Development of Next Generation Intersection Control

CFIRE 04-18
March 2013

National Center for Freight & Infrastructure Research & Education
Department of Civil and Environmental Engineering
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Technical Report Documentation Page

1. Report No. **CFIRE 04-18**	2. Government Accession	3. Recipient's Catalog No.
4. Title and subtitle **Development of Next Generation Intersection Control**		5. Report Date **March 31, 2013** 6. Performing Organization Code
7. Author(s) **Zhixia Li, Madhav V. Chitturi, and David A. Noyce**		8. Performing Organization Report No. **CFIRE 04-18**
9. Performing Organization Name and Address **Traffic Operations and Safety (TOPS) Laboratory University of Wisconsin-Madison 1415 Engineering Drive, Madison, WI 53706**		10. Work Unit No. (TRAIS) 11. Contract or Grant No. **DTRT06-G-0020**
12. Sponsoring Agency Name and Address **Research and Innovative Technology Administration United States Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590**		13. Type of Report and Period Covered **Final Report [11/1/2010 - 3/31/2013]** 14. Sponsoring Agency Code
15. Supplementary Notes **Project performed for USDOT's RITA by TOPS Lab in cooperation with CFIRE.**		

16. Abstract

A reservation-based autonomous intersection control system, named Autonomous Control of Urban TrAffic (ACUTA), was developed as a part of this research effort. ACUTA allows centralized management of autonomous vehicles within a certain distance from an intersection to allow vehicles to pass the intersection with fewer stops and no conflicts. To address the operational issues of reservation-based autonomous intersection management identified in previous studies, three operational enhancement strategies are introduced and incorporated into ACUTA. The three strategies were evaluated and shown to be effective in reducing intersection delay. Along with the operational improvements offered by ACUTA, its implementation in VISSIM, a standard simulation platform is a significant achievement. By using a widely applied standard simulation platform, measures of effectiveness for different autonomous control algorithms can be standardized, and simulation results can be more reliable. Most importantly, results from different studies, particularly for operational performance, can be compared to each other through standardization of the simulation platform. In addition, various simulation experiments were conducted to evaluate operational performance of both multi-tile ACUTA and single-tile ACUTA. Results show that multi-tile ACUTA has significant operational superiority over optimized signal control, especially under high traffic demand conditions, while single-tile ACUTA shows promise in replacing four-way stop control for efficient management of autonomous vehicles at low volume intersections. Evaluation results also indicate that ACUTA system has successfully resolved both minor-road starvation issue under unbalanced demand conditions and slow-speed reservation issue identified in previous studies. To optimize ACUTA system's operational performance, sensitivity analyses were conducted on ACUTA's configurable parameters, identifying parameters that intersection delay is sensitive to, along with their trend in impacting intersection delay. Finally, ACUTA's capability of accommodating heavy trucks was also evaluated. Results show that ACUTA can efficiently accommodate high demands of heavy trucks with short delays.

17. Key Words	18. Distribution Statement
autonomous vehicles, V2I communication, autonomous intersection management, reservation-based control, VISSIM	**No restrictions. This report is available through the Transportation Research Information Services of the National Transportation Library.**

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**	**72**	-0-

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ACKNOWLEDGMENTS

The authors would like to thank the National Center for Freight & Infrastructure Research & Education (CFIRE) for funding this research. The authors would also like to thank Professor Gary Rylander of University Wisconsin-Madison, Mr. John Berg from Federal Highway Administration (FHWA), Professor Xiao Qin of South Dakota State University, Ms. Joanna Bush from Wisconsin Department of Transportation (WisDOT), and Mr. Greg Waidley of CFIRE for serving on the project panel for this project. The authors also want to express their gratitude to Mr. Dongxi Zheng from University of Wisconsin-Madison for his assistance in analyzing the data and report writing.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACUTA	Autonomous Control of Urban TrAffic
AIM	Autonomous Intersection Management
ASL	Advance Stop Location
EBNDZ	End Boundary of Non-Deceleration Zone
EDM	External Driver Model provided by VISSIM
MINQL	MINimum Queue Length to activate the priority reservation
MINSAFSR	MINimum Speed to Allow Fixed-Speed Reservation
MSQV	Maximum Speed to be considered as a Queuing Vehicle
NDZ	Non-Deceleration Zone
PR	priority reservation (PR) for queuing vehicles
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle

SI* (MODERN METRIC) CONVERSIONN FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yard	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised March 2003)

EXECUTIVE SUMMARY

A reservation-based autonomous intersection control system, named Autonomous Control of Urban TrAffic (ACUTA) was developed in this research. ACUTA allows centralized management of autonomous vehicles within a certain distance from an intersection to allow vehicles to pass the intersection with fewer stops and no conflicts. To address the operational issues identified in previous studies on reservation-based autonomous intersection management, three operational enhancement strategies are introduced and incorporated into ACUTA.

ACUTA was successfully implemented in VISSIM, a standard simulation platform. Although implementation of reservation-based autonomous intersection in VISSIM was widely discussed by researchers, the feasibility was always doubted and such implementation was not undertaken in previous studies. The key steps necessary to implement ACUTA in VISSIM are discussed in this report, which will benefit both future researchers implementing their autonomous intersection control algorithms and existing researchers wishing to implement their autonomous intersection algorithm in VISSIM. By using a standard simulation platform, measures of effectiveness for different control algorithms can be unified, and simulation results are more reliable compared to various customized simulation environments developed by different researchers themselves. Most importantly, results from different studies, particularly for operational performance, can be compared to each other using standard simulation input and output.

Various simulation experiments were conducted to evaluate operational performance of ACUTA. Results show: (1) operational enhancement strategies including Advance Stop Location (ASL), Non-Deceleration Zone (NDZ), and Priority Reservation (PR) for Queuing Vehicles are effective in reducing intersection delay; (2) multi-tile ACUTA has significant operational superiority over optimized signal control under high traffic demand conditions; (3) single-tile ACUTA shows promise in replacing four-way stop control for managing autonomous vehicles at low volume intersections; and (4) ACUTA successfully resolves minor-road starvation and slow-speed reservation issues identified in previous related studies. Key findings from performance evaluations are summarized as follows:

- Both single-tile and multi-tile ACUTA systems have balanced delays for left-turn, right-turn, and through movements under any balanced traffic demand conditions.
- Enabling ASL strategy can result in a 95% reduction (compared to no ASL) in overall intersection delay under a high traffic demand of 550 veh/hr/ln.
- Enabling the NDZ strategy can result in a 90% reduction (compared to no NDZ) in overall intersection delay under a high traffic demand of 550 veh/hr/ln.
- Enabling the PR strategy can result in a 7% reduction (compared to no PR) in overall intersection delay under a near capacity traffic demand of 600 veh/hr/ln, if the parameter "maximum speed to be considered a queuing vehicle" (MSQV) is set to 15 mph.
- Overall intersection delay for multi-tile ACUTA system can remain under 5 s/veh when traffic demand is 550 veh/hr/ln or lower. However, delay starts to increase rapidly when

traffic demand is higher than 600 veh/hr/ln, and ACUTA intersection's capacity is approximately 625 veh/hr/ln.

- Multi-tile ACUTA's superiority in delay over the signalized intersection is only marginal under extremely high traffic demands of 800 and 950 veh/hr/ln.
- Single-tile ACUTA operates with a zero intersection delay under traffic demand of 50 veh/hr/ln, outperforming four-way stop control by 37.22 s/veh.
- Single-tile ACUTA operates with a reasonable delay of 27.16 s/veh under traffic demand of 100 veh/hr/ln when four-way stop control already reaches its capacity with a long delay of 103 s/veh.
- Delay for single-tile ACUTA increases dramatically when traffic demand exceeds 100 veh/hr/ln.
- Minor-road starvation issue does not occur when traffic demands of major and minor roads are unbalanced. The magnitude of major-road delay is always higher than minor-road delay due to the larger demand on major road. As minor-road demand increases, both minor-road and major-road delays increase. The magnitude of delay for a traffic movement is positively correlated to traffic demand of that specific movement only, and increases as demand of that movement increases.
- In order to evaluate the possibility of optimizing ACUTA's operational performance, sensitivity analyses were conducted on ACUTA's configurable parameters, including (1) granularity, (2) number of internal simulations, (3) minimum speed to allow fixed-speed reservation (MINSAFSR), (4) advance stop location (ASL), (5) end boundary of non-deceleration zone (EBNDZ), (6) minimum queue length (MINQL) to activate the priority reservation, and (7) maximum speed to be considered a queuing vehicle (MSQV). Analyses show that intersection delay is sensitive to granularity, MINSAFSR, ASL, EBNDZ, and is slightly sensitive to MINQL and MSQV under certain conditions.

Considering that heavy trucks are an essential element of an urban transportation network, ACUTA's capability of accommodating heavy trucks was also evaluated. Results show that ACUTA can efficiently accommodate heavy trucks for up to 35% heavy truck percentage under traffic demand of 500 veh/hr/ln. Key findings for trucks are:

- Heavy trucks generally experience slightly longer delay than passenger cars under all tested traffic demands from 100 to 600 veh/hr/ln.
- Heavy trucks making different movements experience similar delay. This similarity in delay does not change with either traffic demand or heavy truck percentage.
- When traffic demand is 500 veh/hr/ln and lower, intersection delay remains at a near perfect level of no delay for both heavy truck percentages of 15% and 25%, and at a decent level of 30 s/veh for heavy truck percentage of 35%.
- Under the traffic demand of 600 veh/hr/ln, the ACUTA system approximately reaches its capacity when heavy vehicle percentage is equal to 15%, and operates at oversaturated conditions when heavy vehicle percentage is greater than 15%.

In conclusion, ACUTA developed in this research is promising for future applications of accommodating autonomous vehicles at intersections under various conditions. ACUTA's operational performance still has potential to be optimized by fine-tuning the configurable parameters of the system.

CHAPTER 1: INTRODUCTION

With the rapid advances in sensing, information processing, machine learning, control theory and automotive technology, wide application of autonomous vehicles on highway systems is no longer a dream, but a reality in the near future. Autonomous vehicles are vehicles without human intervention (in-vehicle or remote) that are capable of driving in real-world highway systems by performing complex tasks such as merging, weaving, and driving through intersections.

Advances in the autonomous vehicle industry are supported by the rapid strides in wireless communications, especially vehicle-vehicle (V2V) and vehicle-infrastructure (V2I) communications. Communication standards like DSRC (Dedicated short-range communications) have been developed to provide real-time microscopic information, such as speed, location, origin-destination, route, and a host of other variables, about every single vehicle in the transportation network. This information opens a whole new world of possibilities on which transportation engineers can capitalize, thus revolutionizing the way traffic networks operate. Based on these advances, fully autonomous vehicles are under development by most automotive manufacturers, including General Motors, Ford, Mercedes-Benz, Volkswagen, Audi, BMW, Volvo, and Cadillac. Some of these manufacturers have already begun testing their autonomous vehicle models on highway systems (*1*). Google is also developing and testing its Google driverless car. As of 2012, Florida, Hawaii, Oklahoma, Nevada and California are considering legalization or have already legalized use of autonomous cars (*1*). All these facts indicate that autonomous vehicles will likely appear on the road in the near future.

Technically, the application of autonomous vehicles makes it possible to eliminate traditional traffic signals from the intersection, and hence has potential to maximize intersection capacity, significantly enhancing vehicle mobility at intersections. From a safety perspective, considering that 90% of road crashes are attributed to driver errors (*2*), the application of autonomous vehicles, which are designed to operate without any human interaction, is potentially effective in reducing intersection related crashes. Although potential benefits have been seen, how to take full advantage of autonomous vehicles, and maximize the operational performance of autonomous vehicles at intersections, is of great interest to transportation authorities.

To date, most field tests for autonomous vehicles were restricted to highway segments only. Intersection control of autonomous vehicles has been studied by researchers (*3-21*); however, implementation in practice is difficult because intersections create more conflict points than highway segments. For example, when vehicles arrive at an intersection from different approaches, the right of way for traversing the intersection needs to be determined. Traditional intersections use traffic control devices, such as stop signs and traffic signals, to regulate vehicle right of way. For managing autonomous vehicles at intersections, the right of way is usually controlled by an intersection central controller through vehicle-infrastructure (V2I) communications (*3-14*), or is determined through negotiation between vehicles via vehicle-vehicle (V2V) communications (*15-19*). 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 (*19*). Another study found that starvation may occur in the reservation-based system when traffic demands on the mainline and the side road were unbalanced (*8*). 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 the best 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 traffic simulation software, such as VISSIM or CORSIM, when evaluating the performance of their proposed strategies. They all used independently developed simulation software, which makes the results less reliable and trustworthy. Using ununiformed simulation platform also resulted in that their evaluation results could not be comparable to each other.

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 the existing issues and make the system more realistic; (2) develop a VISSIM-based simulation platform to evaluate the ACUTA; and (3) compare the ACUTA with 4-way stop control and signal control, as well as conduct sensitivity analysis to investigate ways to maximize the performance of ACUTA.

CHAPTER 2: LITERATURE REVIEW

To date, much study has been conducted to explore ideas and algorithms for the effective management of autonomous vehicles at intersections. Both centralized and decentralized control strategies were investigated in previous studies.

2.1 Centralized Control

Centralized control features a central intersection controller that regulates the entire intersection. Vehicles only communicate with the central controller to get passing instructions. Dresner and Stone were the first to introduce a reservation-based multi-agent system, named as Autonomous Intersection Management (AIM) (*3*). In their system, the intersection is divided into a grid of n by n tiles. When a vehicle approaches the intersection, the driver agent that represents the vehicle communicates to the intersection manager. Basic mechanism of the AIM is that the driver agent sends requests to the intersection manager to reserve the intersection for certain time-spaces needed for traversing the intersection based on the vehicle's estimated arrival and departure time. Intersection manager checks what and how much resource (tiles) will be occupied by the requesting 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 the reservation will be made. Vehicle agent is notified by the intersection manager about whether the request is approved or rejected. The instruction of travel will be sent to the vehicle agent by the intersection manager with the 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 tool 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. A 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. Impact of restricting left and right turns being made from designated lanes rather than from any lanes was also analyzed. Theoretically, in the reservation-based system, the restriction was not necessary. Relief from the restriction was supposed to provide more flexibility to drivers. However, the results showed that the scenario under the restricted turn conditions resulted in lower delay than the scenario of allowing turns from any lane. Dresner and Stone further stated that the results might be misleading, because the delay incurred by vehicles from the lane change maneuvers can cause longer delay (*6*).

In the later versions of the 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 the unbalanced traffic demands on the mainline and the side road (*8, 9*). The 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., the 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. Intersection controller decides the passing sequence of the vehicles. Decision made by the controller was optimized with an objective to minimize the total time of clearing all autonomous vehicles at the intersection. Key point of the optimization was to decide an optimal vehicle passing sequence. A dynamic programming algorithm was used to solve this problem. The vehicle passing sequence could dynamically change when new vehicles enter the control range. No simulation or validation was performed in their research.

2.2 Decentralized Control

Different from centralized control, decentralized control features no intersection controller, and hence utilizes fewer resources. Vehicles need to communicate with each other to negotiate a passing sequence when arriving at the intersection. Ball and Dulay proposed a contrasting distributed approach to traffic intersection control using *shared journey plans and avoidance* via V2V communications (*15*). vehicles were assumed to be addressable mobile intelligent objects. Vehicles adapt their speed to avoid predicted future collisions with other vehicles, in effect repeatedly micromanaging local speed to minimize journey delay and improve vehicle flow.

VanMiddlesworth et al. modified Dresner and Stone's system into an unmanaged intersection, which has no intersection manager (*16*). The modification aimed at simplifying the intersection infrastructure. In their system, vehicles communicate with each other to request claim of reservation of intersection. If the vehicle does not receive a conflicting claim from another vehicle, the reservation will be made. Rather than relying solely on theoretical research, Alonso et al. conducted practical experiments to test their decentralized control algorithm in the field (*17*). An approach called "Priority Attribution Methods at an Intersection" was developed, which was based on a predefined priority rule of yielding. Stopping was mostly required for each vehicle. Alonso et al.tested their approach in field using a previously developed vehicle-to-vehicle (V2V) communication system (*18*). Test results showed that the priority rule-based method worked well for very low volume condition.

2.3 Comparison between Centralized and Decentralized Control Strategies

Wu et al. compared both their centralized control strategies based on dynamic programing and their negotiation-based decentralized control strategy to an adaptive traffic controller, and the 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 the centralized and decentralized systems had similar operational performance. Wu et al. concluded that despite the fact that the reservation-based system maximizes the use of space in the intersection, it lacks considerations of safe distance between two vehicles in both the non-conflicting and conflicting movements.

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

2.4 Summary

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, the 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.

CHAPTER 3: THE NEXT-GENERATION INTERSECTION CONTROL

3.1 Enhanced Reservation-based Autonomous Intersection Control

Considering the superiority of the reservation-based system in terms of maximizing the intersection capacity, the next-generation intersection control system developed in this project was based on the First-Come-First-Serve (FCFS) reservation-based protocol (*3*), with enhancements to improve some operational issues identified in previous studies (*3, 10*). The system was named Autonomous Control of Urban TrAffic (ACUTA). The following subsections give details about the ACUTA's working mechanism and enhancement strategies.

3.1.1 Logics of the ACUTA System

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

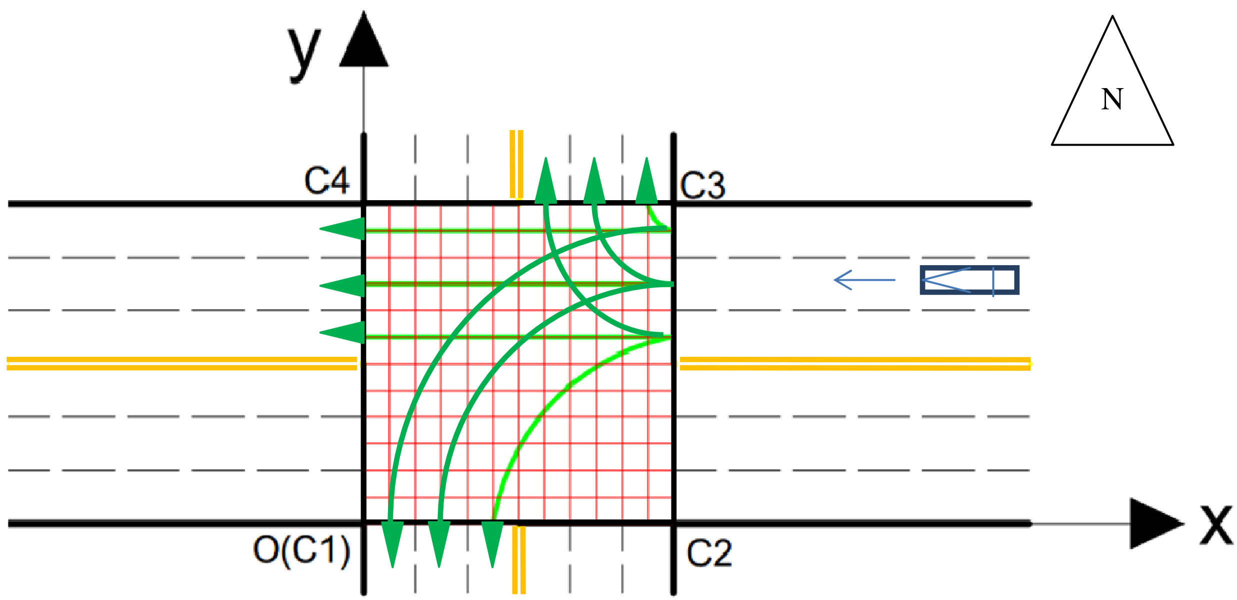

Figure 1: Intersection mesh of tiles and example of vehicle's possible routing decisions

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

$$a_i = 0 \qquad (i = 1)$$

$$a_i = a_{\max} - (i-1)\frac{1}{m}a_{\max} \qquad (i > 1) \qquad (1)$$

Where, α_i = i^th alternative acceleration rate (ft/s^2);

α_{max} = maximum acceleration rate (ft/s^2); and,

m = maximum number of internal simulations.

Maximum acceleration rate is one of the characteristics particularly pertaining to the requesting vehicle. However, the vehicle must maintain a constant speed when traversing the intersection. In other words, after the vehicle's center point enters the intersection, the vehicle speed does not change until the vehicle completely clears the intersection. The 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 iterative 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 the ACUTA system. The MINSAFSR defines the speed threshold to allow the IM to use a zero acceleration rate in the internal simulation. If the speed of an approaching vehicle falls below the MINSAFSR, zero cannot be used as an alternative acceleration rate in the internal simulation. If all alternative acceleration rates are tried out in the internal simulation and conflicts in reservation still exist, the reservation request will be rejected; otherwise, the reservation request will be approved by the IM. The IM automatically rejects requests from a vehicle following a vehicle that is without a reservation.

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

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

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 analogous to the driver's perception reaction time in human-operating vehicles. In the ACUTA system, 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 the ACUTA system, which designates a predefined advance stop location other than stop line for vehicles with rejected reservations. The ASL is introduced in the ACUTA system as a major enhancement strategy to address the slow-reservation-speed issue pertaining to vehicles stopping at the traditional stop line. By using the ASL, vehicles with rejected reservations can stop at an upstream distance from the entrance of the intersection; hence can gain higher speed when reaching the entrance point of the intersection. A higher entrance speed can increase the chance for the vehicle to get a reservation, meanwhile saving the intersection time-space resources by reducing the vehicle's total traverse time within the intersection. 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 the 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 strictly follow the acceleration instruction as soon as it receives the approval message until the vehicle completely clears the intersection.

3.1.2 Strategies for Enhancing the Operational Performance

Previous research identified that unbalanced traffic demands could cause a starvation issue where approaching vehicles on the 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 the previous study (*5*). To address these issues, three enhancement strategies have been incorporated into the ACUTA system, trying to maximize the operational performance of the reservation-based autonomous intersection, as shown by Figure 2.

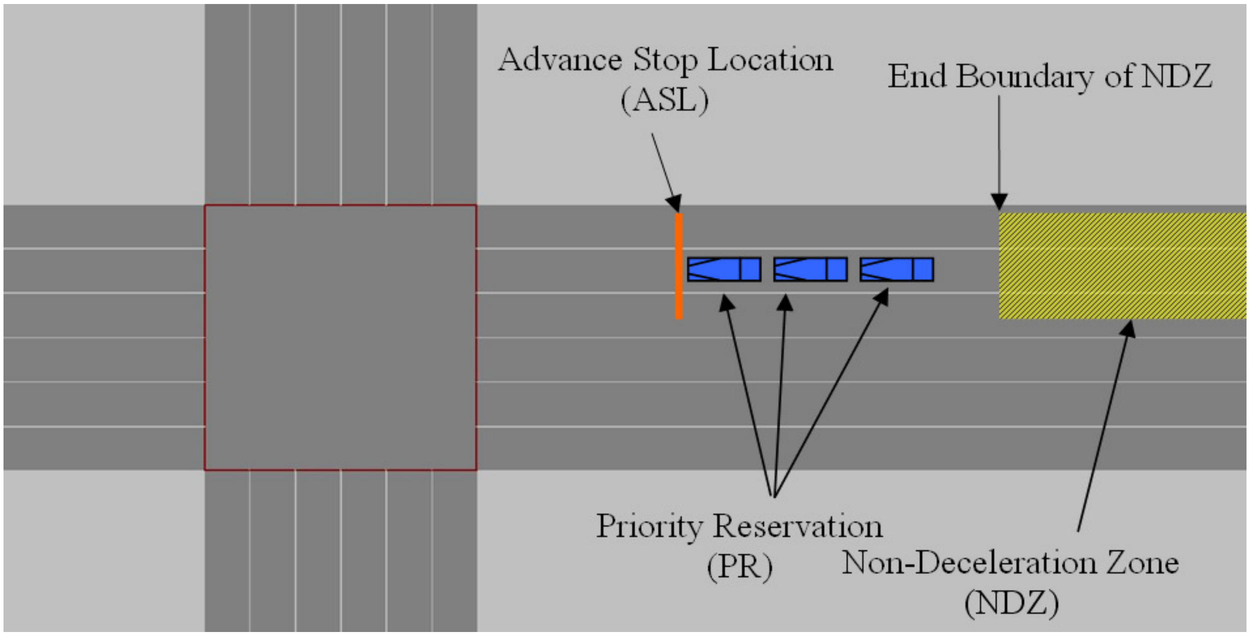

Figure 2: Operational enhancement strategies incorporated in the ACUTA system

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

- **Advance Stop Location (ASL):** the ASL designates a predefined advance stop location other than stop line for vehicles with rejected reservations. The ASL is introduced into the ACUTA system as a major enhancement strategy to address the slow-reservation-speed issue pertaining to vehicles stopping at the traditional stop line. By using ASL, vehicles with rejected reservations can stop at an upstream distance from the entrance of the intersection, hence capable of gaining a higher speed when reaching the entrance point of the intersection. A higher entrance speed can increase the chance for the vehicle to get a reservation, meanwhile saving the intersection time-space resources by reducing the vehicle's total traverse time within the intersection. In the ACUTA system, the ASL is configured by the parameter "ASL," which is in terms of the distance from the intersection. The value for ASL is typically within the range between 30 and 50 feet from the intersection. The short distance from intersection minimizes the effect on roadway geometric design in terms of accessibility from driveways.
- **Non-Deceleration Zone (NDZ):** the NDZ defines a zone in which vehicles do not need to decelerate if its reservation request is rejected. There is no upstream boundary for the NDZ, while the downstream boundary of NDZ is typically at a location that can assure that a vehicle can stop at the ASL with a reasonably high declaration rate (e.g. 15 ft/s^2). This introduction of the 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 the ACUTA system, the NDZ is configured by the parameter "End Boundary of NDZ (EBNDZ)", which specifies the location of the downstream boundary of the NDZ in terms of the distance from the intersection.

