Las Vegas, Nevada, USA, June 2005.
6. Dresner, K. and Stone, P. (2008). "A Multiagent Approach to Autonomous Intersection Management." *Journal of Artificial Intelligence Research*, 31, pp. 591–656.
7. Dresner, K. and Stone, P. (2008). "Mitigating Catastrophic Failure at Intersections of Autonomous Vehicles", *Proceedings of the Seventh International Conference on Autonomous Agents and Multiagent Systems*, Estoril, Portugal, May 2008, pp. 1393-1396.
8. Shahidi, N., Au, T.C., and Stone, P. (2011). “Batch reservations in autonomous intersection management.” *Proceeding of The 10th International Conference on Autonomous Agents and Multiagent Systems - Volume 3*, Richland, SC, 2011.
9. Au, T.C., Shahidi, N., and Stone, P. (2011). "Enforcing Liveness in Autonomous Traffic Management", *Proceedings of the 25th AAAI Conference of Artificial Intelligence*, pp. 1317-1322.

10. Quinlan, M., Au, T.C., Zhu, J., and Stiurca, N., and Stone, P. (2010). “Bringing Simulation to Life: A Mixed Reality Autonomous Intersection.” *Proceedings of 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2010)*, October 2010.
11. Fajardo, D., Au, T.C., Waller, S.T., Stone, P. and Yang D. (2011). "Automated Intersection Control: Performance of Future Innovation Versus Current Traffic Signal Control", *Transportation Research Record: Journal of the Transportation Research Board, No. 2259*, pp. 223-232.
12. Wu, J., A. Abbas-Turki, A. Corréïa and A. EL Moudni, (2007). “Discrete Intersection Signal Control”, *IEEE International Conference on Service Operations and Logistics, and Informatics*, Aug. 2007.
13. Yan, F., M, Dridi and A. EL Moudni, (2008) “Control of traffic lights in intersection: A new branch and bound approach”, *IEEE International Conference on Service Systems and Service Management*, June, 2008.
14. Yan, F. Dridi, M., and Moudni, A. E. (2009) “Autonomous Vehicle Sequencing Algorithm at Isolated Intersections”, *Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems*, St. Louis, MO, USA, October 3-7, 2009.
15. Ball, R. and Dulay, N. (2010). "Enhancing Traffic Intersection Control with Intelligent Objects", *First International Workshop the Urban Internet of Things*, 2010.
16. VanMiddlesworth, M., Dresner, K., and Stone, P. (2008). “Replacing the Stop Sign: Unmanaged Intersection Control for Autonomous Vehicles.” *Proceedings of AAMAS Workshop on Agents in Traffic and Transportation*, Estoril, Portugal, pp. 94–101.
17. Alonso, J., Milanés, V., Joshué, P., Onieva, E., González, C., de Pedro, T., (2011). "Autonomous vehicle control systems for safe crossroads", *Transportation Research Part C*, 19, pp. 1095–1110.
18. Milanés, V., Alonso, J., González, C., Bouraoui, L., Ploeg, J., de Pedro, T., (2011). "Cooperative maneuvers in close enviroments among cycabs and dual-mode cars." *IEEE Transactions on Intelligent Transportation Systems*, 12 (1), pp. 15–24.
19. Wu, J., A. Abbas-Turki, and A. El Moudni. (2010) “Contextualized Traffic Controlling At Isolated Urban Intersection.” *The 14th World Multi-Conference on Systemics, Cybernetics and Informatics: WMSCI 2010*, 2010.
20. Vasirani, M. and Ossowski, S. (2009). "Evaluating Policies for Reservation-based Intersection Control." *Proceedings of the 14th Portuguese Conference on Artificial Intelligence (EPIA'09)*, Vol. 14, 2009.
21. Naumann, R., & Rasche, R. (1997). “Intersection collision avoidance by means of decentralized security and communication management of autonomous vehicles.” *Proceedings of the 30th ISATA - ATT/IST Conference.*
22. Alvarez, L., & Horowitz, R. (1997). “Traffic flow control in automated highway systems.” *Report UCB-ITS-PRR-97-47*, University of California, Berkeley, Berkeley, California, USA.
23. Naumann, R., Rasche, R., & Tacken, J. (1998). “Managing autonomous vehicles at intersections.” *IEEE Intelligent Systems*, 13 (3), pp. 82-86.
24. Schonberg, T., Ojala, M., Suomela, J., Torpo, A., & Halme, A. (1995). “Positioning an autonomous off-road vehicle by using fused DGPS and inertial navigation.” 2nd *IFAC Conference on Intelligent Autonomous Vehicles*, pp. 226-231.
25. Highway Capacity Software 2010, McTrans, University of Florida.