- **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. The PR takes effect only when a certain queue length is detected by the intersection manager. In the ACUTA system, two parameters are used to configure the PR, namely, Maximum Speed to be Considered as a Queuing Vehicle (MSQV), and Minimum Queue Length (MINQL) to activate the priority reservation. Once PR is activated, the reservation requests from all vehicles in the queue have priority.

The performance of these enhancement strategies was specifically evaluated and the results are presented in the following chapters.

3.2 Modeling the ACUTA System in VISSIM

Due to the complexity of field implementation, most researchers used traffic simulation to validate their developed strategies for autonomous vehicle control. However, none of the existing studies used standard commercial traffic simulation software such as VISSIM or CORSIM when evaluating the performance of their proposed strategies. Rather, simulation tools developed by the authors of those studies were used in the evaluation process, which made the results less reliable and hard to be comparable to each other.

In addition, it was noticed that most existing studies lacked standard usage of terms and clear descriptions of simulation parameter settings when presenting the evaluation results. For example, when presenting the traffic volume, no clarification of whether the volume was per lane or per entire approach was presented. Also, terms to define lane configurations, speed distribution, volume, and delay, as well as the number of runs per experiment, random seed selection, simulation period, and whether results from the warm-up period (usually the first 5-15 minutes of a simulation run) were excluded from the analysis, were not consistently defined across the studies. This inconsistency may be due to the usage of various customized simulation software programs, rather than standard commercial simulation packages.

Standard simulation packages like VISSIM and CORSIM can provide standard parameter settings and outputs. In addition, using a standard simulation package can guarantee reliable vehicle generation, car-following, lane-changing, and many other driving behavior-related modeling in the simulation. Flexible settings of speed distribution, heavy vehicle percentage, and distributions of acceleration and deceleration rates can also be simply achieved, along with strong evaluation outputs like travel time, delay and queue length. Moreover, commercial packages like VISSIM have options to output vehicle trajectories, which can be directly imported into Surrogate Safety Assessment Model (SSAM) to comprehensively analyze the safety performance of the intersection (*21*).

Wu et al. chose to develop their own simulation tool, rather than use standard traffic simulation packages like VISSIM, AIMSUN, or PARAMICS, because the standard packages do not allow vehicles to be controlled individually (*19*). In fact, VISSIM offers flexible customization functions to facilitate building different special applications through APIs and COM extensions. All these functions offer the potential to implement any application for autonomous intersection control, including one of the most complex centralized control strategies: reservation-based system. In this project, the possibility of using VISSIM for modeling is explored by building a reservation-based system in VISSIM using VISSIM External Driver Model. The establishment of the simulation model, implementation of the reservation-based control algorithm, and final evaluations of the operational and safety performances will be specifically discussed.

Therefore, the enhanced reservation-based system (ACUTA) described in the previous section was implemented in VISSIM, a microscopic traffic simulation software package used extensively worldwide. This section discusses how the ACUTA system was modeled in VISSIM, specifically focusing on the setup of the simulation model, the algorithm for determining occupied intersection tiles, and eventually the implementation of the ACUTA system using the VISSIM external driver model.

3.2.1 Simulation Model of the ACUTA System

The intersection where the ACUTA system operates at is a four-legged intersection with three lanes per direction, as shown in Figure 3. Different from traditional signalized intersections, vehicles can turn from any lane in the ACUTA intersection, as shown in Figure 4. Therefore, no en-route lane change is required for turning vehicles, thus theoretically minimizing the delays due to the conflicts caused by vehicle lane change maneuvers. Because of the absence of lane changes, each lane in the simulation model is built as a separate link to simplify the complexity of the simulation model. Roadways are assumed to have zero grades in 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 the routing decisions are the same for all lanes, namely 25% for left turn, 60% for through, and 15% for right turn. Figure 5 illustrates the routing decisions of a particular lane. The vehicle composition takes 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. Vehicle maximum deceleration rate follows the default maximum deceleration rate distribution predefined in VISSIM. Vehicle maximum acceleration rate is set as 9.8 ft/s^2. No turning speed restriction is considered in this version of the ACUTA system.

Figure 6 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.

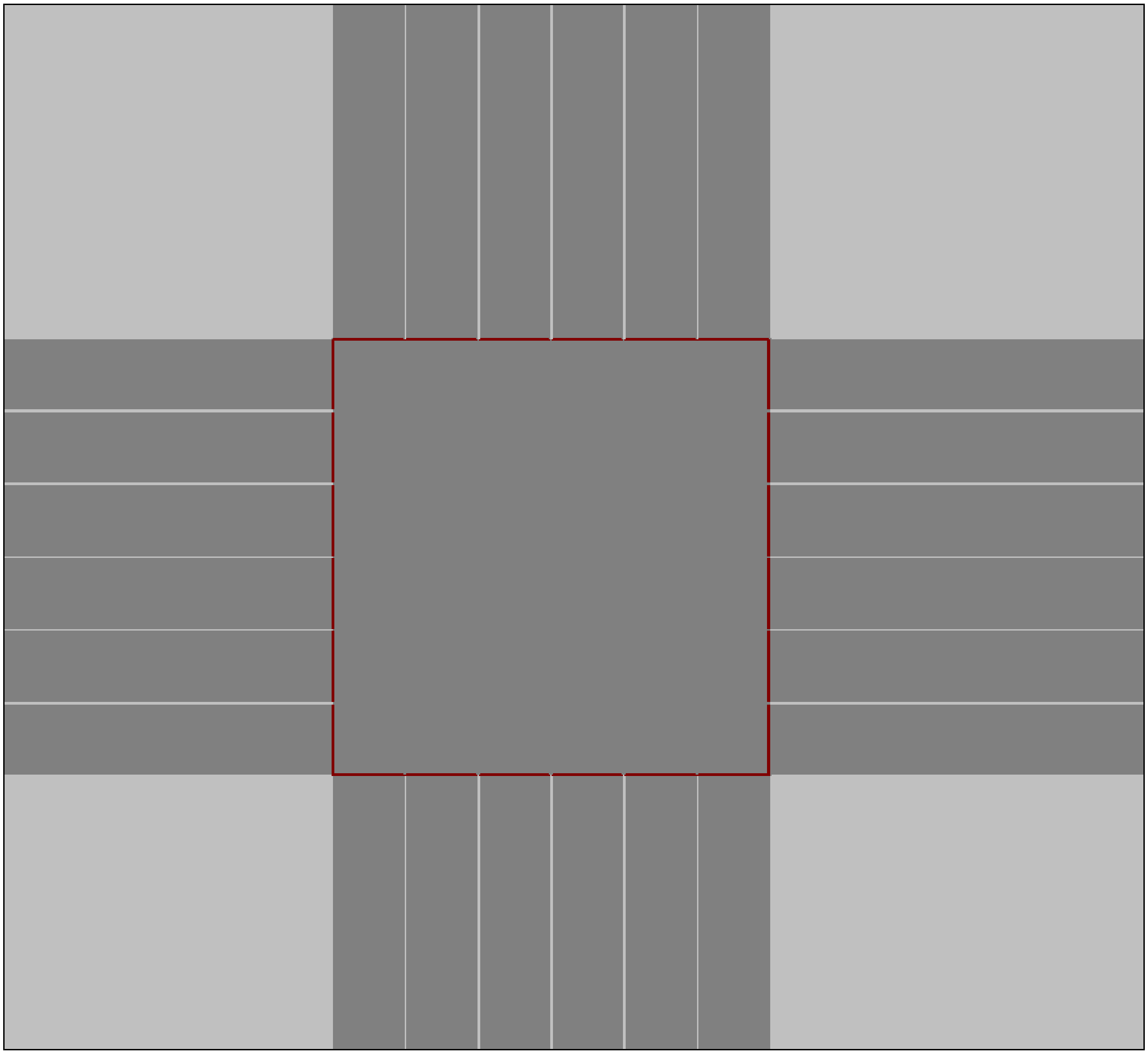

Figure 3: Intersection design for the VISSIM ACUTA model

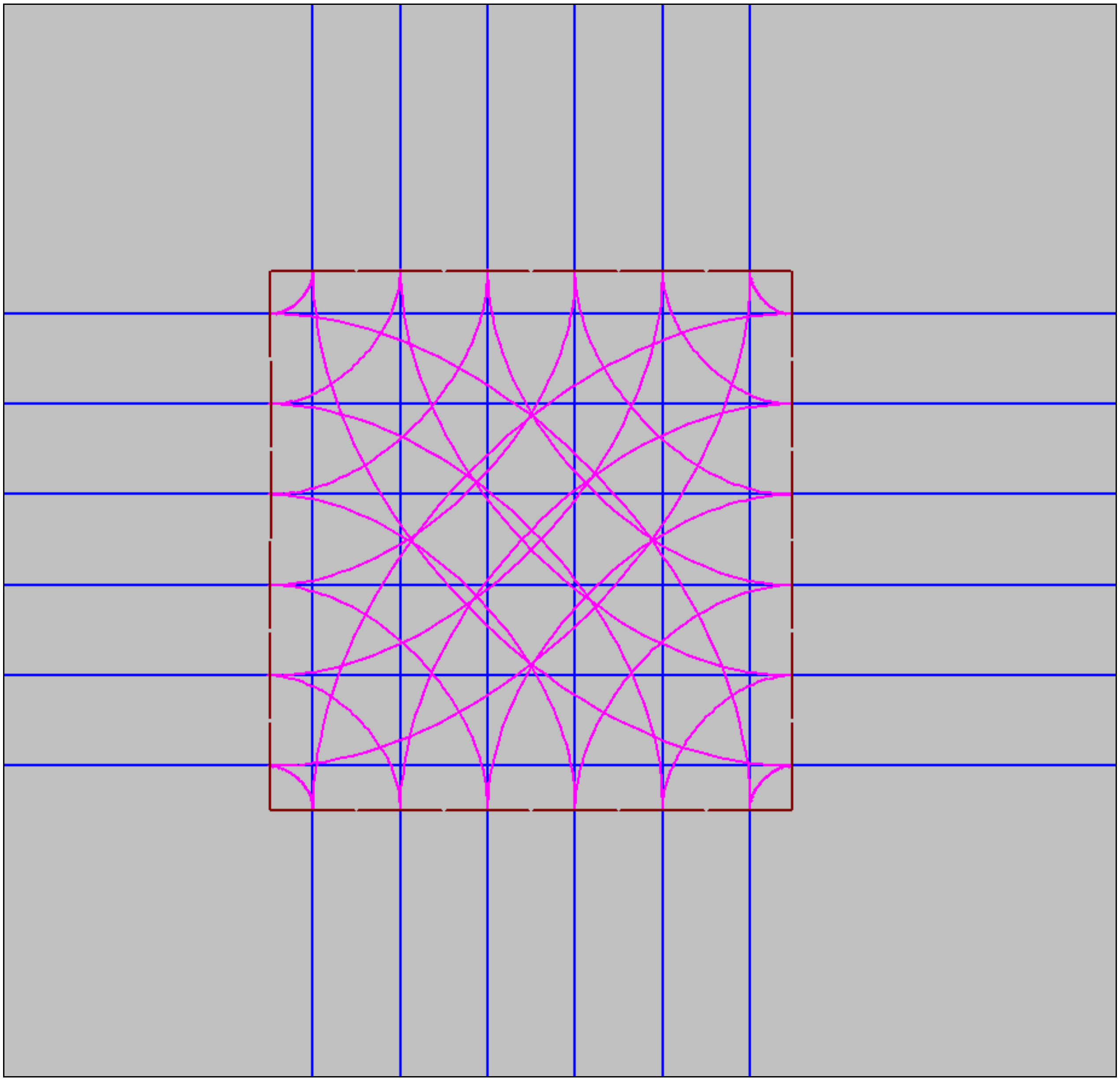

Figure 4: Turning movement design for the VISSIM ACUTA model

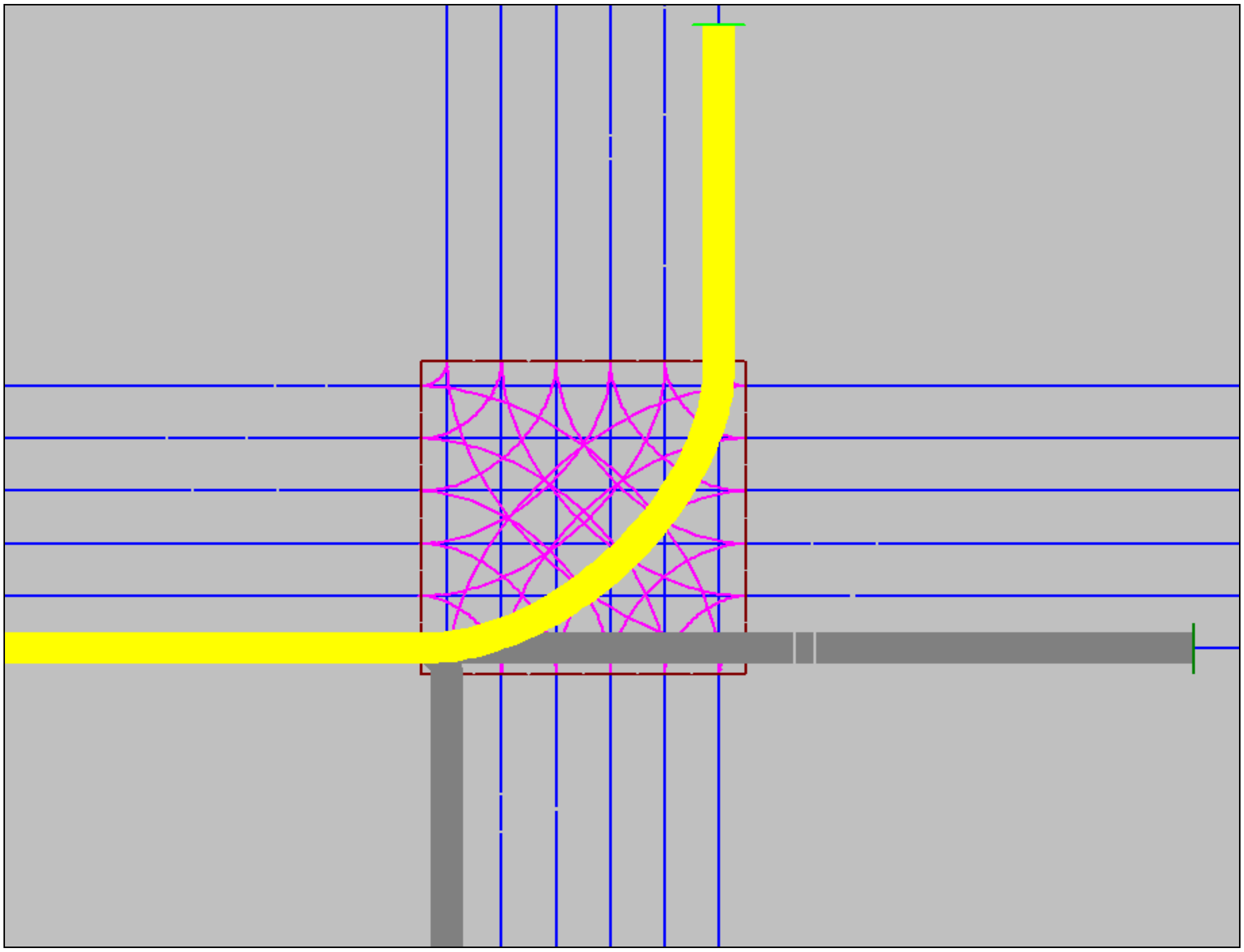

Figure 5: Typical routing decision for a lane in the VISSIM ACUTA model

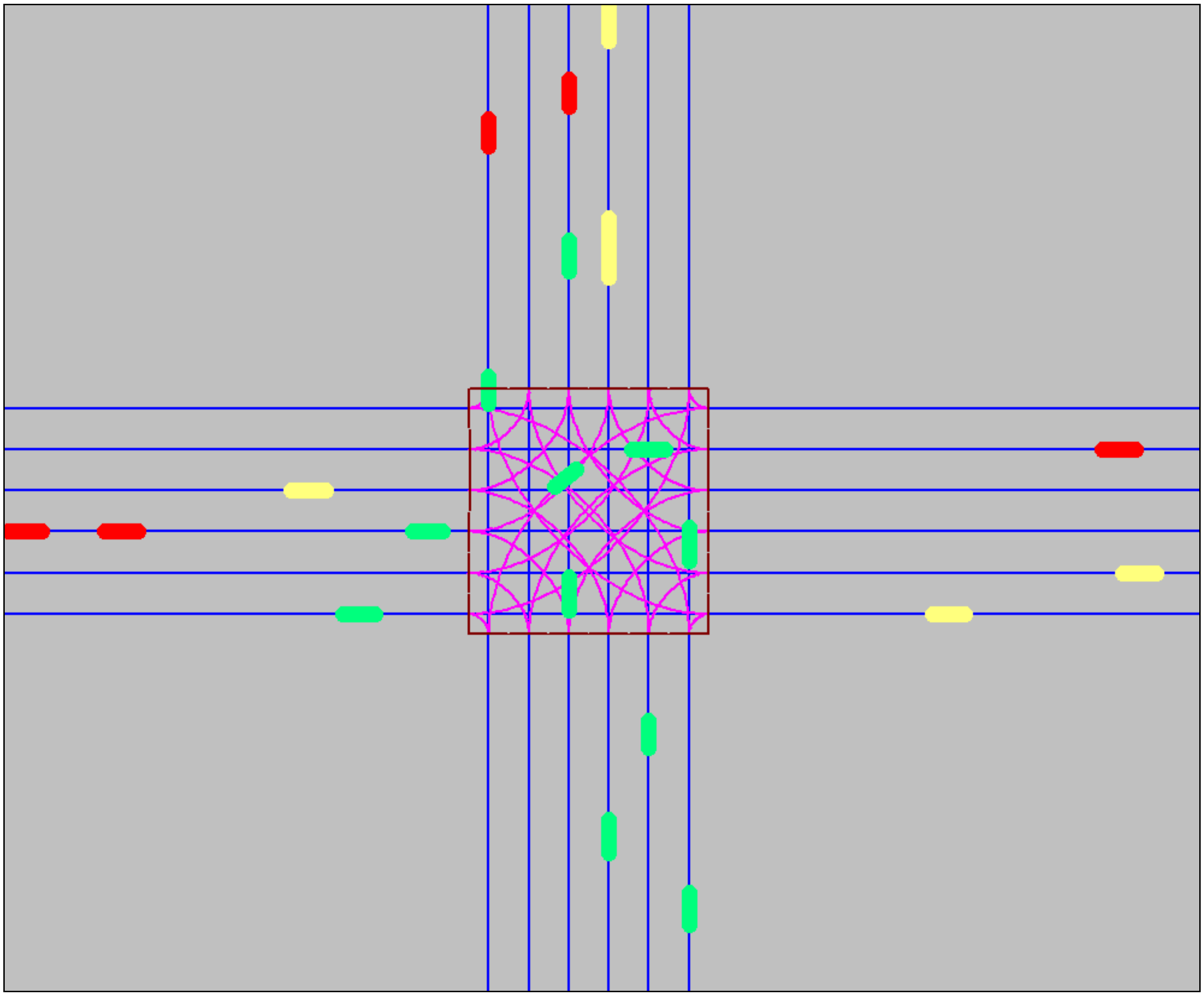

Figure 6: Example of the simulation animation for the VISSIM ACUTA model

3.2.2 Implementing the ACUTA System using VISSIM External Driver Model

Before the VISSIM External Driver Model (EDM) was selected to implement the ACUTA system, the feasibility of using VISSIM COM Interface and VISSIM C2X API was investigated. The C2X API specializes in modeling Car-Car communications with a designated communication range for each vehicle. Therefore, by using the C2X API, it might not be possible to obtain information from all of the vehicles, which is not appropriate for implementing centralized control strategies. The COM interface is quite flexible and versatile in collecting vehicle information and modifying vehicle parameters during the simulation period. However, the COM interface does not provide a direct function to modify a vehicle's acceleration rate. It was also found that executing a command through COM interface may take up to 0.2 sec, which is too long to assure the efficiency of the ACUTA simulations.

The VISSIM EDM, on the other hand, can meet all requirements for implementing the ACUTA system. 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 particular vehicle at each simulation step. The intersection manager processes all reservation requests at the beginning of each simulation step, and passes its decision and the suggested acceleration/deceleration rate to the drivers in the same simulation step. The vehicles then pass their acceleration/deceleration rate back to VISSIM at the same simulation step, thus the real-time control of each vehicle's acceleration rate is realized.

In summary, the EDM offers technical readiness for implementing the ACUTA system in VISSIM. Key steps for realizing the reservation-based system are discussed in the following subsections.

3.2.3 Modeling the Intersection Mesh in VISSIM

In VISSIM, the intersection can be viewed as an overlapping square between the two crossing roads. The entire intersection area can be divided into a mesh of n by n tiles, as shown in Figure 1. The n is the granularity of the intersection mesh. More or fewer tiles can be obtained by adjusting the granularity. Using Westbound as an example, the green lines with arrows illustrate all possible vehicle paths to traverse the intersection.

In Figure 1, a two-dimensional coordinate system is projected onto the intersection area to facilitate the computation of a vehicle's location. The origin O is located at the southwest corner (C1) of the intersection. The southeast, northeast, and northwest corners are labeled by C2, C3, and C4, respectively. The following sections use this coordinate system as a global coordinate system for computing vehicle locations.

3.2.4 Locating Vehicle's Central Point

A key step in the internal simulation is to compute a vehicle's location at a given simulation time step. For convenience in the following discussion, the beginning of time is assumed to be the moment when a vehicle's central point reaches the boundary of the intersection area (i.e., at the Point *S* in Figures 7 through 9**Error! Reference source not found.**).

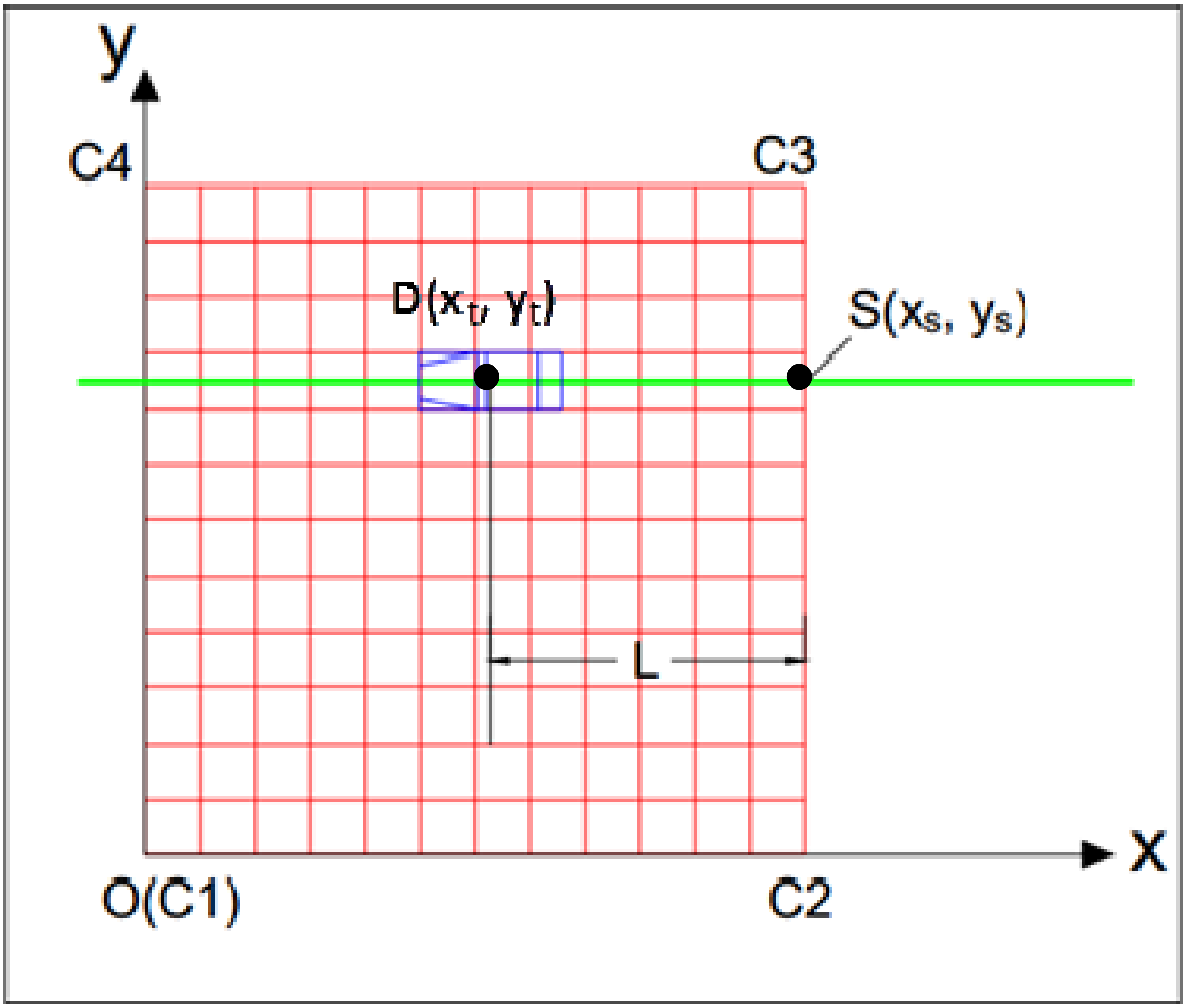

Figure 7: Determination of the central point location of a through vehicle

In the ACUTA system, a vehicle maintains a constant speed after its central point enters and before its central point clears the intersection area. Figure 7 illustrates a case of through movement. The path of a through vehicle is parallel to either of the axes (Figure 3.a) depending upon whether the vehicle is going EB/WB or NB/SB. Assuming that the through vehicle's central point reaches the boundary point $S(x_s,y_s)$ at time 0, the coordinates of the vehicle's central point can be calculated using the following equation.

$$\begin{cases} x_t = x_s - L \\ y_t = y_s \end{cases} \tag{3}$$

where, x_t = x coordinate of the vehicle's central point at time t (ft);

y_t = y coordinate of the vehicle's central point at time t (ft);

x_s = x coordinate of the vehicle's central point at time 0 (ft);

y_s = y coordinate of the vehicle's central point at time 0 (ft);
L = $v \times t$ (ft);
v = speed of the vehicle when it is in the intersection (ft/s); and,
t = any time when the vehicle's central point is within the intersection (s).

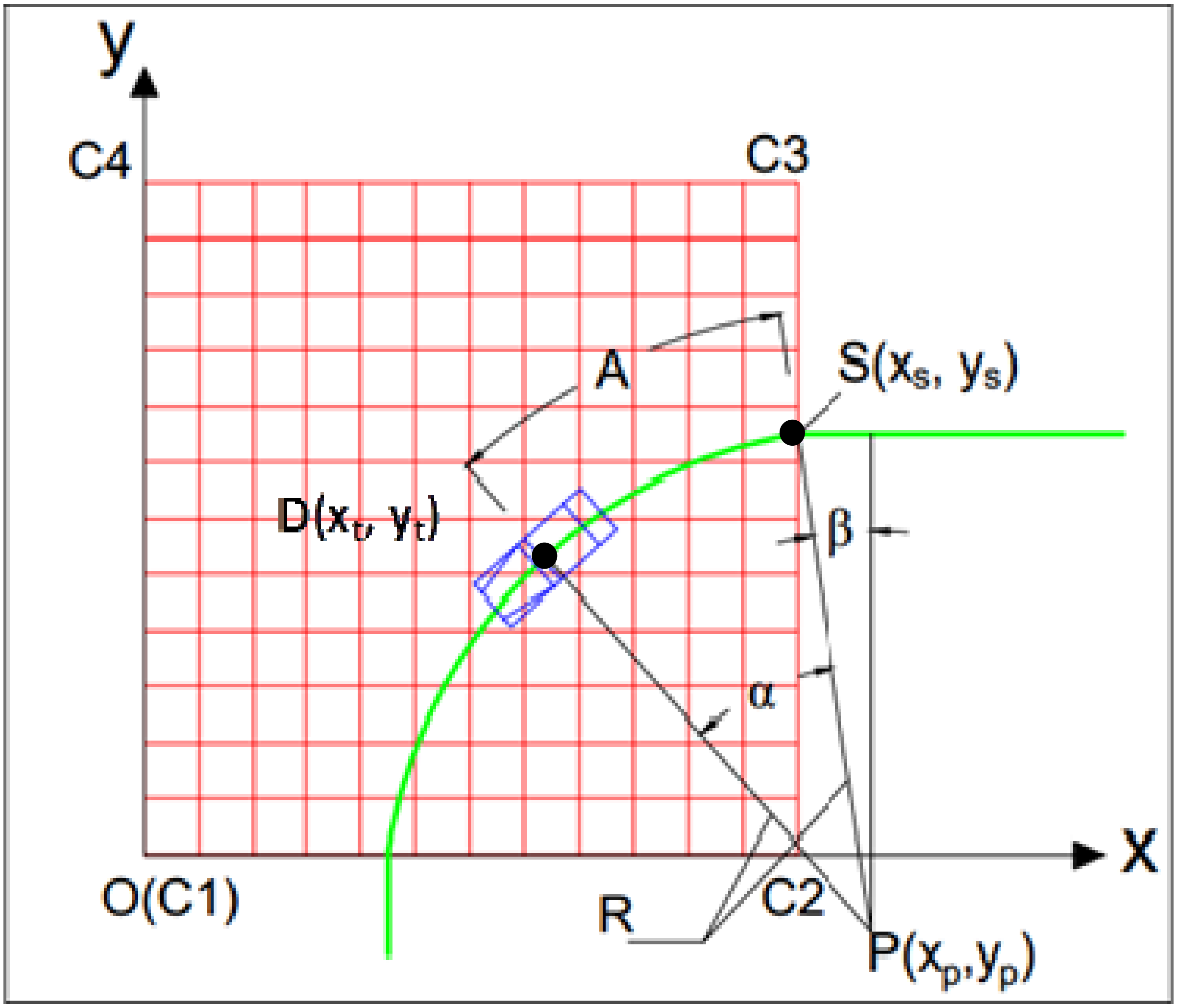

Figure 8: Determination of the central point location of a left-turn vehicle

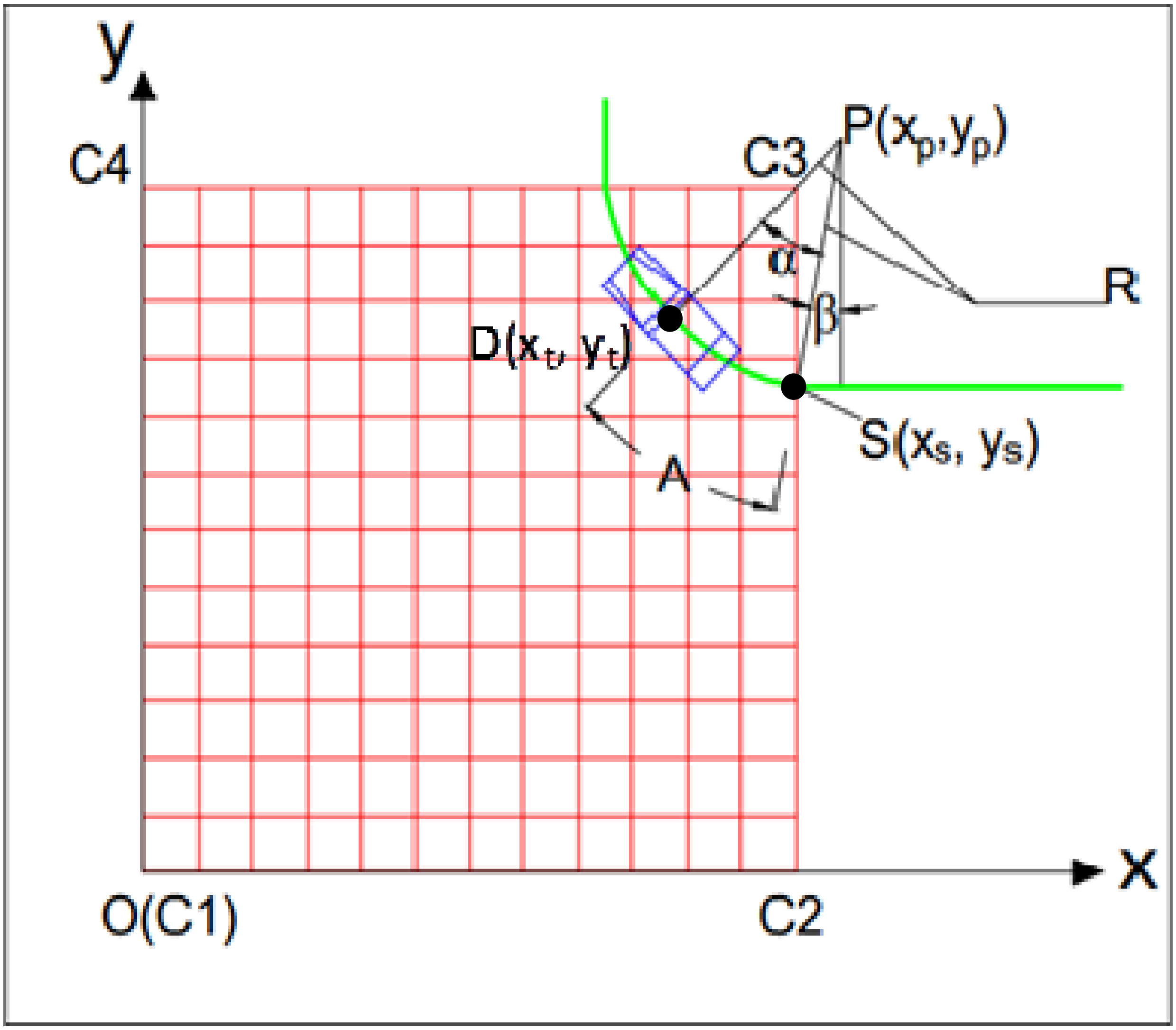

Figure 9: Determination of the central point location of a right-turn vehicle

For turning movements, the vehicle's path within the intersection can be modeled as arcs whose center coordinates are known (left turn shown in Figure 8 and right turn shown in Figure 9, with the arc centers denoted as P). Assuming that the left-turn vehicle's central point reaches the boundary point $S(x_s,y_s)$ at time 0, the coordinates of the vehicle's central point can be calculated using the following equation.

$$\begin{cases} x_t = x_p - R\times\sin(\alpha+\beta) \\ y_t = y_p + R\times\cos(\alpha+\beta) \end{cases} \quad (4)$$

where, x_t = x coordinate of the vehicle's central point at time t (ft);

y_t = y coordinate of the vehicle's central point at time t (ft);

x_p = x coordinate of the turning arc's center (ft);

y_p = y coordinate of the turning arc's center (ft);

R = $\sqrt{(x_p - x_s)^2 + (y_p - y_x)^2}$, the radius of the turning arc (ft);

α = A/R, radian;

β = $\arctan(\frac{|x_p - x_s|}{|y_p - y_s|})$ (radian);

x_s = x coordinate of the vehicle's central point at time *0* (ft);

y_s = y coordinate of the vehicle's central point at time *0* (ft);

A = $v \times t$, the arc length (ft);

v = speed of the vehicle when it is in the intersection (ft/s); and,

t = Any time when the vehicle's central point is within the intersection (s)

Similarly, assuming that the right-turn vehicle's central point reaches the boundary point $S(x_s,y_s)$ at time 0, the coordinates of the vehicle's central point can be calculated using the following equation.

$$\begin{cases} x_t = x_p - R \times \sin(\alpha + \beta) \\ y_t = y_p - R \times \cos(\alpha + \beta) \end{cases} \tag{5}$$

where, x_t = x coordinate of the vehicle's central point at time t (ft);

y_t = y coordinate of the vehicle's central point at time t (ft);

x_p = x coordinate of the turning arc's center (ft);

y_p = y coordinate of the turning arc's center (ft);

R = $\sqrt{(x_p - x_s)^2 + (y_p - y_x)^2}$, the radius of the turning arc (ft);

α = A/R (radian);

β = $\arctan(\frac{|x_p - x_s|}{|y_p - y_s|})$ (radian);

x_s = x coordinate of the vehicle's central point at time *0* (ft);

y_s = y coordinate of the vehicle's central point at time *0* (ft);

A = $v \times t$, the arc length (ft);

v = speed of the vehicle when it is in the intersection (ft/s); and,

t = any time when the vehicle's central point is within the intersection (s);

3.2.5 Calculating the Coordinates of Vehicle Vertices

Representing a vehicle with its central point is not adequate to describe the vehicle's location. A more comprehensive representation of a vehicle is by the coordinates of the vehicle's vertices. Figure 10 illustrates the vehicle's vertices in the intersection mesh. In Figure 10, the length of the rectangle is l_v and the width of the rectangle is w_v, equal to the corresponding vehicle's length and width, respectively. The vertices of the rectangle represent the four corners of the vehicle: head left (PT_{HL}), head right (PT_{HR}), tail left (PT_{TL}), and tail right (PT_{TR}). When the coordinates of the vehicle central point are known, they can be used to calculate the coordinates of the four vertices. When the vehicle is paralleled to either of the axes, the coordinates of the four vertices can be easily calculated using the central point coordinates by subtracting or adding an offset of $l_v/2$ or $w_v/2$. When a vehicle is in a position shown in Figure 10, more complex coordinate transformation is needed.

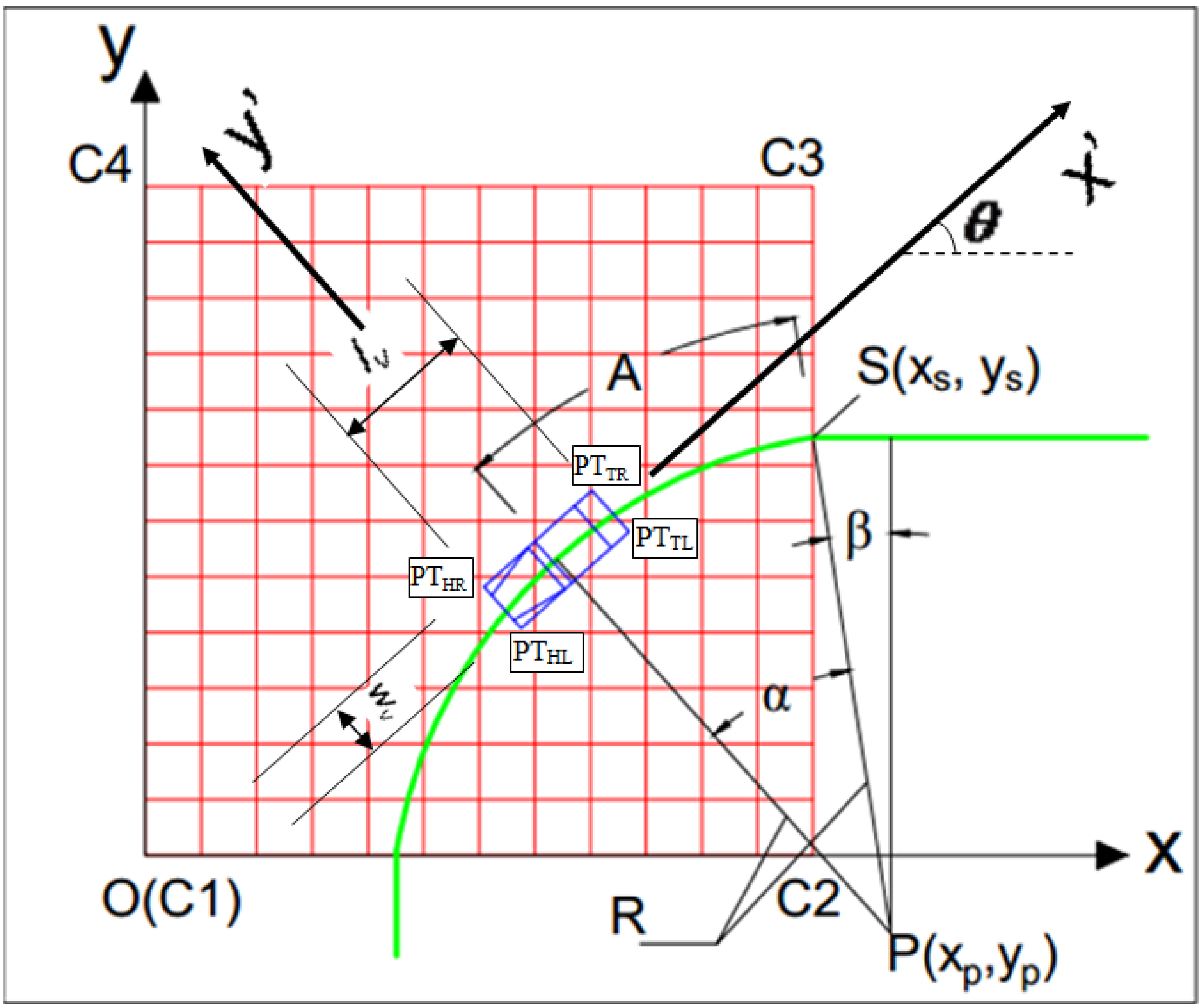

Figure 10: Determination of the coordinates of vehicle vertices

To conduct the coordinate transformation, a local coordinate system (in comparison with the global coordinate system defined in Figure 1) needs to be defined. The origin of the local coordinate system is located at the central point of the vehicle, with the x-axis pointing against the vehicle's traveling direction. To avoid confusion with the global coordinate system, an apostrophe is added to the notations of the local coordinate systems (e.g., *x'* and *y'* in Figure 10).

Given a point (x', y') in the local coordinate system, its coordinates in the global system (x, y) can be calculated using a coordinate rotation followed by a coordinate transfer. The formula is given below:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \times \begin{bmatrix} x' \\ y' \end{bmatrix} + \begin{bmatrix} x_t \\ y_t \end{bmatrix} \quad (6)$$

where, x_t = *x* coordinate of the vehicle's central point at time *t* (ft);

y_t = *y* coordinate of the vehicle's central point at time *t* (ft); and,

θ = the smallest angle measured counterclockwise from the x axis to the x' axis. In the case of Figure 1, $\theta = \alpha + \beta$ (radian).

Based on Equation 6, the global coordinates of the vehicle vertices can be easily converted from their local coordinates. For example, the local coordinates of the PT_{HR} vertex are (x' = $-l_v/2$, y' = $w_v/2$). By substituting x' and y' with $-l_v/2$ and $w_v/2$ in Equation 6, the global coordinates of PT_{HR} are ($x = -\frac{l_v \cdot \cos\theta + w_v \cdot \sin\theta}{2} + x_t$, $y = -\frac{l_v \cdot \sin\theta - w_v \cdot \cos\theta}{2} + y_t$).

3.2.6 Determining Tile Occupation

When the coordinates of a vehicle's vertices are known, the intersection manager needs to determine which tiles are occupied by the vehicle. Figure 11 depicts a vehicle with all occupied tiles highlighted in red. The criterion to determine whether a tile is occupied by a vehicle is: at least one vertex of the tile is inside the vehicle rectangle.

In the ACUTA system, a vector based method is used to decide whether a point falls in the vehicle rectangle. As shown in Figure 11, four vectors are defined counterclockwise along the vehicle rectangle. The four vectors are $\overline{v_1}$ (PT_{HR}→PT_{HL}), $\overline{v_2}$ (PT_{HL}→PT_{TL}), $\overline{v_3}$ (PT_{TL}→PT_{TR}), and $\overline{v_4}$ (PT_{TR}→PT_{HR}). A point is within the vehicle rectangle only if it falls to the left of all four vectors. Given a point $p(x_0, y_0)$ and a vector $\overline{v_i}$ [(x_{start}, y_{start}) → (x_{end}, y_{end})], *p* falls to the left of $\overline{v_i}$ only when the following formula is satisfied:

$$(x_0 - x_{start}) \times (y_{end} - y_0) - (x_{end} - x_0) \times (y_0 - y_{start}) < 0 \quad (7)$$

where, x_0 = *x* coordinate of the testing point (ft);

y_0 = *y* coordinate of the testing point (ft);

x_{start} = x coordinate of the vector's start point (ft);

y_{start} = y coordinate of the vector's start point (ft);

x_{end} = x coordinate of the vector's end point (ft); and,

y_{end} = y coordinate of the vector's end point (ft);

On the other hand, deciding whether a vertex of the vehicle rectangle falls in a tile is relatively easy. The reason is that a tile is bounded by two horizontal lines and two vertical lines. More specifically, any point within the area of a tile can be formulated as:

$$\begin{cases} x_{low} < x_0 < x_{high} \\ y_{low} < y_0 < y_{high} \end{cases} \tag{8}$$

where, x_0 = x coordinate of the testing point (ft);

y_0 = y coordinate of the testing point (ft);

x_{low} = shared x coordinate of left vertices of the tile (ft);

y_{low} = shared y coordinate of bottom vertices of the tile (ft);

x_{high} = shared x coordinate of right vertices of the tile (ft); and,

y_{high} = shared y coordinate of top vertices of the tile (ft);

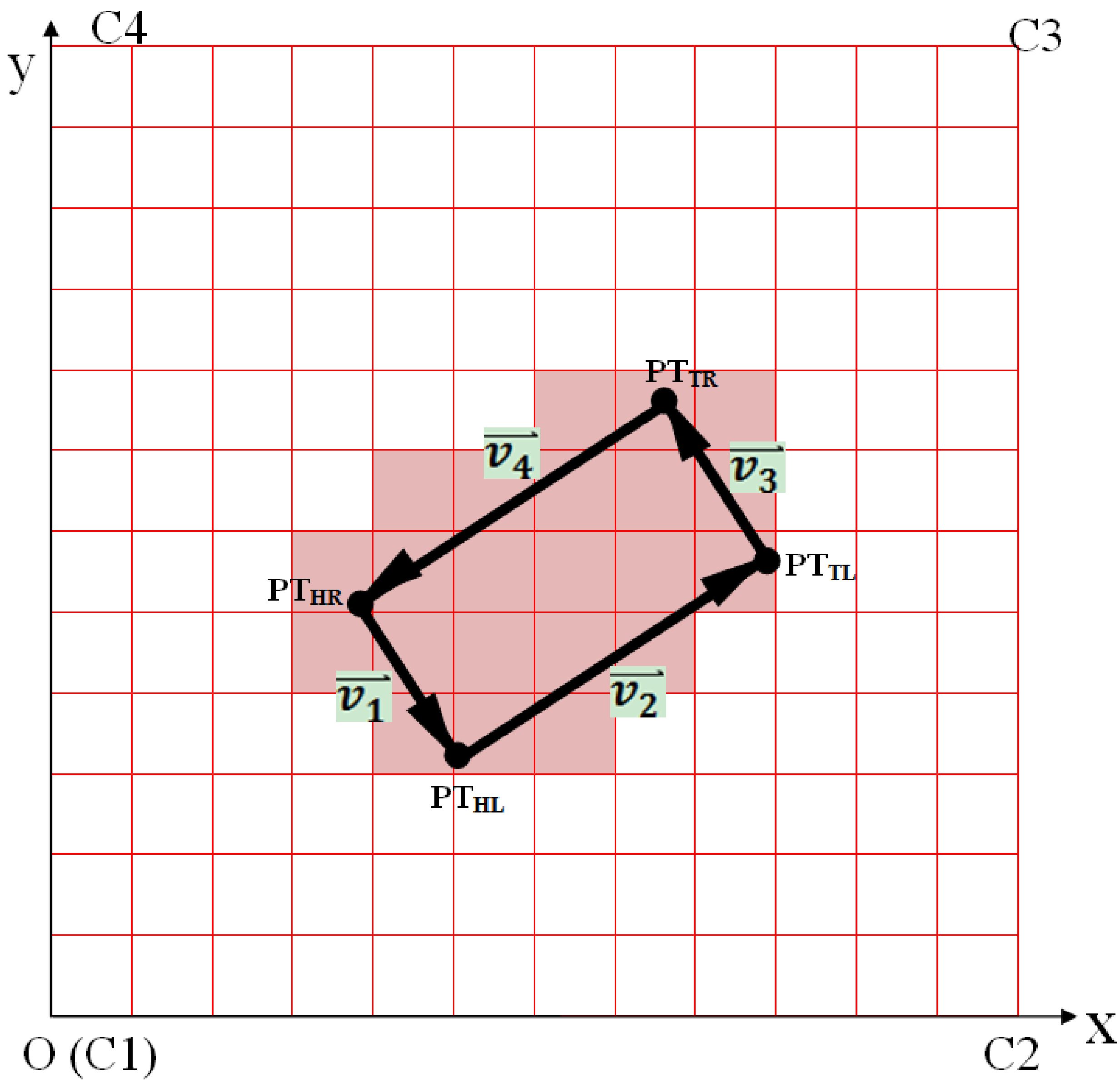

Figure 11: Tile occupation by a vehicle rectangle

In summary, given a tile and a vehicle rectangle, Equations 7 and 8 are used to judge whether the vehicle rectangle has occupied the tile. If any of the four vertices of the tile satisfies Equation 7 or if any of the four vertices of the vehicle rectangle satisfies Equation 8, the tile is considered occupied by the vehicle.

CHAPTER 4: PERFORMANCE EVALUATIONS

This chapter summarizes the results of the analyses that were conducted to evaluate the enhancement strategies and the operational performance of the ACUTA compared with traditional signal control and four-way stop control. Numerically, the operational performance was assessed by delay. In most evaluations, the delay was reflected by overall delay of the entire intersection. In some cases, the delay was distinguished between left-turn (LT), right-turn (RT), and through (Thru) vehicles. All the experiments discussed in this chapter were performed using five simulation runs with different random seeds. Each simulation run lasted 2,100 seconds (i.e, 35 minutes), and the first 300 warm-up seconds were dropped from the evaluation.

4.1 Evaluation of the Effectiveness of Operational Enhancement Strategies

In this section, effectiveness of the three operational enhancement strategies introduced in Section 3.1.2 was examined by performing simulation experiments. Specifically, the three strategies that were evaluated were: Advance Stop Location (ASL), Non-Deceleration Zone (NDZ), and Priority Reservation (PR) for Queuing Vehicles.

Evaluation of each enhancement strategy was realized through simulation experiments. Each experiment included a benchmark analysis and an evaluation analysis. In the benchmark analysis, the operational performance of the ACUTA system without applying the specific enhancement strategy was recorded. In the evaluation analysis, the specific enhancement strategy was applied, and the ACUTA system's performance was recorded. Figures 12 through 14 summarize the impact on the delay by enabling the ASL, NDZ, and PR, respectively. The simulations experiments for evaluating the ASL and NDZ were performed under a traffic demand of 550 veh/hr/ln. This traffic demand is considered a high demand based on engineering experience, because it usually results in a level of service E or F for typical signalized intersections. In these experiments, the ACUTA parameters of granularity, communication range, number of internal simulations and MINSAFSR were set as 24, 600 ft, 10, and 30 mph, respectively.

Figure 12 compares the intersection delays under two scenarios: (1) ASL disabled, and (2) ASL enabled and set as 35 ft from the intersection. For both scenarios, the NDZ was enabled with the EBNDZ set as 200 ft from the intersection, and the PR was enabled as well, with the MSQV and MINQL set as 0 mph and 3 veh, respectively. The results indicated that by enabling the ASL, the intersection delay was substantially reduced by approximately 95 s/veh, which reflects a 95% reduction in the overall intersection delay.

Figure 13 illustrates the comparison between the scenarios in which the NDZ was disabled and enabled. When the NDZ was enabled, the EBNDZ was set as 200 ft from the intersection. For both scenarios, the ASL was enabled and set as 35 ft from the intersection, and the PR was enabled as well, with the MSQV and MINQL set as 0 mph and 3 veh, respectively. The results show that the use of the NDZ resulted in a substantial 50 – 55 s/veh reduction in the overall intersection delay, which is reflective of a higher than 90% reduction.

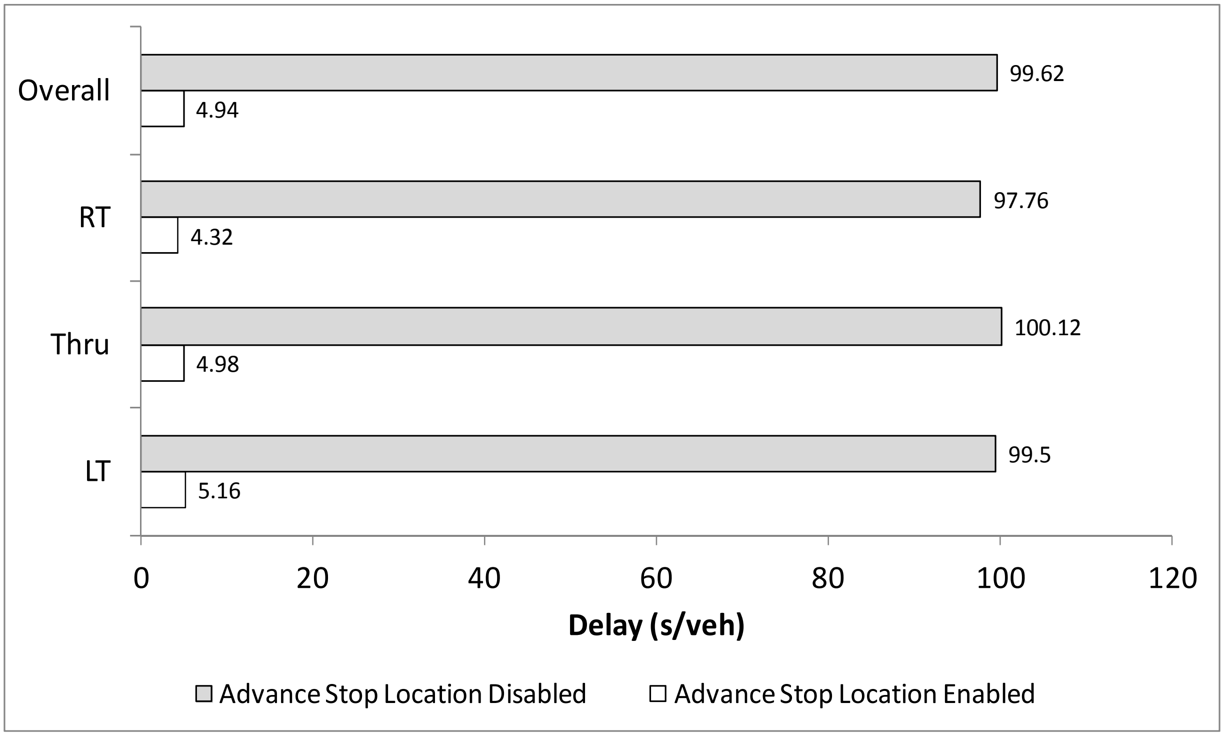

Figure 12: Evaluation of the effectiveness of advance stop location (ASL)

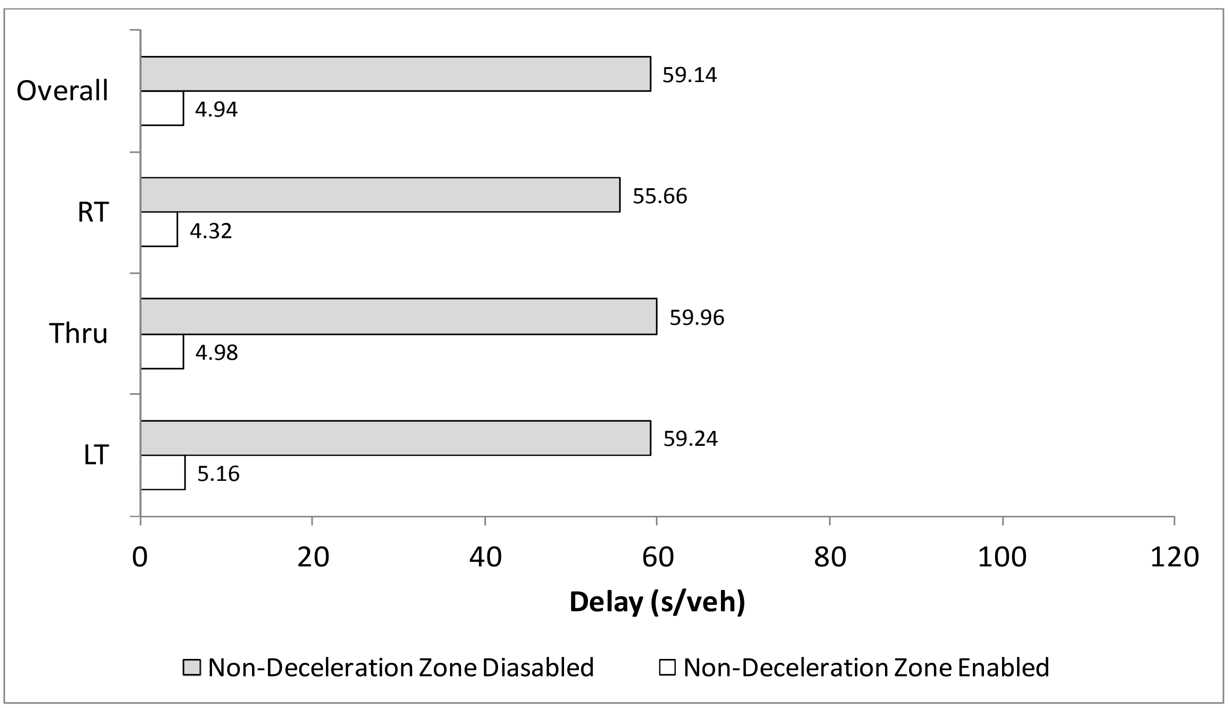

Figure 13: Evaluation of the effectiveness of non-deceleration zone (NDZ)

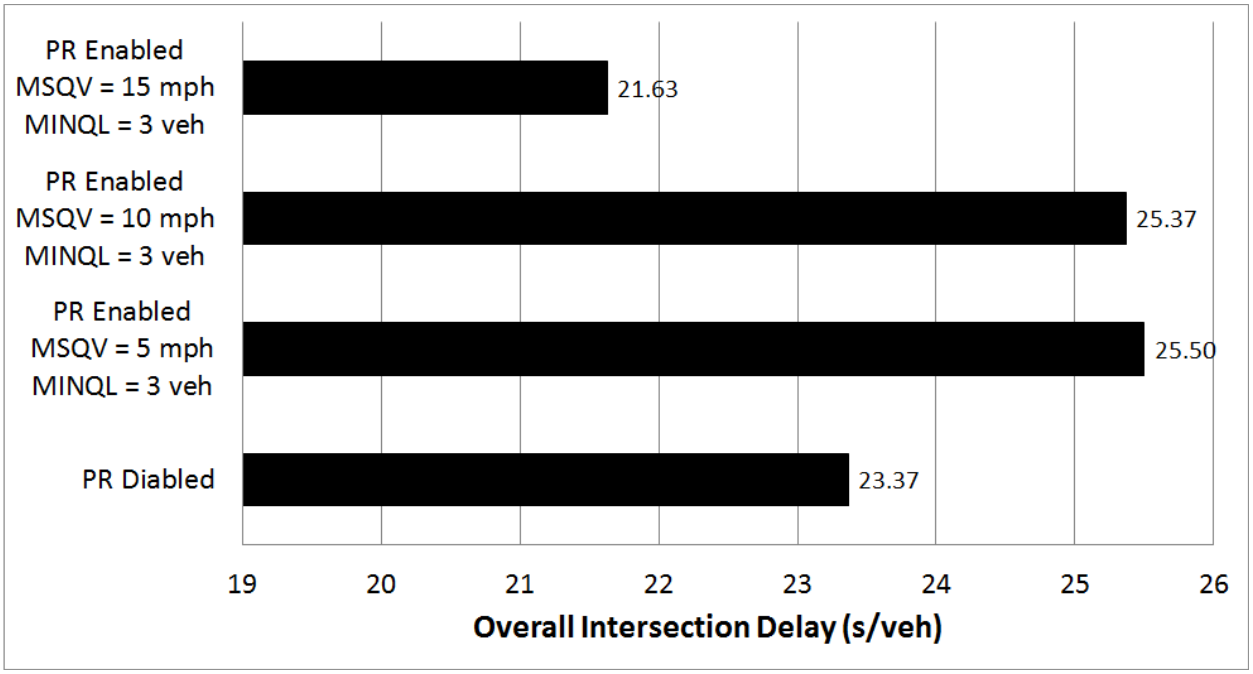

Figure 14: Evaluation of the effectiveness of priority reservation (PR)

Figure 14 shows the evaluation of the effectiveness of the PR. Four scenarios were tested in the evaluation experiments under a near capacity traffic demand of 600 veh/hr/ln. The 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.

First scenario was the benchmark scenario in which the PR was disabled. In the second, third, and fourth scenarios, the PR was enabled with the MSQV set as 5 mph, 10 mph, and 15 mph, respectively, and the MINQL set as 3 veh. The results presented in Figure 14 indicate that when the MSQV was below 15 mph, enabling the PR resulted in no improvement in the intersection delay; instead, intersection delay increased by about 2 s/veh. When the MSQV was set to 15 mph, the reduction in the intersection delay compared to the benchmark scenario was around 2 s/veh, which reflects a 7% reduction in delay. In summary, the PR can reduce the delay only when the MSQV is set to a large number 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.

4.2 Evaluation of the Operational Performance of Multi-Tile ACUTA System

Granularity of the intersection mesh is one of the most important parameters in the ACUTA system. 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 system. When the granularity is greater than one, the system is termed as Multi-Tile ACUTA system.

In this section, the operational performance of the Multi-Tile ACUTA system under various traffic demand conditions was evaluated. The evaluation results were summarized and compared with the performance of a comparable signalized intersection after signal timing optimization. In the evaluation, the experiment testing each traffic demand condition included five simulation runs with different random seeds. In an experiment, the demand volumes for all the approaches were the same. The demand volumes varied from 50 veh/hr/ln to 950 veh/hr/ln in order to cover the possible range of real-world traffic demand. In all the experiments, the ACUTA parameters of granularity, communication range, number of internal simulations, MINSAFSR, ASL, EBNDZ, MSQV, MINQL were set as 24, 600 ft, 10, 30 mph, 35 ft, 200 ft, 0 mph, and 3 veh, respectively. The signal timing plans were optimized using the Highway Capacity Software 2000 (HCM2000) based on the various traffic demands and the phasing plans that implement the leading left turns.

The evaluation results are summarized in Table 1, with comparison with the corresponding results for the optimized signalized intersection. Figures 15 through 18 graphically illustrate the impact of the traffic demand on the left-turn delay, the right-turn delay, the through delay, and the overall intersection delay, respectively.

Table 1: Delays for the Multi-Tile ACUTA System with Comparison with the Optimized Signalized Intersection

	Optimized Signalized Control				**Multi-tile ACUTA**			
	Delay (s/veh)				**Delay (s/veh)**			
Traffic Demand (veh/hr/ln)	*LT*	*Thru*	*RT*	*Overall*	*LT*	*Thru*	*RT*	*Overall*
50	7.36	15.54	17.06	13.70	0.00	0.00	0.00	0.00
100	9.26	15.90	17.26	14.34	0.00	0.00	0.00	0.00
200	13.12	17.72	20.74	16.90	0.00	0.00	0.00	0.00
300	21.52	19.74	22.48	20.62	0.04	0.04	0.06	0.02
350	36.24	21.04	24.38	25.48	0.26	0.42	0.44	0.38
400	53.62	28.70	32.56	35.66	0.98	0.70	0.76	0.78
450	118.72	35.82	38.68	56.86	1.46	1.48	1.64	1.50
500	186.70	53.02	56.64	85.44	2.82	2.30	2.14	2.42
550	230.04	81.46	84.82	117.90	5.16	4.98	4.32	4.94
600	278.72	133.74	137.08	169.42	25.70	24.78	24.12	24.90
650	298.04	161.54	162.30	194.98	97.00	100.20	97.86	99.04
700	331.78	182.34	184.22	218.32	102.20	104.04	102.52	103.34
800	336.26	206.02	204.48	237.88	198.72	205.50	200.64	203.06
950	355.66	211.78	213.28	247.86	227.24	231.28	226.52	229.58

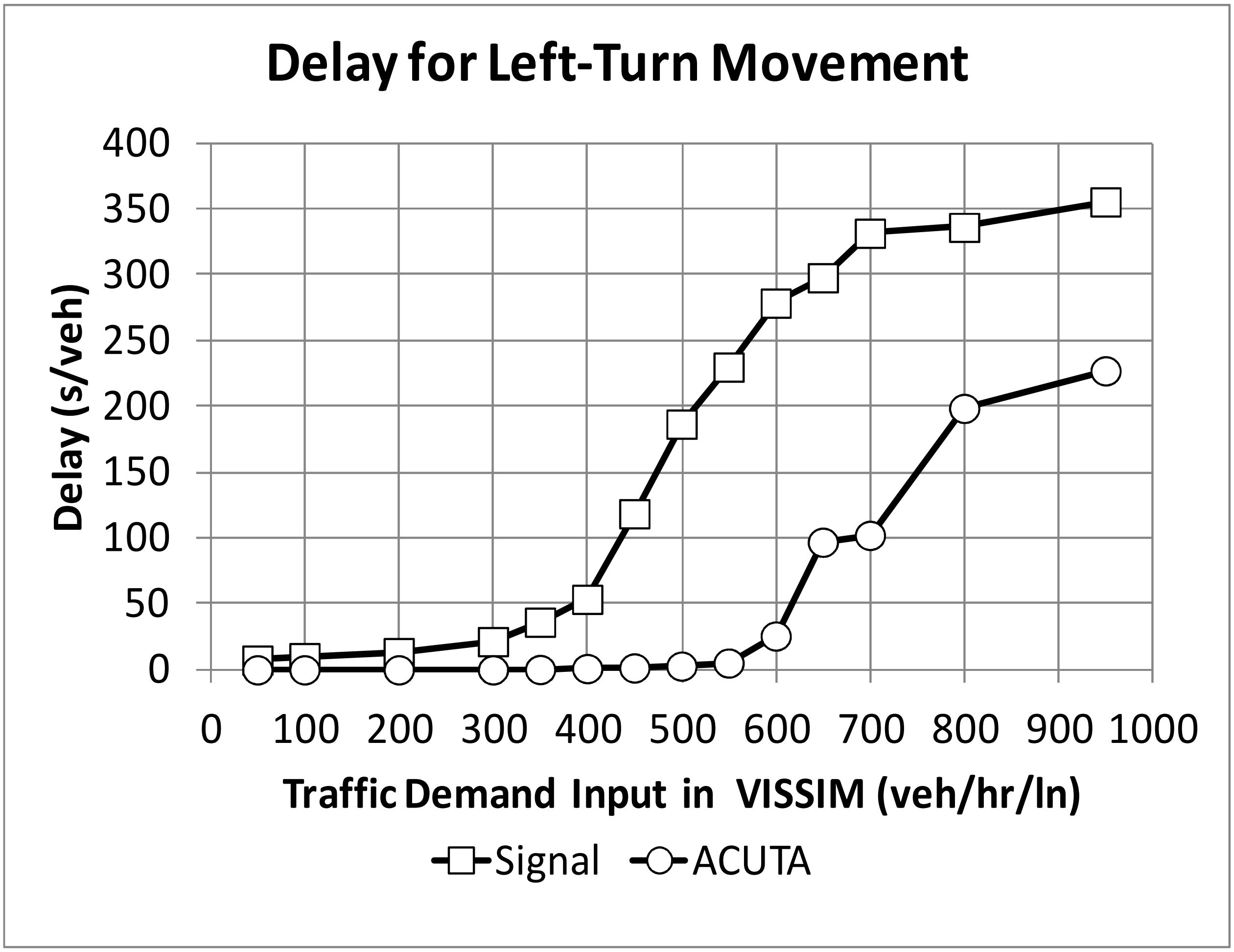

Figure 15: Average delay for left-turn movements under various traffic demand conditions (Multi-tile ACUTA vs. Optimized Signal Control)

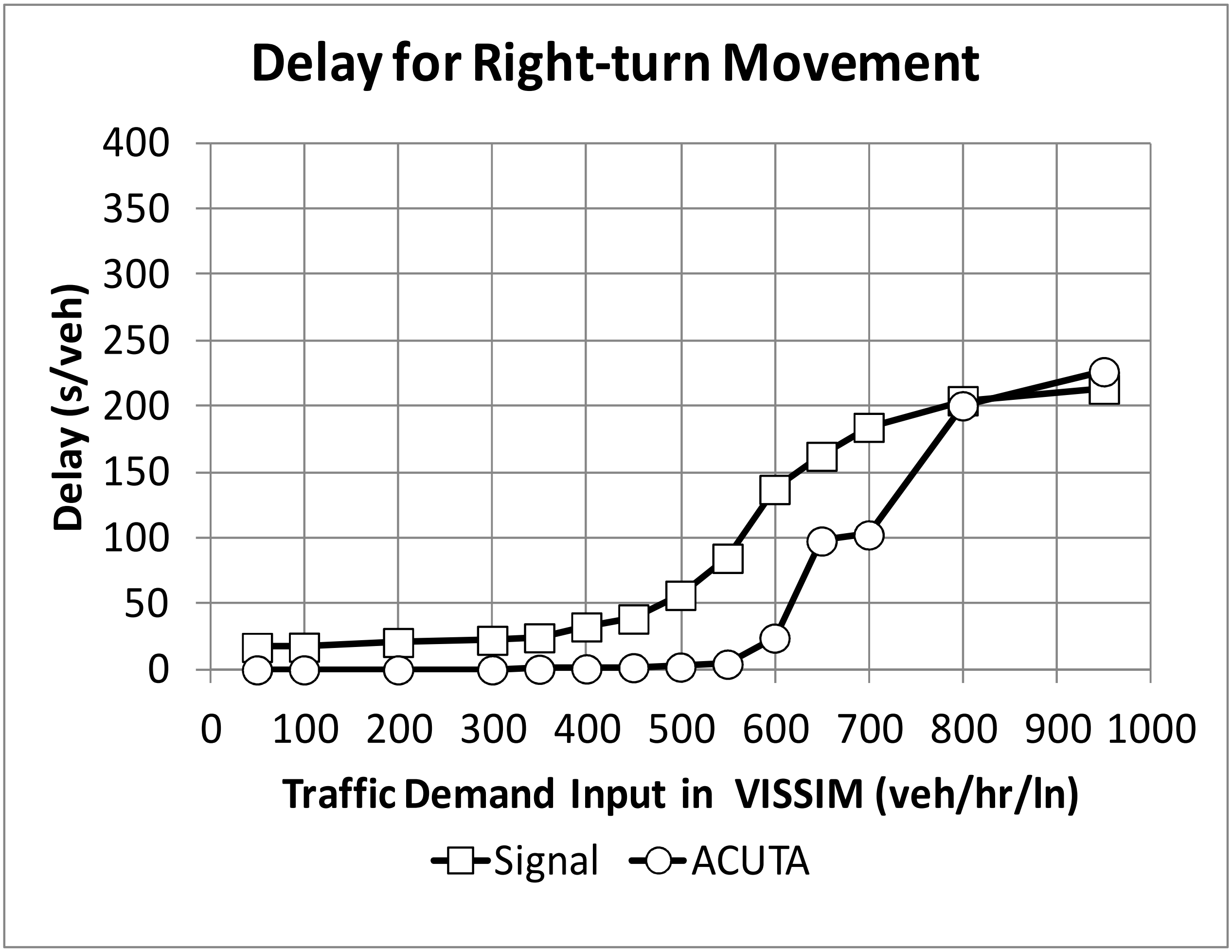

Figure 16: Average delay for right-turn movements under various traffic demand conditions (Multi-tile ACUTA vs. Optimized Signal Control)

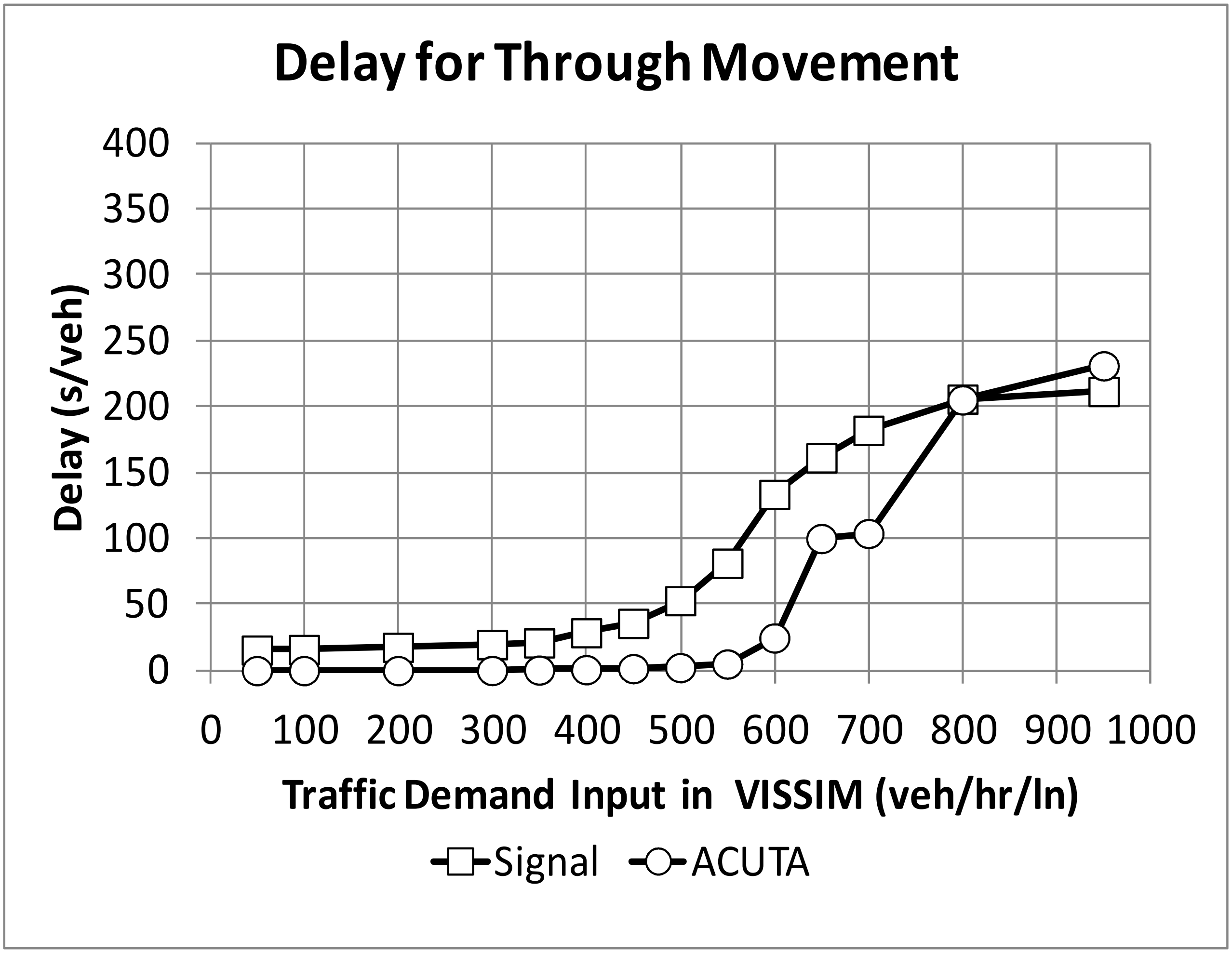

Figure 17: Average delay for through movements under various traffic demand conditions (Multi-tile ACUTA vs. Optimized Signal Control)

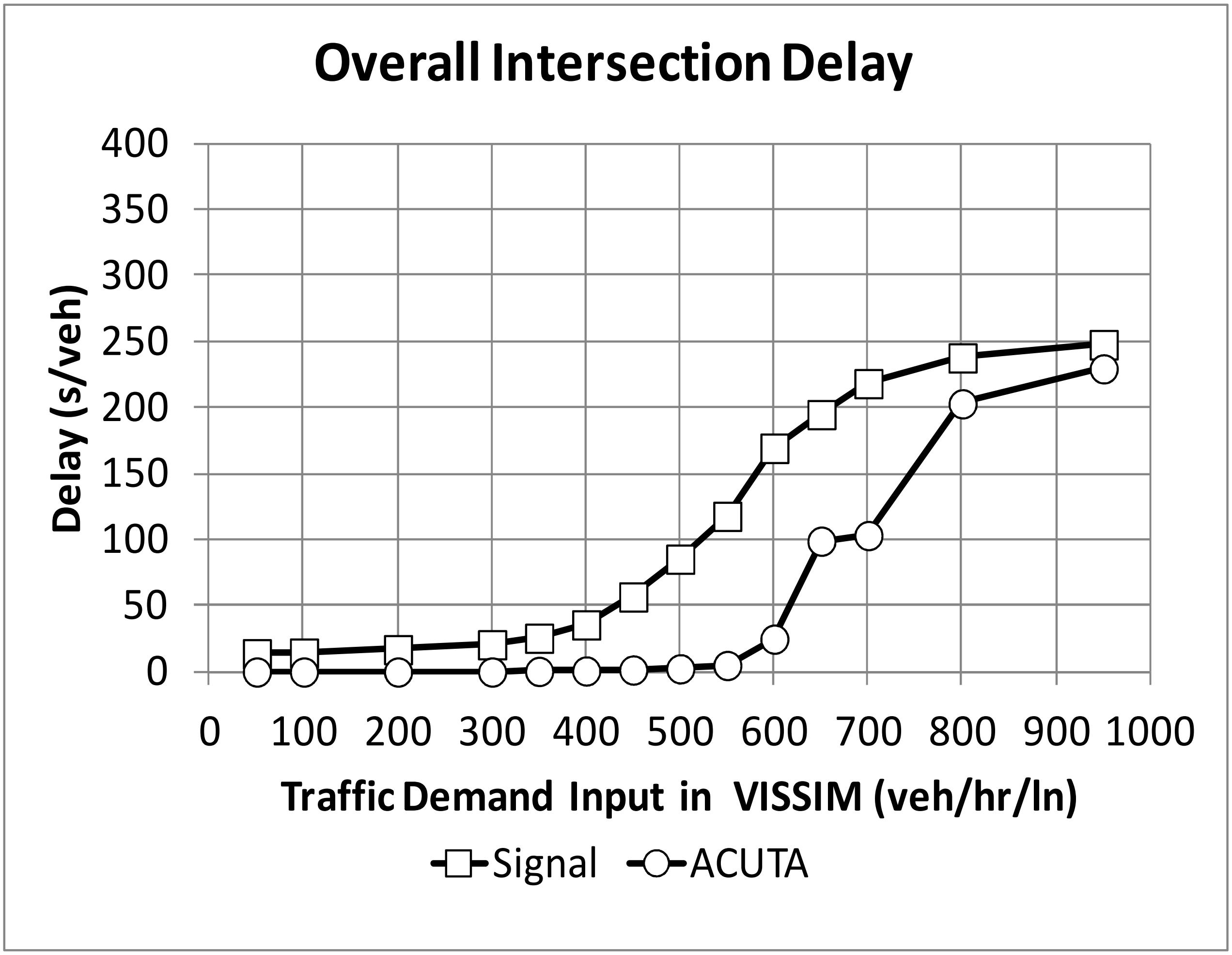

Figure 18: Overall intersection delay for all movements under various traffic demand conditions (Multi-tile ACUTA vs. Optimized Signal Control)

These figures indicate that the operational performance of the different traffic movements in the ACUTA system was very balanced as the delays for the left-turn, right-turn, and through movements were observed to be similar under any specific traffic demand conditions. On the other hand, the signalized intersection had unbalanced operational performance because the left turn movements experienced substantially longer delays than the through and right-turn movements.

The overall intersection delay shown in Figure 18 was calculated by taking the weighted average of the delays for all the movements. According to Figure 18, the overall intersection delay for the ACUTA system remained at an extremely low level (under 5 s/veh) when the traffic demand was less than 550 veh/hr/ln, while the signalized intersection already started to operate at near capacity conditions when the traffic demand reached 450 veh/hr/ln. The delay for the ACUTA system started to increase rapidly when the traffic demand reached 600 veh/hr/ln. According to Figure 18, the x coordinate of the deflection point for the ACUTA curve is located approximately at the traffic demand of 625 veh/hr/ln, which indicates that the capacity for the ACUTA system is approximately 625 veh/hr/ln. Although the ACUTA system did not perform well when the traffic demand was greater than 600 veh/hr/ln, the delays were still half of the delays for the signalized intersection for the traffic demands of 650 and 700 veh/hr/ln. The superiority of the ACUTA system became marginal at the extremely high traffic demands of 800 and 950 veh/hr/ln.

4.3 Evaluation of the Operational Performance of Single-Tile ACUTA System

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. The major difference between these two control strategies is that the vehicles in the ACUTA system do not necessarily need to stop before their entry into the intersection. However, at a four-way stop intersection, whoever stops at the stop line first gets the right of way. For comparison purposes, a four-way stop intersection was modeled in VISSIM to compare with the single-tile ACUTA system in terms of the operational performance. This comparison aimed at exploring the possibility of replacing the stop controlled intersection with the single-tile ACUTA in order to accommodate autonomous vehicles in future.

In this section, the operational performance of the single-tile ACUTA system under various traffic demand conditions was evaluated, and the evaluation results were summarized and compared with the performance of the four-way stop intersection. The simulation experiment for each traffic demand condition included five simulation runs with different random seeds. In an experiment, the demand volumes for all the approaches were the same. The tested traffic demands ranged from low volumes to extreme high volumes including 50, 100, 200, 400, and 950 veh/hr/ln. In all the experiments, the ACUTA parameters of granularity, communication range, number of internal simulations, MINSAFSR, ASL, EBNDZ, MSQV, MINQL were set as 1, 600 ft, 10, 30 mph, 35 ft, 200 ft, 0 mph, and 3 veh, respectively.

The evaluation results are summarized in Table 2 with comparison to the corresponding results obtained from the four-way stop intersection. Figures 19 through 22 graphically illustrate the impact of the traffic demand on the left-turn delay, right-turn delay, through delay, and the overall intersection delay, respectively.

Table 2: Delays for the Single-Tile ACUTA System with Comparison with the Four-way Stop Intersection

Traffic Demand (veh/hr/ln)	Four-Way Stop Control Delay (s/veh)				Single-Tile ACUTA Delay (s/veh)			
	LT	*Thru*	*RT*	*Overall*	*LT*	*Thru*	*RT*	*Overall*
50	40.54	34.62	41.80	37.22	0.00	0.00	0.00	0.00
100	110.44	96.30	114.48	103.00	27.88	28.32	20.92	27.16
200	449.50	545.16	567.22	520.02	477.50	397.40	351.50	410.80
400	783.56	820.18	866.56	816.32	680.50	668.80	675.80	673.20
950	964.48	978.48	1034.90	981.98	949.30	965.80	982.40	964.00

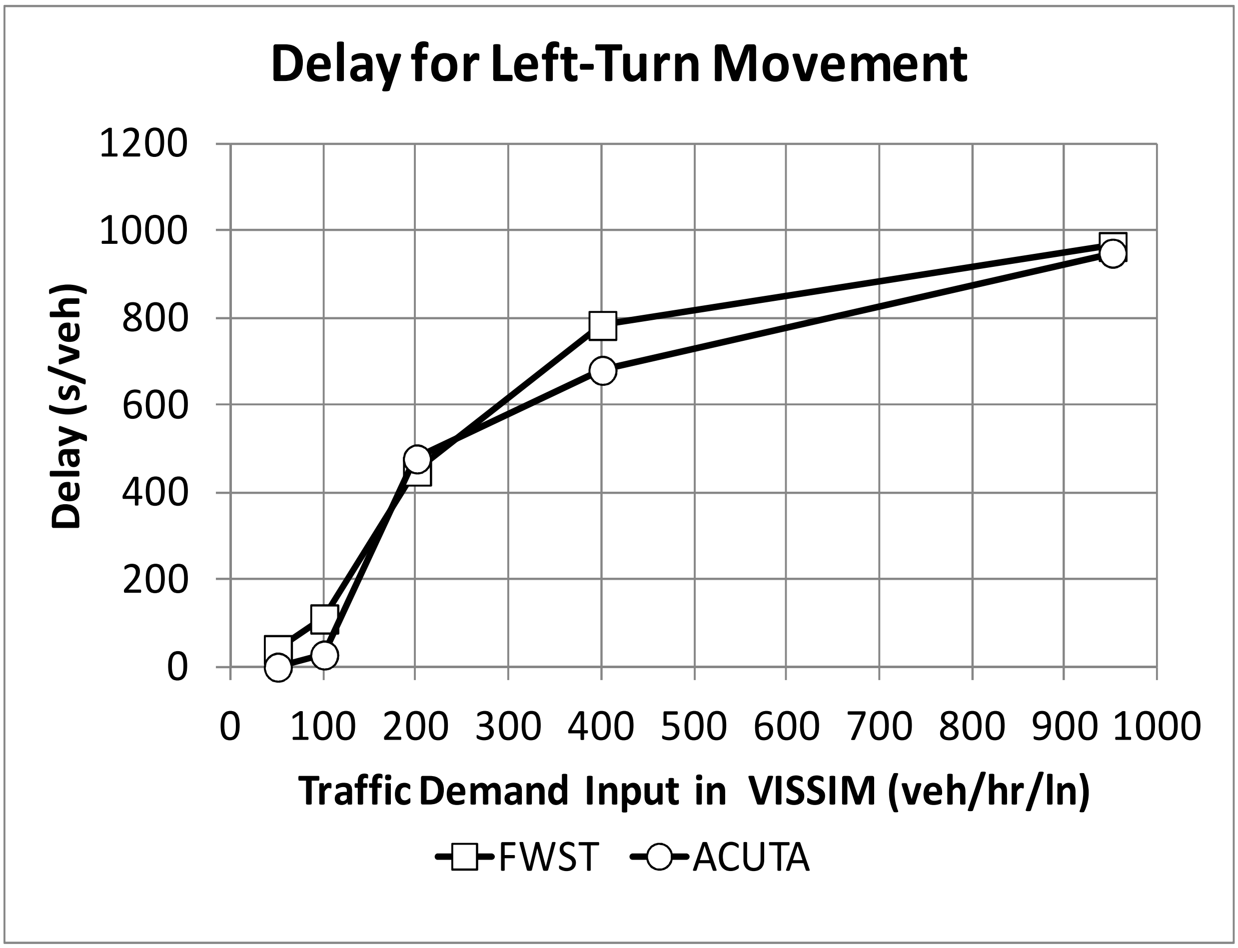

Figure 19: Average delay for left-turn movements under various traffic demand conditions (Single-tile ACUTA vs. Four-way Stop Control)

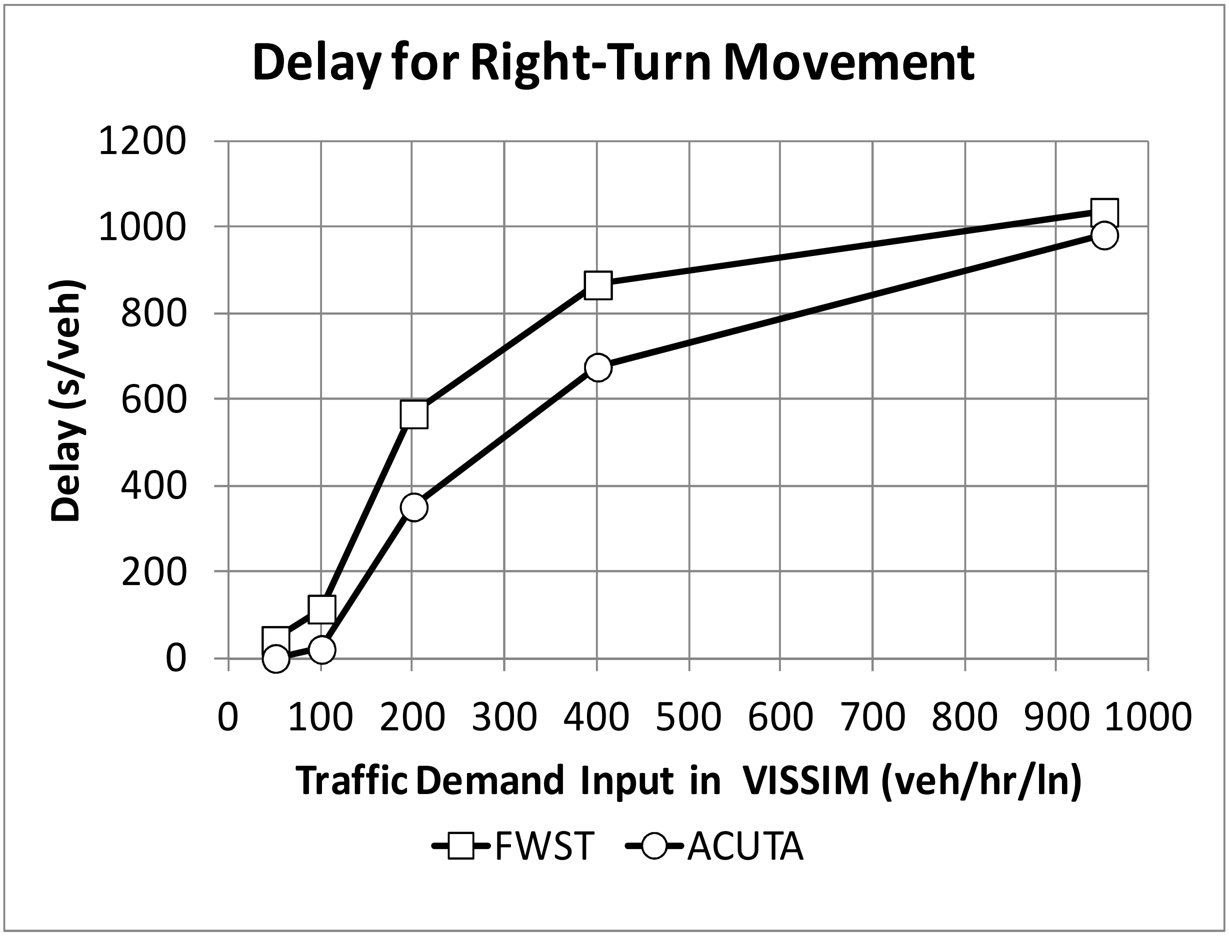

Figure 20: Average delay for right-turn movements under various traffic demand conditions (Single-tile ACUTA vs. Four-way Stop Control)

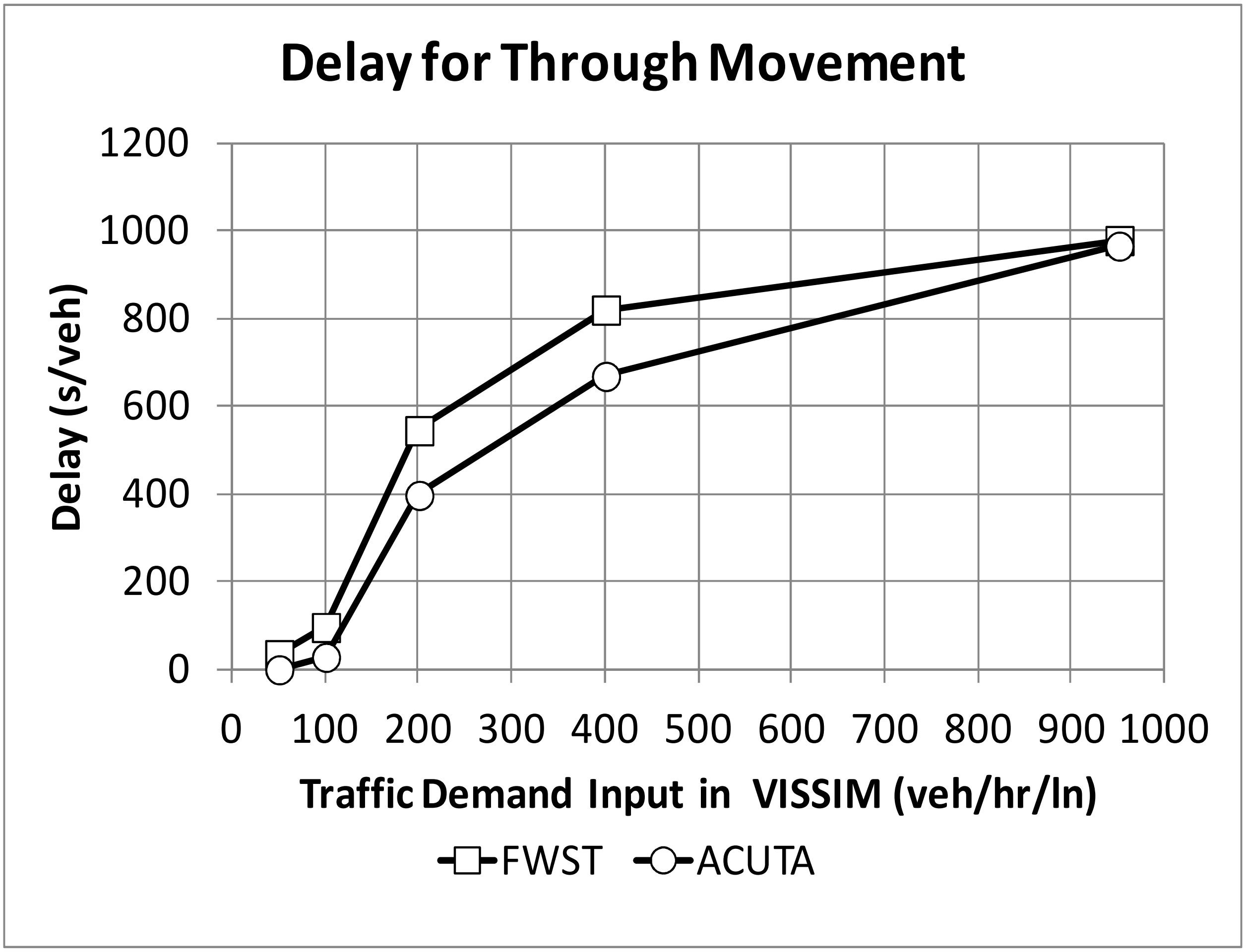

Figure 21: Average delay for through movements under various traffic demand conditions (Single-tile ACUTA vs. Four-way Stop Control)

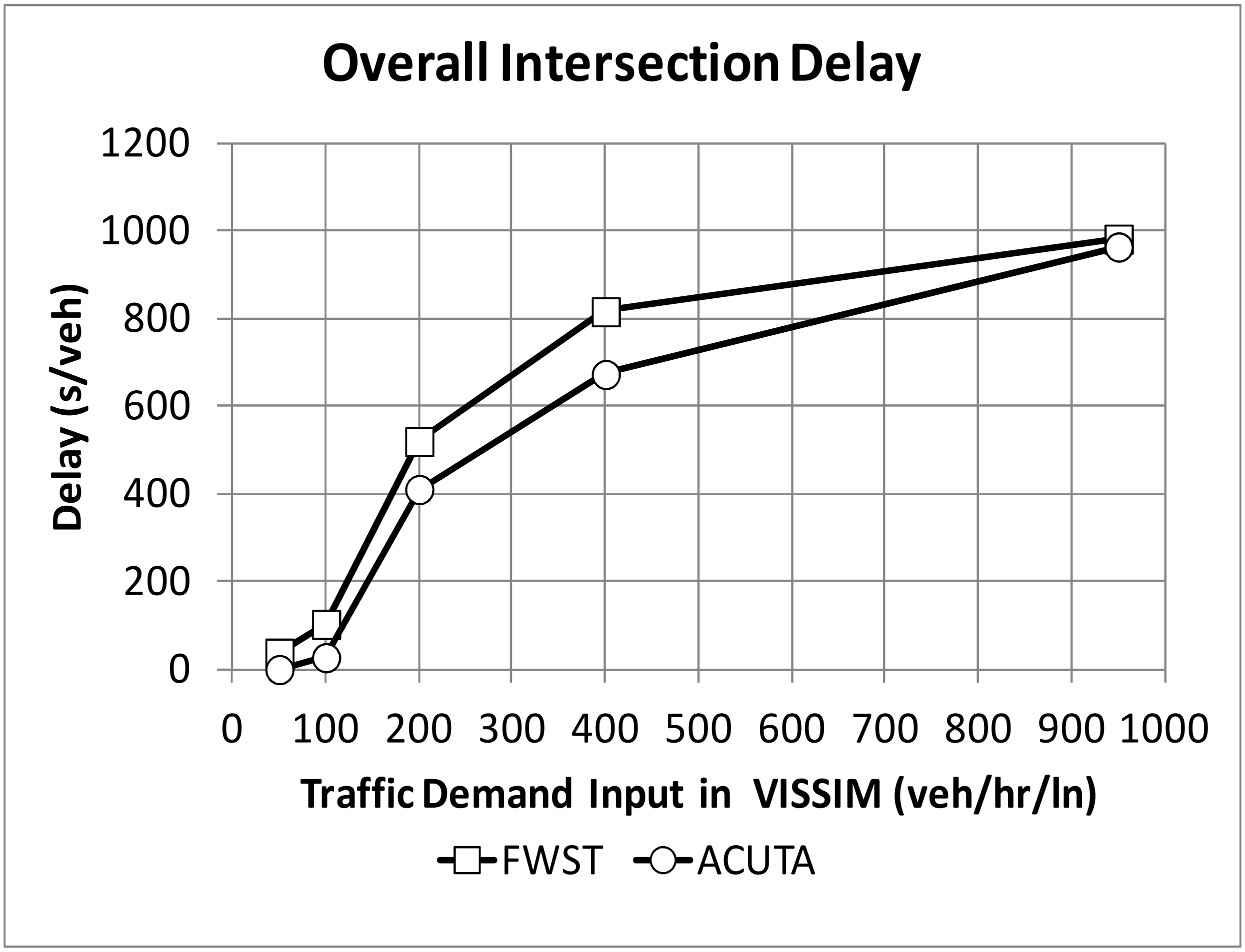

Figure 22: Overall intersection delay for all movements under various traffic demand conditions (Single-tile ACUTA vs. Four-way Stop Control)

According to Figures 19 through 21, delays for both the single-tile ACUTA system and the four-way stop intersection increased as the traffic demand increased. Both the single-tile ACUTA and the four-way stop control operated in a balanced manner for different movements, as all the movements had similar patterns and magnitudes of delay.

Figure 22 illustrates the distribution of the overall intersection delay at various traffic demands. Figure 23 indicates that the single-tile ACUTA operated extremely well with a zero delay under the traffic demand of 50 veh/hr/ln, outperforming the four-way stop control by 37.22 s/veh. The single-tile ACUTA still worked decently under the traffic demand of 100 veh/hr/ln with a moderate delay of 27.16 s/veh, while the four-way stop control already reached its capacity with a long delay of 103 s/veh. As the traffic demand exceeded 100 veh/hr/ln, the delays started to increase dramatically for both the stop control and the ACUTA. However, the delay curve of the single-tile ACUTA was always below the delay curve of the four-way stop control through the spectrum of the tested traffic demands, which suggested an overall better operational performance.

In summary, the single-tile ACUTA performed much more efficiently than the four-way stop control when traffic demand was lower than 100 veh/s. For traffic demands higher than 100 veh/s, the single-tile ACUTA performed worse than the four-way stop control. Therefore, for higher traffic demands, the multi-tile ACUTA is recommended to replace the single-tile ACUTA to efficiently accommodate more traffic.

4.4 Evaluation of the Performance of Multi-Tile ACUTA System under Unbalanced Traffic Demand Conditions

A previous study found the FCFS-based reservation-based system could have a "starvation" issue on the minor road when the traffic demands of the major and minor roads were unbalanced (*8*). In that case, the major road demand was much higher than the minor road demand. Therefore, it was difficult for the minor road vehicles to obtain reservations. They had to stop, causing a queue to form, which meant that minor road vehicles experienced a much longer delay than major road vehicles.

The section evaluates the operational performance of the ACUTA system under unbalanced traffic conditions. In the evaluation, the major road traffic demand always remained at 600 veh/hr/ln, while the minor road demand varied from 100 to 500 veh/hr/ln, thus creating the unbalanced traffic demand conditions. The experiment testing each unbalanced demand condition included five simulation runs with different random seeds. In all the experiments, the ACUTA parameters of granularity, communication range, number of internal simulations, MINSAFSR, ASL, EBNDZ, MSQV, MINQL were set as 24, 600 ft, 10, 30 mph, 35 ft, 200 ft, 0 mph, and 3 veh, respectively.

The evaluation results are summarized in Table 3. Figures 23 through 27 graphically illustrate the delays of different movements under the minor road demands of 100, 200, 300, 400, and 500 veh/hr/ln, respectively. Figure 28 shows the trends for the overall delays incurred by the major and minor road traffic versus the minor street demand.

Table 3: Delays for the Multi-Tile ACUTA System under Unbalanced Traffic Demand Conditions

Traffic Demand (veh/hr/ln)		**Major Road Delay (s/veh)**				**Minor Road Delay (s/veh)**			
Major Road	*Minor Road*	*LT*	*Thru*	*RT*	*Overall*	*LT*	*Thru*	*RT*	*Overall*
600	100	5.78	5.4	5.46	5.50	0.03	0	0.04	0.01
600	200	7.6	7.14	6.73	7.19	0.04	0	0.01	0.01
600	300	9.8	9.28	8.69	9.32	0.5	0.48	0.16	0.44
600	400	9.91	9.46	8.71	9.46	0.7	0.69	0.32	0.64
600	500	20.47	18.96	17.76	19.16	4.27	3.21	2.66	3.39

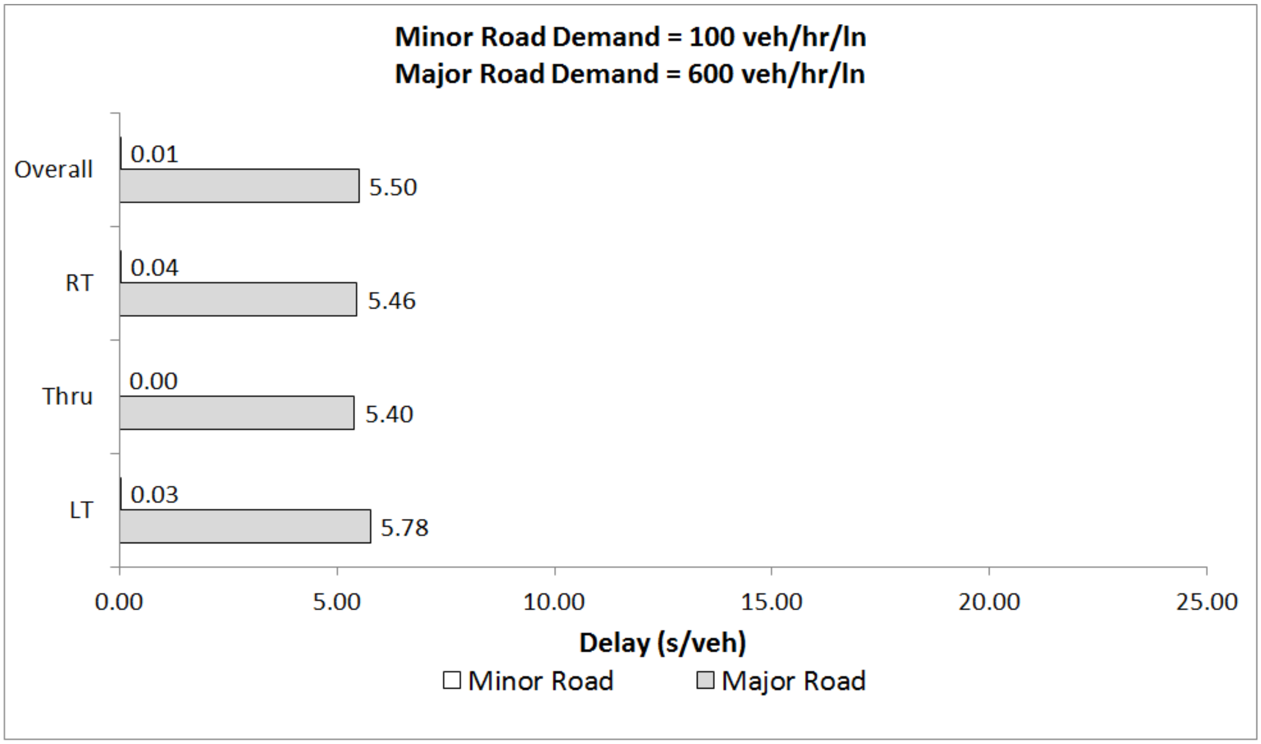

Figure 23: Delays of the ACUTA system under unbalanced traffic conditions (minor road demand = 100 veh/hr/ln)

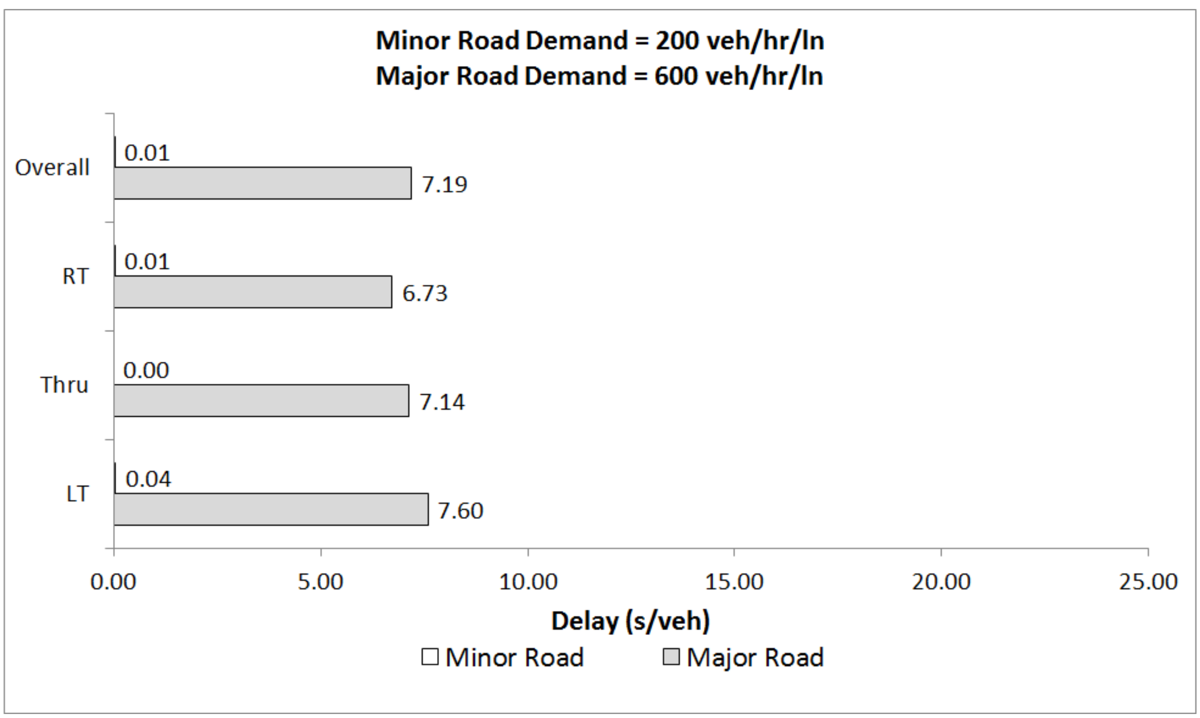

Figure 24: Delays of the ACUTA system under unbalanced traffic conditions (minor road demand = 200 veh/hr/ln)

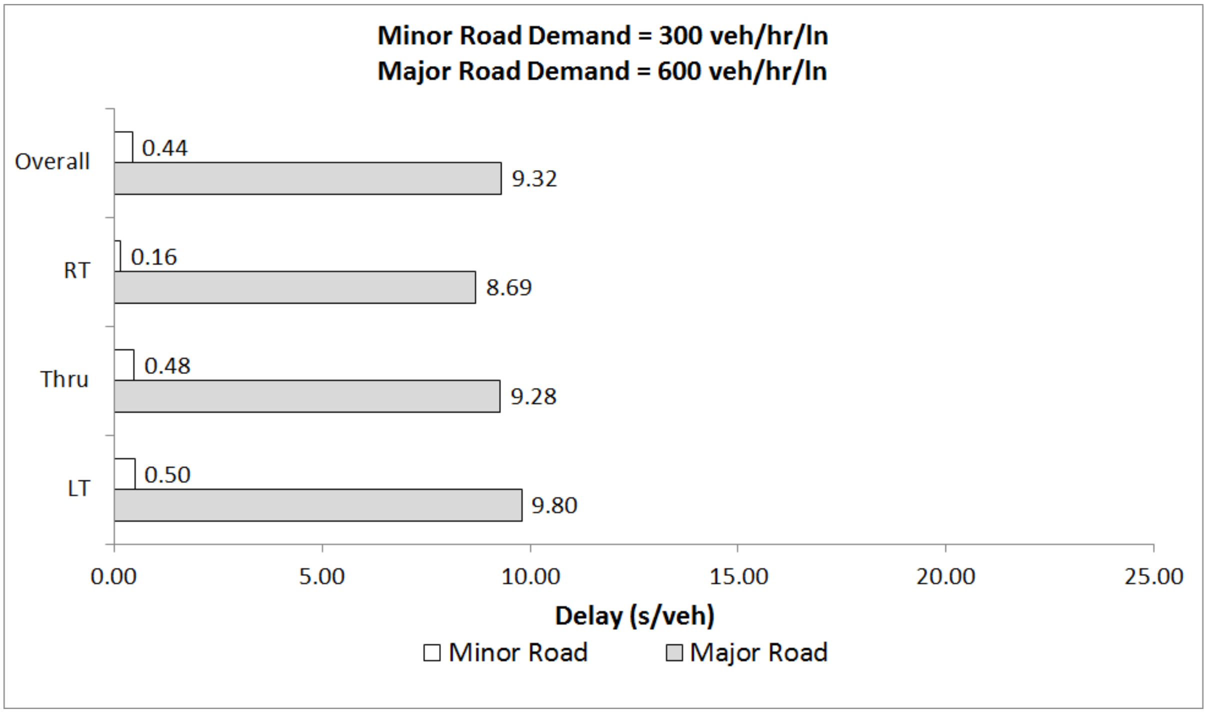

Figure 25: Delays of the ACUTA system under unbalanced traffic conditions (minor road demand = 300 veh/hr/ln)

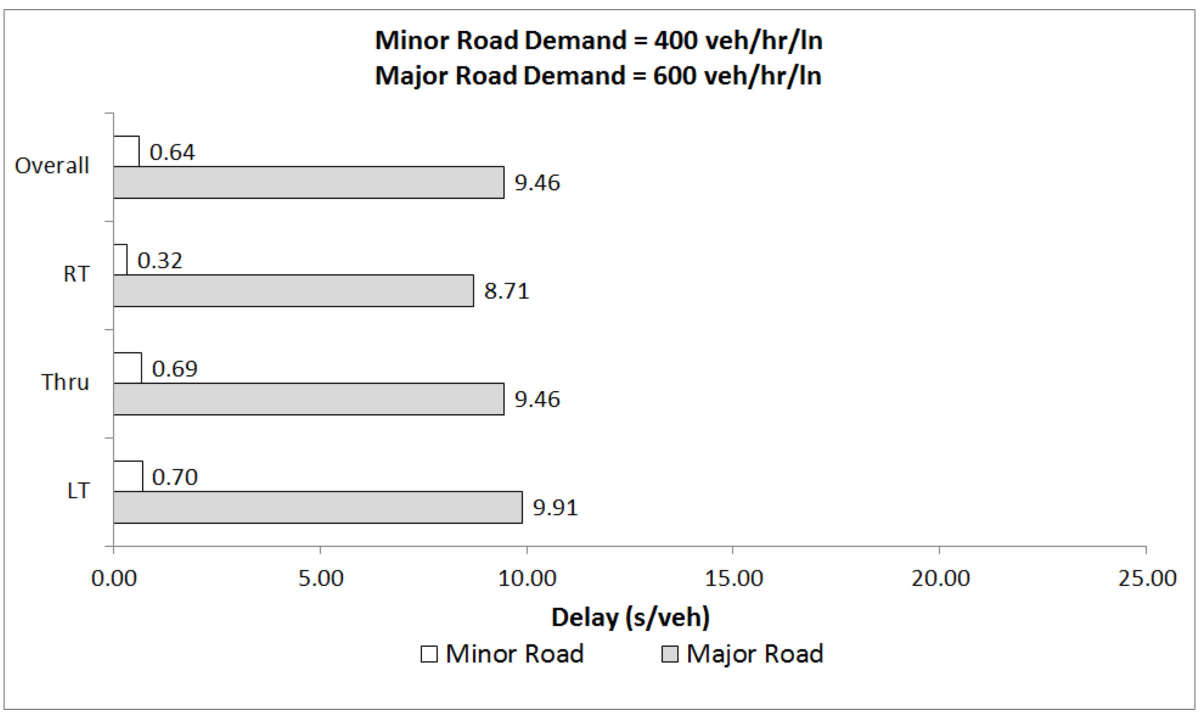

Figure 26: Delays of the ACUTA system under unbalanced traffic conditions (minor road demand = 400 veh/hr/ln)

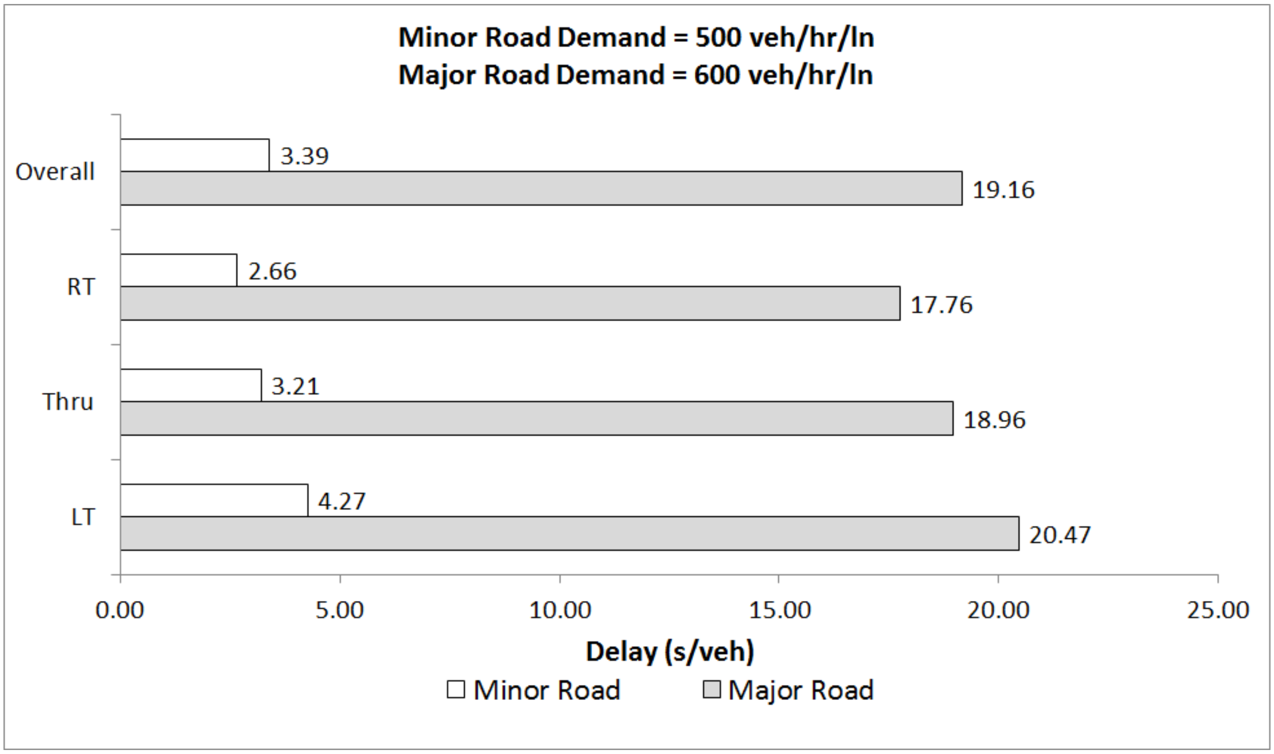

Figure 27: Delays of the ACUTA system under unbalanced traffic conditions (minor road demand = 500 veh/hr/ln)

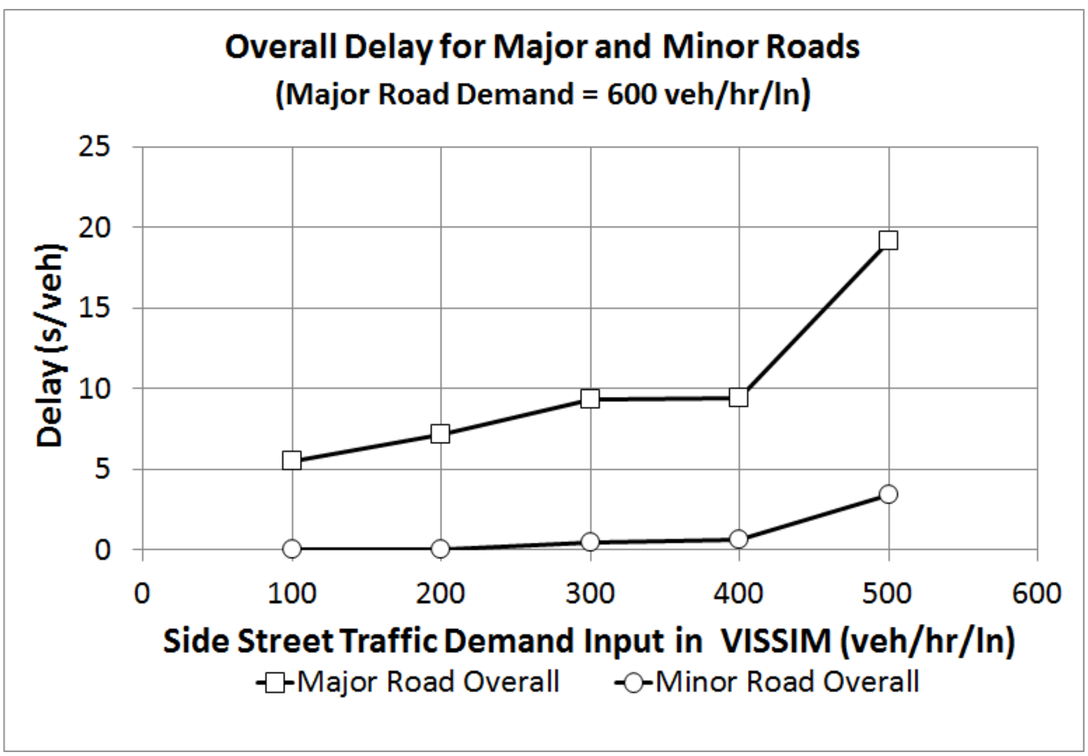

Figure 28: Delays of the ACUTA system vs. minor street demand under unbalanced traffic conditions

According to Figures 23 through 27, when the minor road demand was as low as 100, 200, 300 or 400 veh/hr/ln, the delay experienced by the minor road traffic was negligible while the major road delay ranged from 5 to 10 s/veh. When the minor road demand reached 500 veh/hr/ln, the minor road delay started to increase, however, remained below 5 s/veh, while the major road delay reached around 20 s/veh. There was also no significant difference in delay between the left turn, right turn, and through movements under any one of the five unbalanced demand conditions. These findings indicate that the starvation issue did not occur on the minor road when the traffic demands of the major and minor roads were unbalanced. Figure 28 gives a combined view showing how the overall delays for the major and minor roads changed with the minor road demand. The magnitude of the major road delay was always higher than the minor road delay due to the larger demand on the major road. As the minor road demand increased, both the minor road and the major road delays increased.

Figure 29 gives a simulation screen shot showing the traffic operations under an unbalanced demand condition. In Figure 29, the major road is the EB/WB approach, and the minor road is the NB/SB approach. It can be determined from the figure that no queues formed on the minor road, while a queue formed on the EB approach of the major road.

In summary, no starvation issue was found in the ACUTA system. The magnitude of delay for a traffic movement was positively correlated to traffic demand of that specific movement. Major road traffic movements had higher traffic demand, hence experienced longer delay. Also, the delay of a traffic movement increased as the demand of that movement increased.

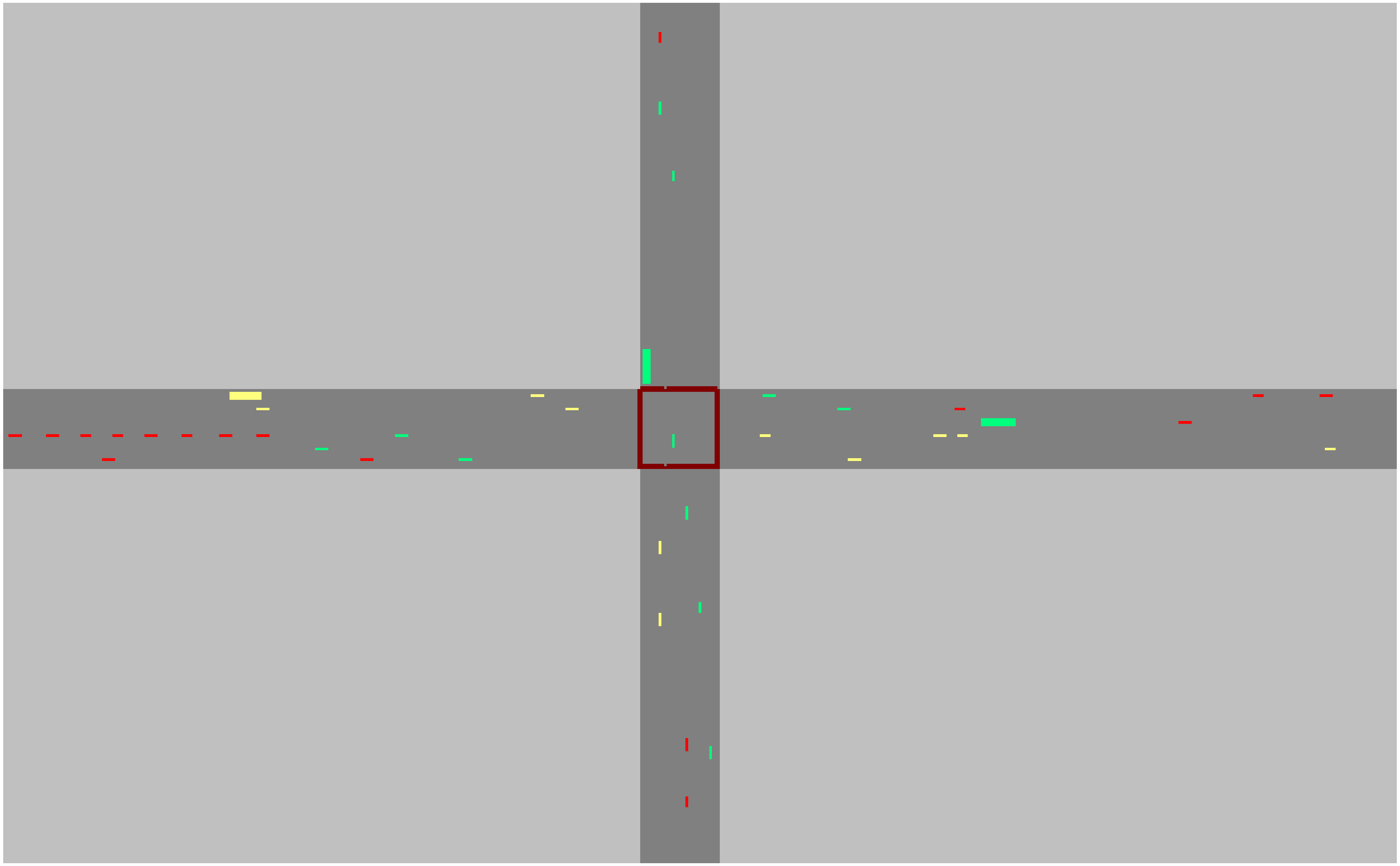

Figure 29: Traffic operations under unbalanced traffic demand conditions (major road = EB/WB, minor road = NB/SB)

CHAPTER 5: FURTHER ANALYSIS AND INVESTIGATION

5.1 Sensitivity Analysis of ACUTA Parameters

As discussed in Chapters 3 and 4, the ACUTA system has the following important configurable parameters: (1) granularity, (2) number of internal simulations, (3) minimum speed to allow fixed-speed reservation (MINSAFSR), (4) advance stop location (ASL), (5) end boundary of non-deceleration zone (EBNDZ), (6) minimum queue length (MINQL) to activate the priority reservation, and (7) maximum speed to be considered as a queuing vehicle (MSQV). Among these parameters, MINQL and MSQV are the parameters of the priority reservation (PR) enhancement strategy for queuing vehicles; ASL is the only parameter of the advance stop location enhancement strategy; and EBNDZ is the only parameter of the non-deceleration zone (NDZ) enhancement strategy.

Based on the goal of exploring the possibility of optimizing the operational performance of the ACUTA system by adjusting the configurable parameters, sensitivity analyses on the aforementioned parameters were conducted in this section. For each parameter, a series of delays were observed by changing the value of the parameter and maintaining the default values of the other parameters. All experiments were performed under a medium demand of 350 veh/hr/ln, except for the experiments that tested the PR parameters, i.e., MINQL and MSQV. Because the strategy of PR is not supposed to be effective under low or medium traffic demands, it was more accurate to analyze the PR's parameters under higher traffic demands. In the experiments testing the parameters other than MINQL and MSQV, the default MINQL and MSQV were set as 3 veh and 0 mph, respectively. In all the experiments, the ACUTA parameter of the communication range was always fixed at 600 ft.

Table 4 summarizes the results of the sensitivity analyses of granularity, number of internal simulations, MINSAFSR, ASL, and EBNDZ. In Table 4, the parameter values that are marked by an asterisk indicate the parameter's default value, which was the value used in the experiments for the analyses of other parameters. Figures 30 through 34 graphically demonstrate the sensitivity of the ACUTA's operational performance when the value of granularity, number of internal simulations, MINSAFSR, ASL, or EBNDZ was changed.

Table 4: Sensitivity Analysis Results for the ACUTA Configuration Parameters except PR

		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
Number of Internal Simulations	2	0.22	0.46	0.48	0.40
	6	0.26	0.48	0.44	0.40
	*10	0.26	0.42	0.44	0.38
	20	0.24	0.44	0.44	0.38
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
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
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

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

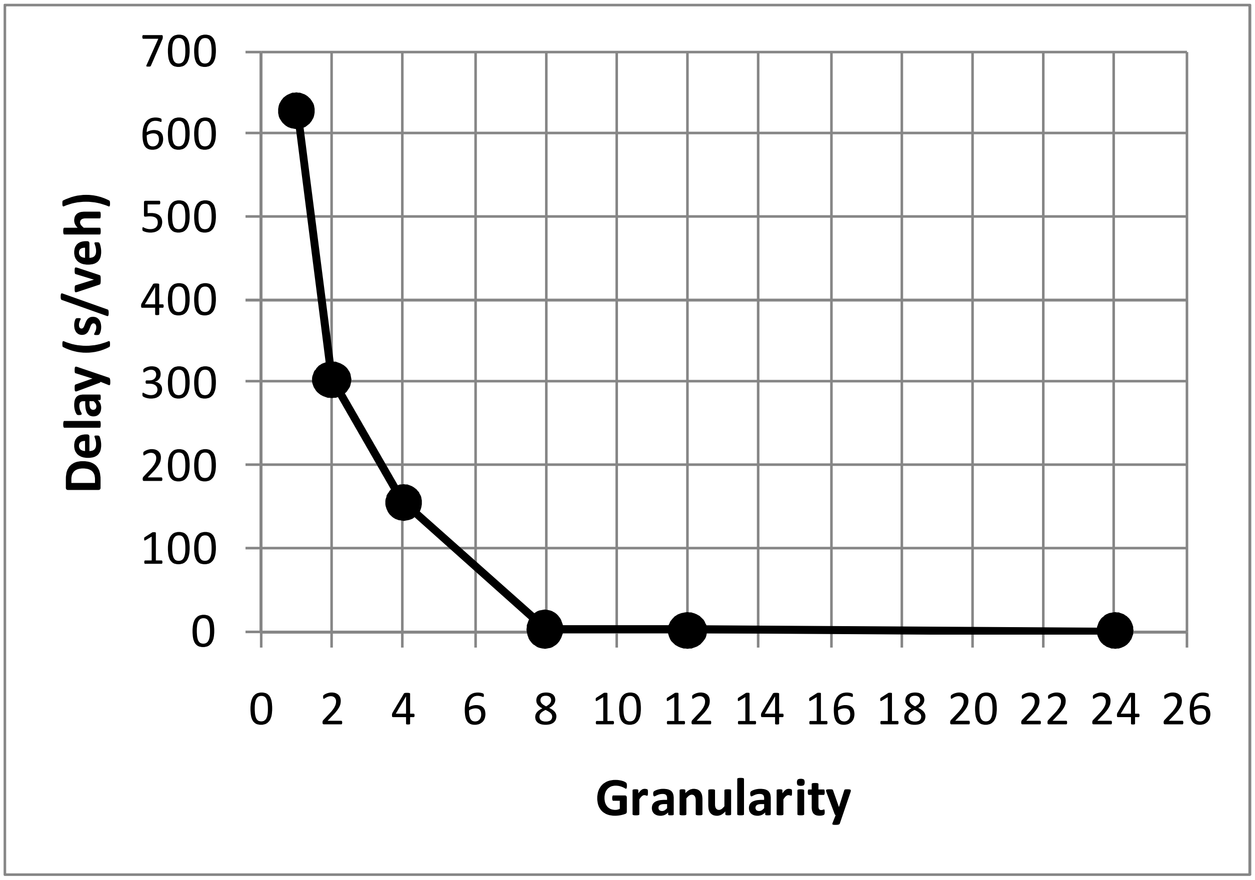

Figure 30: Overall intersection delay for the ACUTA under different granularity settings

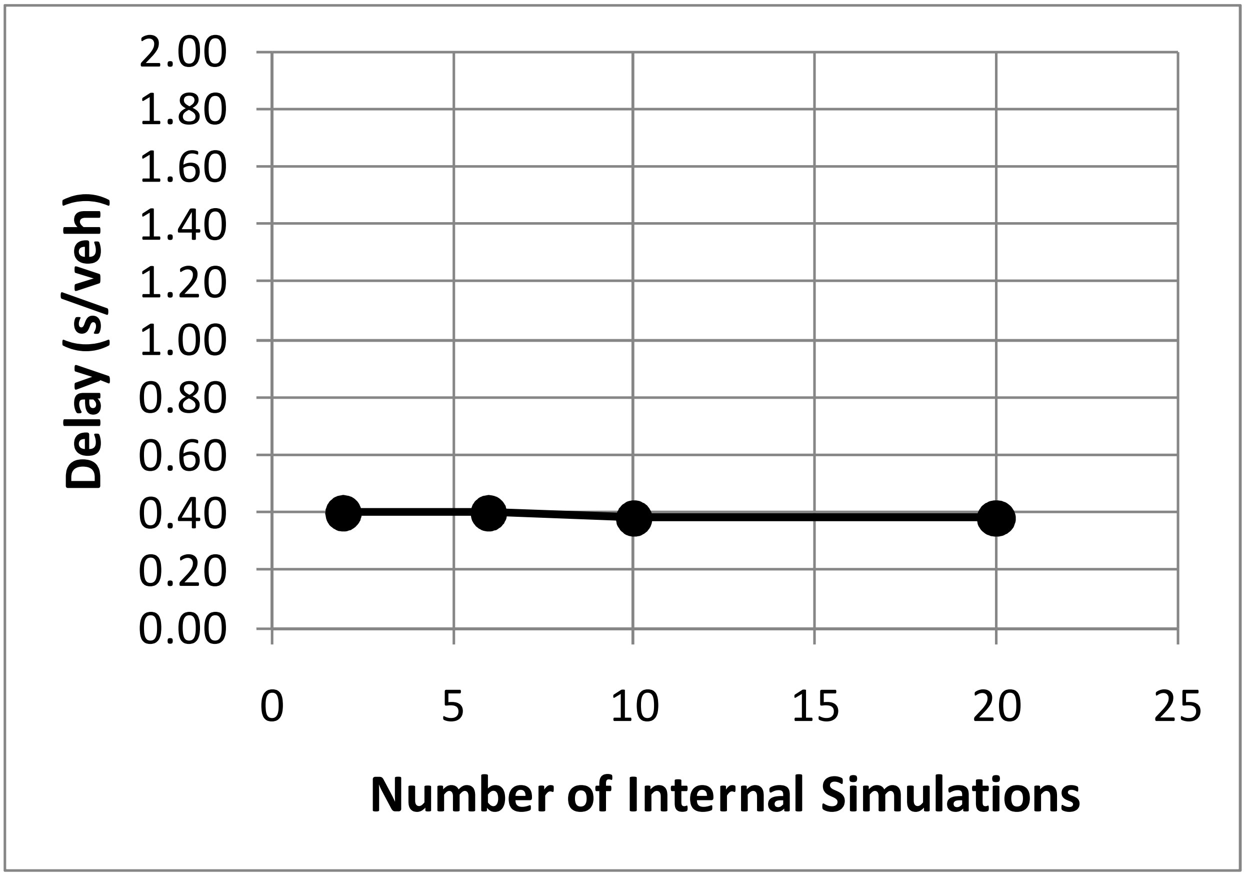

Figure 31: Overall intersection delay for the ACUTA under different settings of number of internal simulations

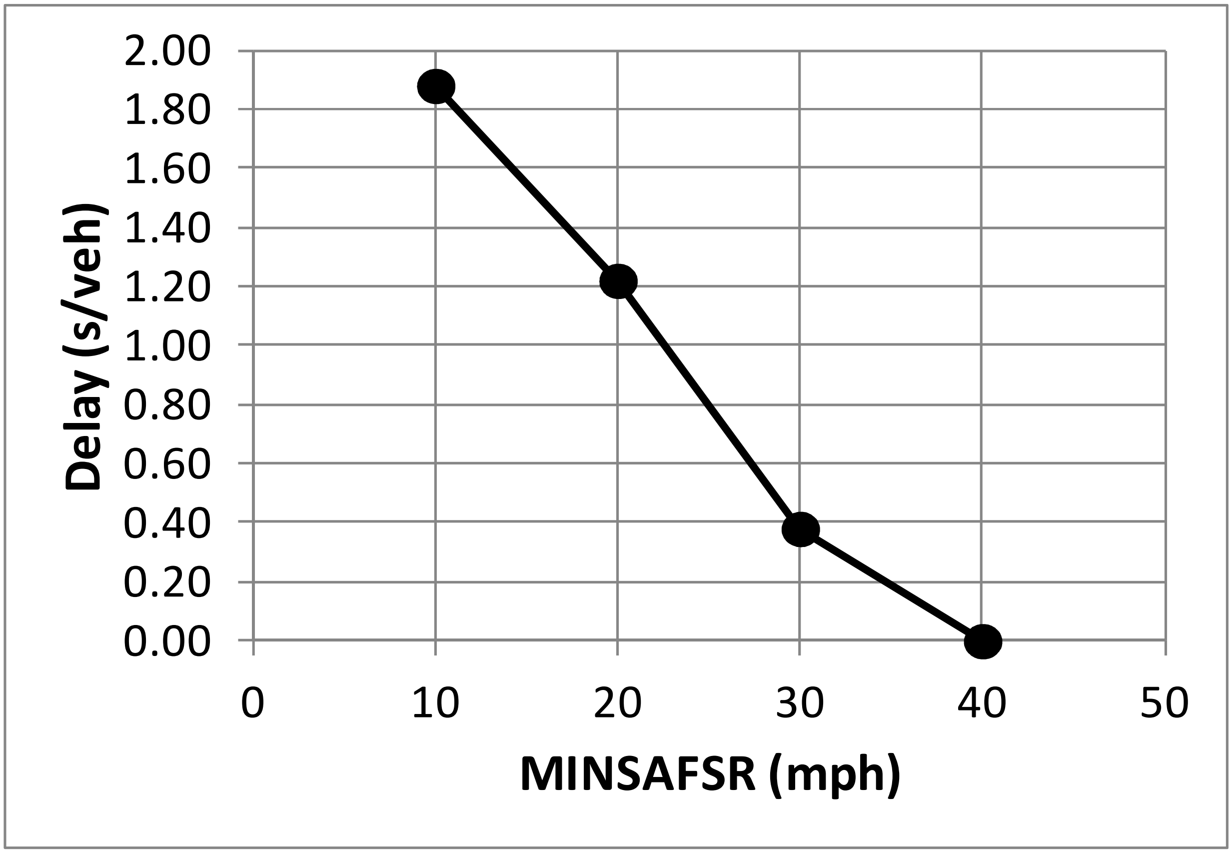

Figure 32: Overall intersection delay for the ACUTA under different MINSAFSR settings

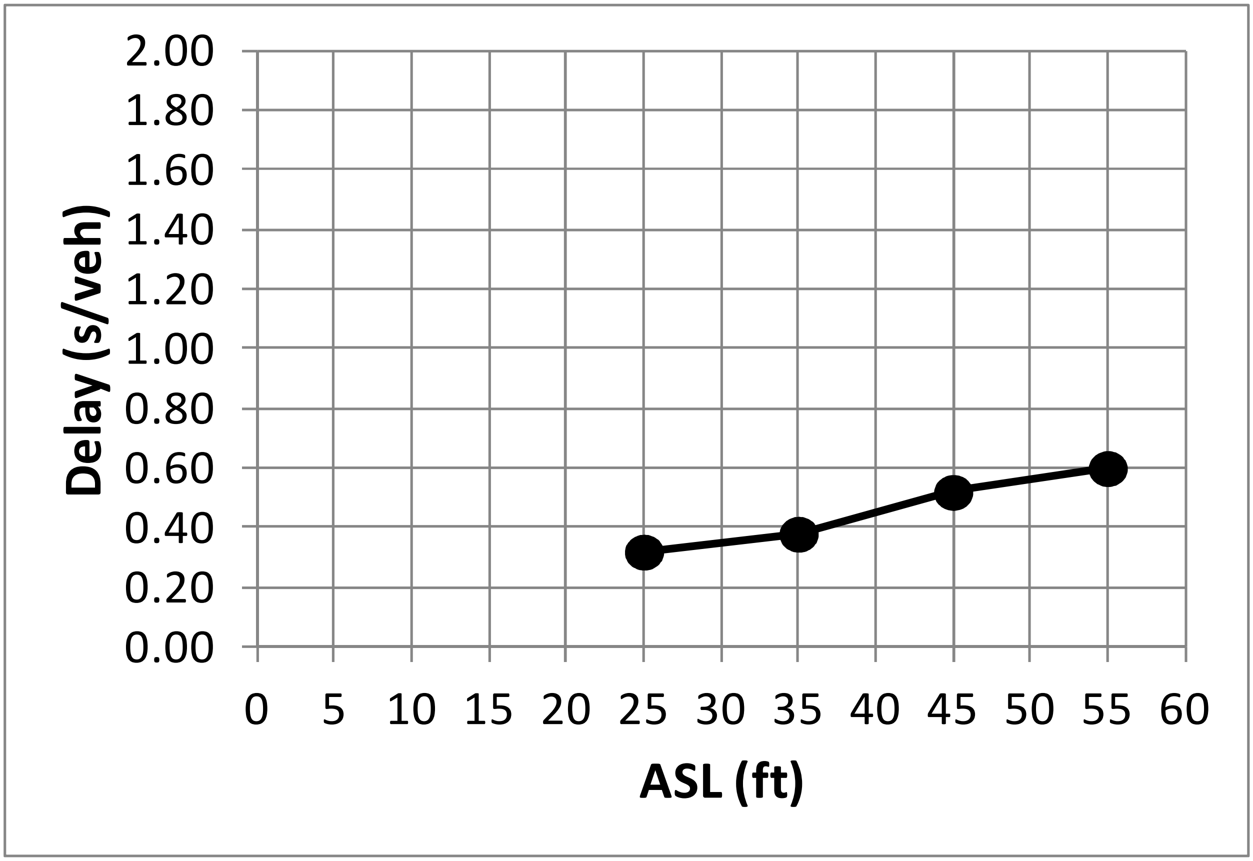

Figure 33: Overall intersection delay for the ACUTA under different ASL settings

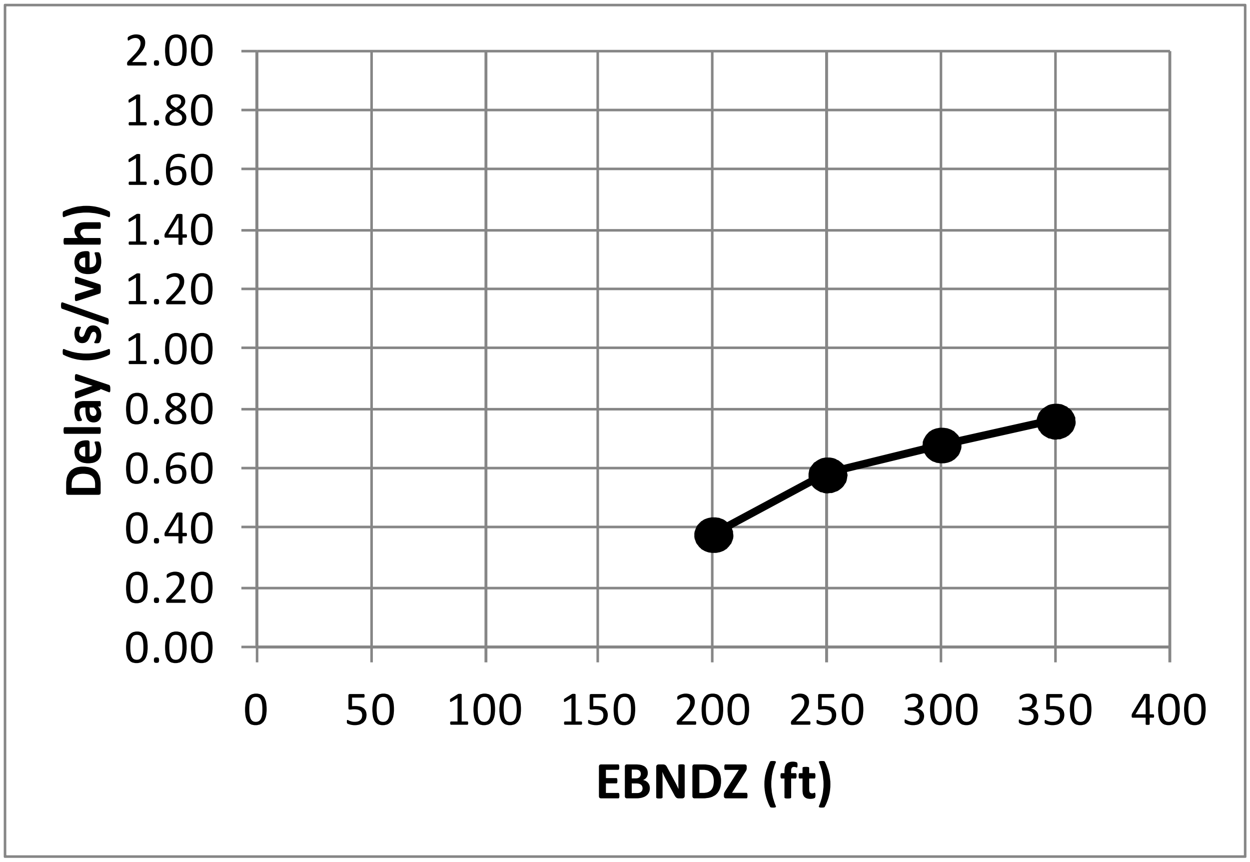

Figure 34: Overall intersection delay for the ACUTA under different EBNDZ settings

According to Figure 30, the intersection delay was extremely sensitive to the granularity. The intersection delay decreased rapidly as the granularity increased from 1 to 8. After the granularity reached 8, the reduction in delay became much smaller in magnitude. By referring back to Table 3, the intersection delay was roughly halved every time the granularity doubled, except for the transition between 4 and 8.

According to Figure 31, no obvious change was identified when the setting of the number of internal simulations was changed. However, a slight reduction trend was found when the number of internal simulations was increased. Note that these findings were obtained under the moderate traffic demand of 350 veh/hr/ln. The sensitivity of the delay by changing the number of internal simulations might be different under high demand and near-capacity demand conditions.

According to Figure 32, the intersection delay was very sensitive to the MINSAFSR. Specifically, the intersection delay dropped from around 2 s/veh to 0 s/veh as the MINSAFSR was increased from 10 mph to 40 mph. The benefit was because a higher MINSAFSR required more vehicles to accelerate even though their speeds were already high enough. This solution might diminish the safety performance of the ACUTA by raising the crash severity if a crash happens. Therefore, the selection of the MINSAFSR should take this trade-off into account.

According to Figure 33, the change in the ASL significantly impacted the intersection delay. As the ASL increased, the intersection delay increased accordingly. Similar findings were found for the EBNDZ according to Figure 34.

Table 5 summarizes the results of sensitivity analyses of the PR parameters of MINQL and MSQV. In Table 5, the parameter values that are marked by an asterisk indicate the parameter's default value, which was the value used in the experiments for the analysis of the other parameters. In all the experiments, other ACUTA parameters of granularity, communication range, number of internal simulations, MINSAFSR, ASL, and EBNDZ were set as 24, 600 ft, 10, 30 mph, 35 ft, and 200 ft, respectively.

Table 5: Sensitivity Analysis Results for PR's Parameters of MINQL and MSQV

		Delay (s/veh)			
Factor	**Value**	**LT Overall**	**Thru Overall**	**RT Overall**	**Overall**
MINQL, ft	*3	25.80	25.53	24.80	21.63
	5	25.63	25.30	25.10	23.93
	8	23.93	23.23	23.10	23.23
MSQV, mph	5	25.80	25.53	24.80	25.50
	10	25.80	25.43	24.37	25.37
	*15	22.30	21.30	21.63	21.63

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

Figures 35 and 36 graphically demonstrate the sensitivity of the ACUTA's operational performance when the MINQL and MSQV were changed. Figure 35 indicates that the intersection delay was sensitive to the MINQL setting. When the MINQL was set as 3 veh, the delay was the lowest among the three tested values. However, the pattern of the change in delay resulting from the change in MINQL was hard to determine as the delay was also dependant upon the setting of the MSQV. Similar findings were identified from Figure 36 for the MSQV. The MSQV affected results when it was set greater than 10 mph. However, no obvious pattern could be identified.

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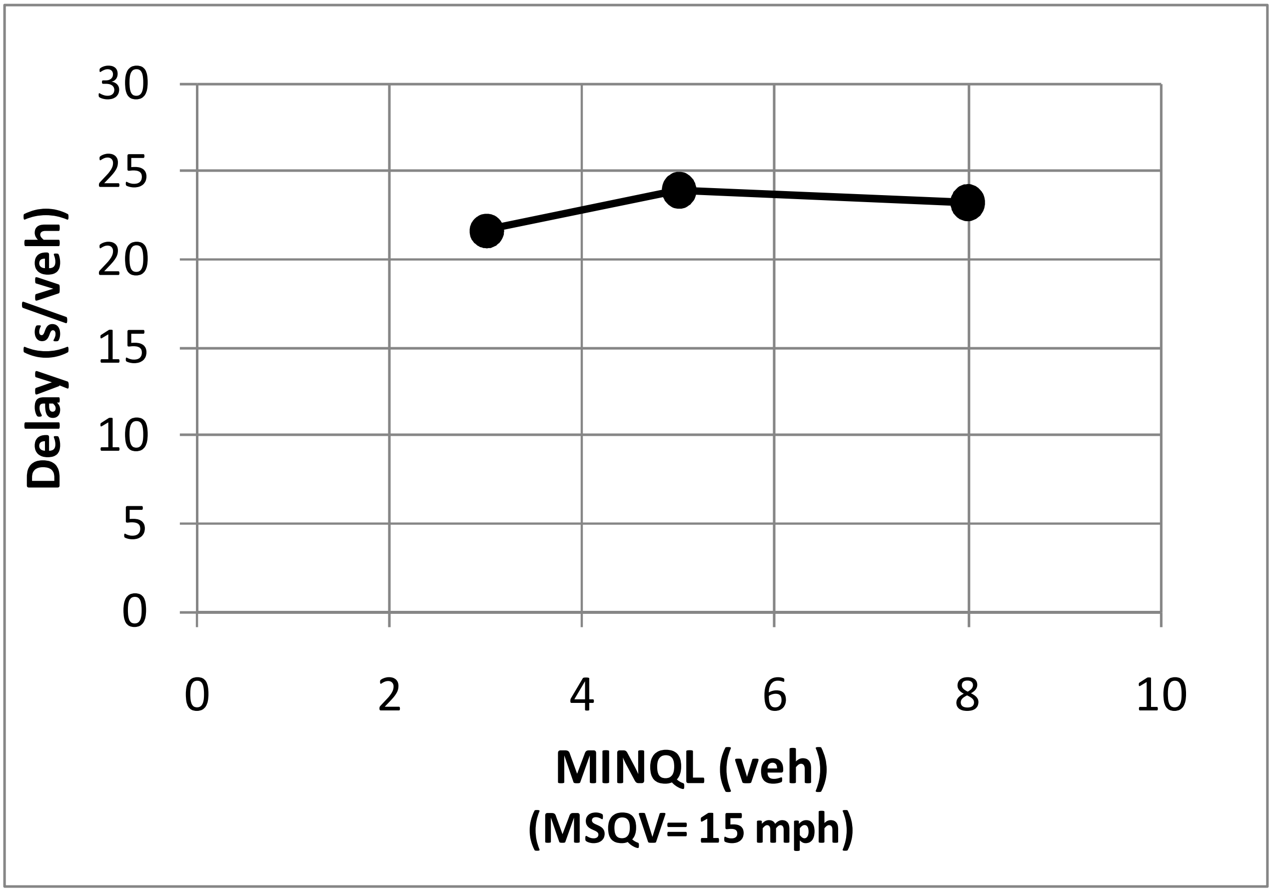

Figure 35: Overall intersection delay for the ACUTA under different MINQL settings

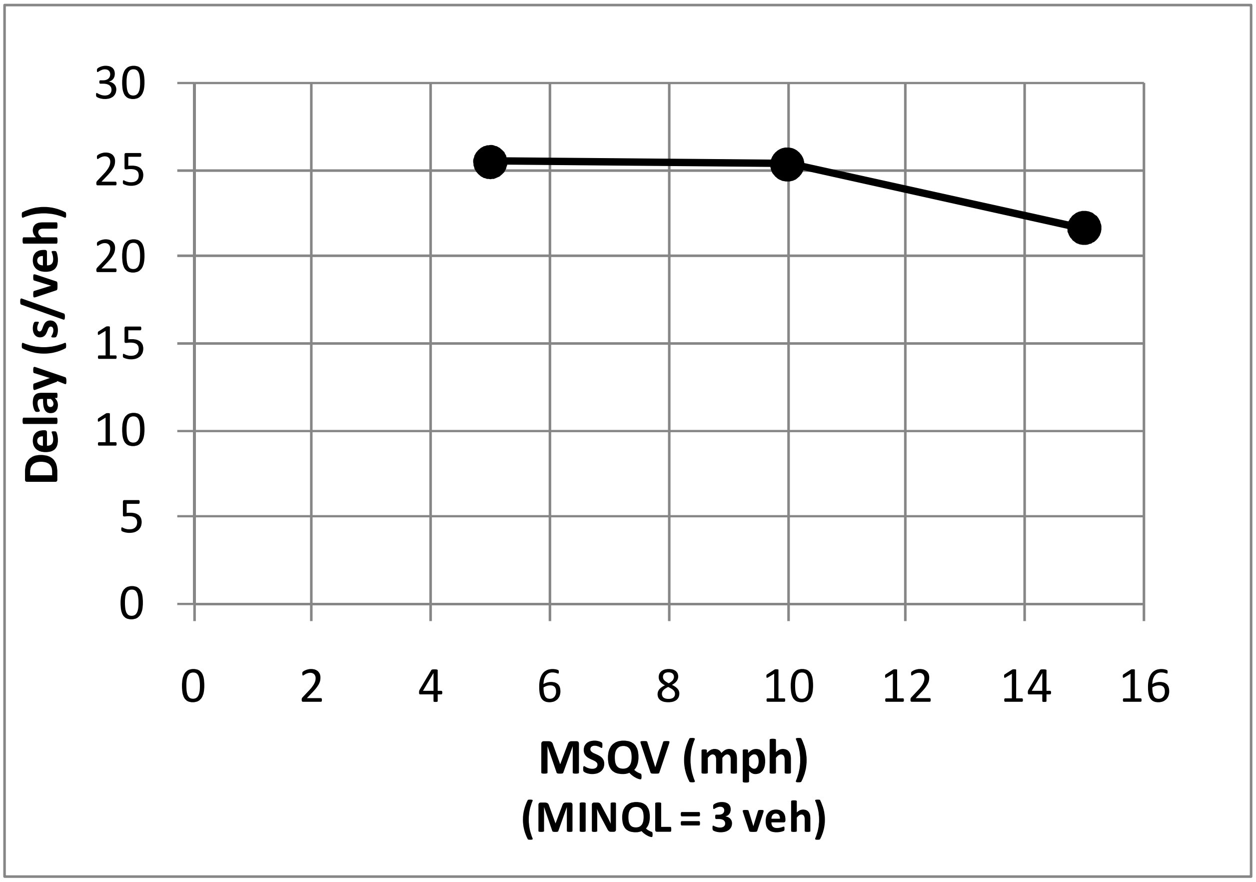

Figure 36: Overall intersection delay of the ACUTA under different EBNDZ settings

5.2 Analysis of ACUTA's Capability of Accommodating Heavy Trucks

Heavy trucks are an essential element in the urban transportation network. The accommodation of the heavy trucks must be taken into account when analyzing the performance of the ACUTA system. This section is dedicated to the analysis of the ACUTA's operational performance under different heavy truck demands. Specifically, the performance of the ACUTA system under heavy truck percentages of 15%, 25%, and 35% was tested in the analysis. In the test of each heavy truck percentage, various traffic demand conditions ranging from 100 to 600 veh/hr/ln were incorporated to explore the heavy truck percentage's impact on the intersection delay under different traffic demand conditions.

The experiment testing each heavy truck percentage and traffic demand combination included five simulation runs with different random seeds. In all the experiments, the ACUTA parameters of granularity, communication range, number of internal simulations, MINSAFSR, ASL, EBNDZ, MSQV, MINQL were set as 24, 600 ft, 10, 30 mph, 35 ft, 200 ft, 0 mph, and 3 veh, respectively.

Tables 6 through 11 summarize the delays of different movements as well as the overall intersection delay under different heavy truck percentages for the traffic demands of 100 to 600 veh/hr/ln. Figures 37 through 42 provide a graphic presentation of the results summarized in Tables 6 through 11. Figure 43 provides a brief overview of the intersection delay by different heavy vehicle percentages under different traffic demand conditions.

Table 6: Delay by Different Heavy Truck Percentages for Traffic Demand of 100 veh/hr/ln

Heavy Truck Percentage	Delay (s/veh)							
	LT ALL	*LT Truck*	*Thru ALL*	*Thru Truck*	*RT ALL*	*RT Truck*	*ALL Overall*	*Truck Overall*
15%	0.00	0.02	0.00	0.02	0.00	0.54	0.00	0.02
25%	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00
35%	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00

Table 7: Delay by Different Heavy Truck Percentages for Traffic Demand of 200 veh/hr/ln

Heavy Truck Percentage	Delay (s/veh)							
	LT ALL	*LT Truck*	*Thru ALL*	*Thru Truck*	*RT ALL*	*RT Truck*	*ALL Overall*	*Truck Overall*
15%	0.00	0.08	0.00	0.00	0.00	0.08	0.00	0.00
25%	0.00	0.02	0.00	0.00	0.00	0.06	0.00	0.00
35%	0.00	0.04	0.00	0.00	0.00	0.02	0.00	0.00

Table 8: Delay by Different Heavy Truck Percentages for Traffic Demand of 300 veh/hr/ln

Heavy Truck Percentage	Delay (s/veh)							
	LT ALL	*LT Truck*	*Thru ALL*	*Thru Truck*	*RT ALL*	*RT Truck*	*ALL Overall*	*Truck Overall*
15%	0.14	0.46	0.14	0.72	0.12	0.16	0.12	0.56
25%	0.30	0.78	0.32	0.72	0.20	0.30	0.30	0.70
35%	0.68	1.26	0.60	1.00	0.40	0.40	0.60	0.92

Table 9: Delay by Different Heavy Truck Percentages for Traffic Demand of 400 veh/hr/ln

Heavy Truck Percentage	**Delay (s/veh)**							
	LT ALL	*LT Truck*	*Thru ALL*	*Thru Truck*	*RT ALL*	*RT Truck*	*ALL Overall*	*Truck Overall*
15%	1.38	1.90	0.98	1.68	1.00	0.98	1.08	1.62
25%	2.12	3.14	1.62	2.32	1.36	1.62	1.74	2.44
35%	3.56	4.80	2.66	3.12	2.14	2.72	2.82	3.48

Table 10: Delay by Different Heavy Truck Percentages for Traffic Demand of 500 veh/hr/ln

Heavy Truck Percentage	**Delay (s/veh)**							
	LT ALL	*LT Truck*	*Thru ALL*	*Thru Truck*	*RT ALL*	*RT Truck*	*ALL Overall*	*Truck Overall*
15%	5.38	6.36	4.50	5.64	3.94	4.18	4.64	5.60
25%	12.18	14.20	10.72	12.40	10.96	12.36	11.14	12.84
35%	31.52	32.60	29.26	31.22	29.84	31.38	29.92	31.58

Table 11: Delay by Different Heavy Truck Percentages for Traffic Demand of 600 veh/hr/ln

Heavy Truck Percentage	**Delay (s/veh)**							
	LT ALL	*LT Truck*	*Thru ALL*	*Thru Truck*	*RT ALL*	*RT Truck*	*ALL Overall*	*Truck Overall*
15%	60.28	65.1	60.58	60.7	59.48	61.86	60.36	62
25%	101.06	108.2	102.18	103.32	99.1	102.68	101.46	104.44
35%	140.22	145.7	143.8	142.56	139.78	137.42	142.3	142.6

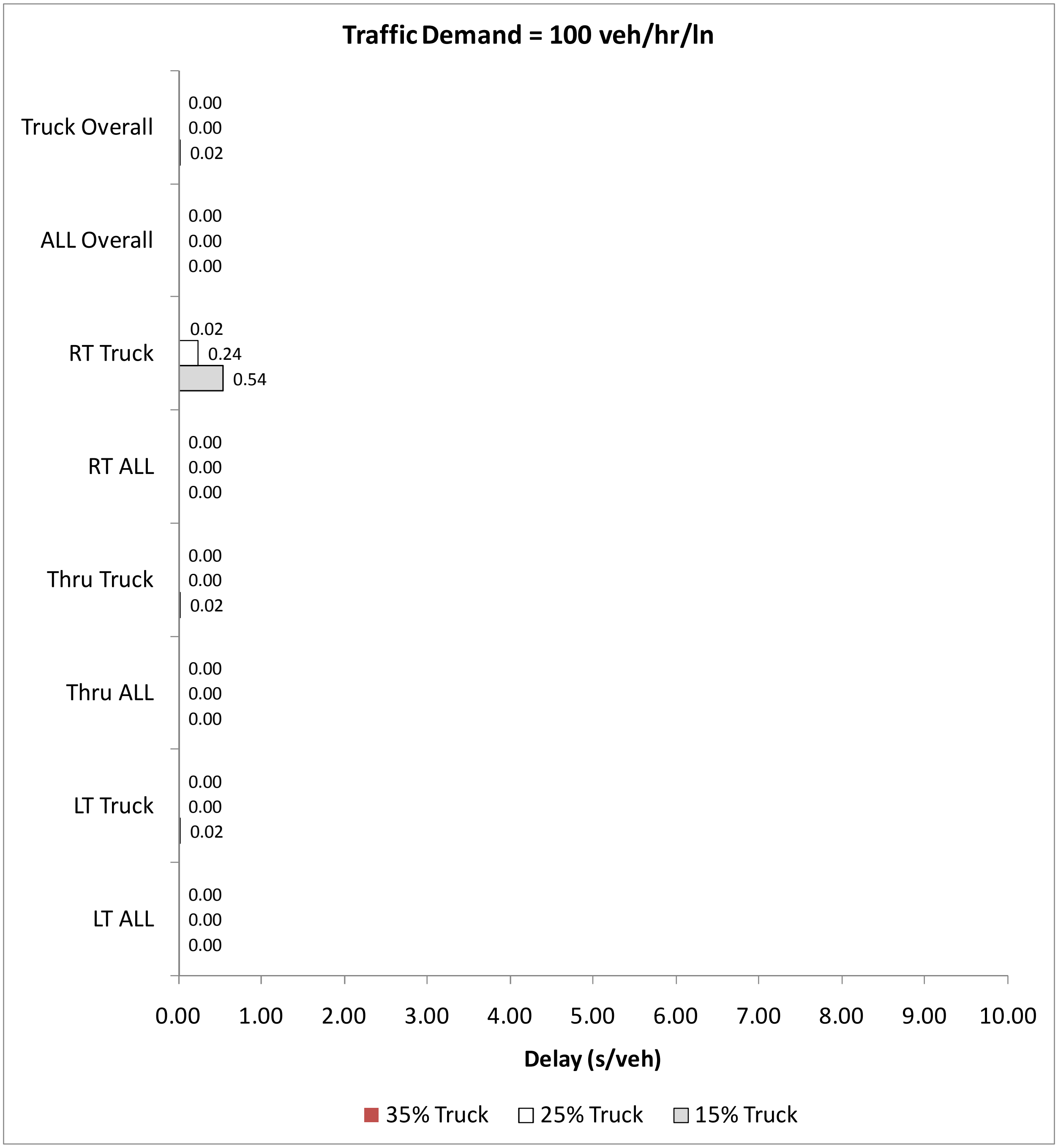

Figure 37: Delay for different movements by different heavy truck percentages for traffic demand of 100 veh/hr/ln

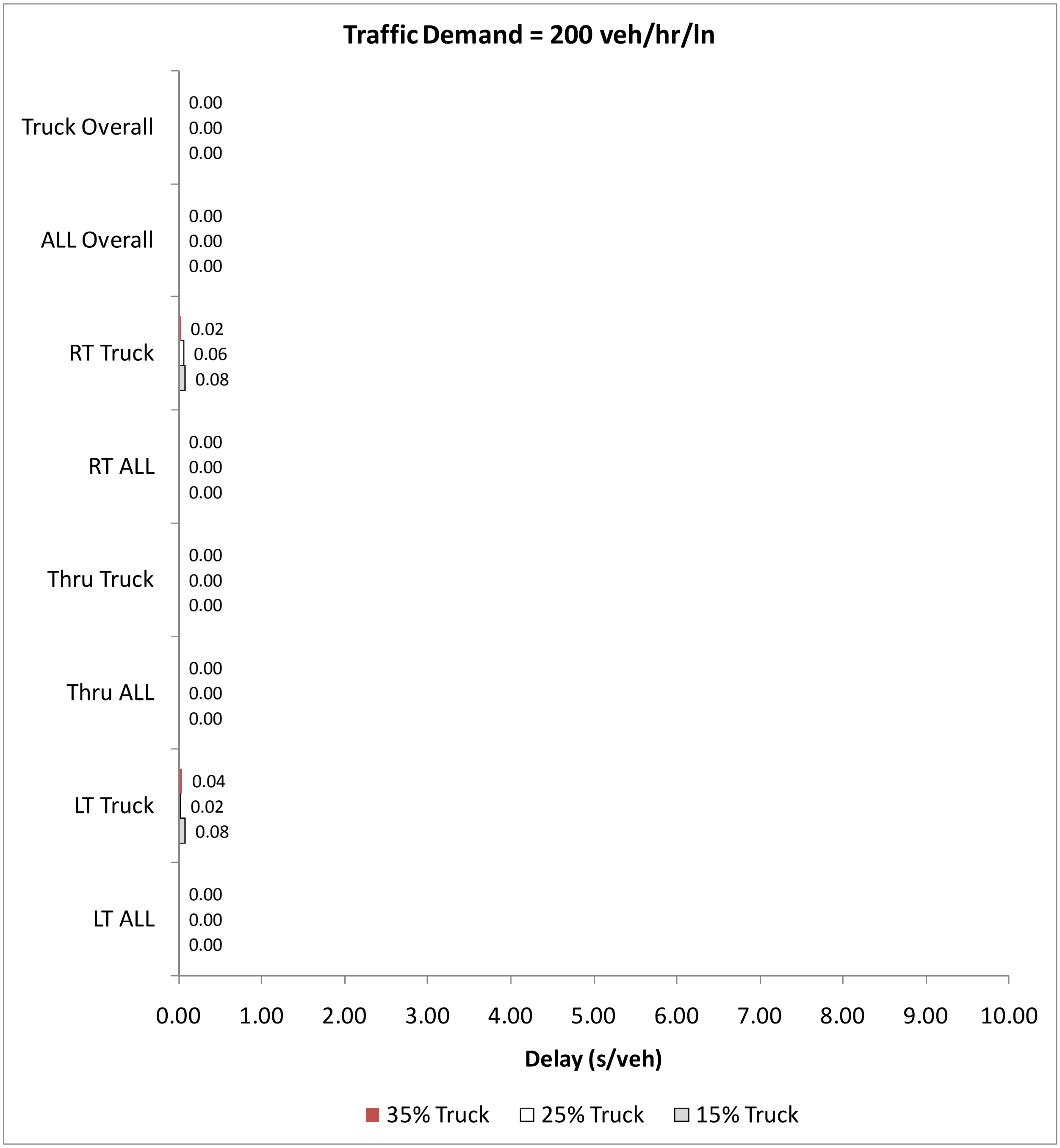

Figure 38: Delay for different movements by different heavy truck percentages for traffic demand of 200 veh/hr/ln

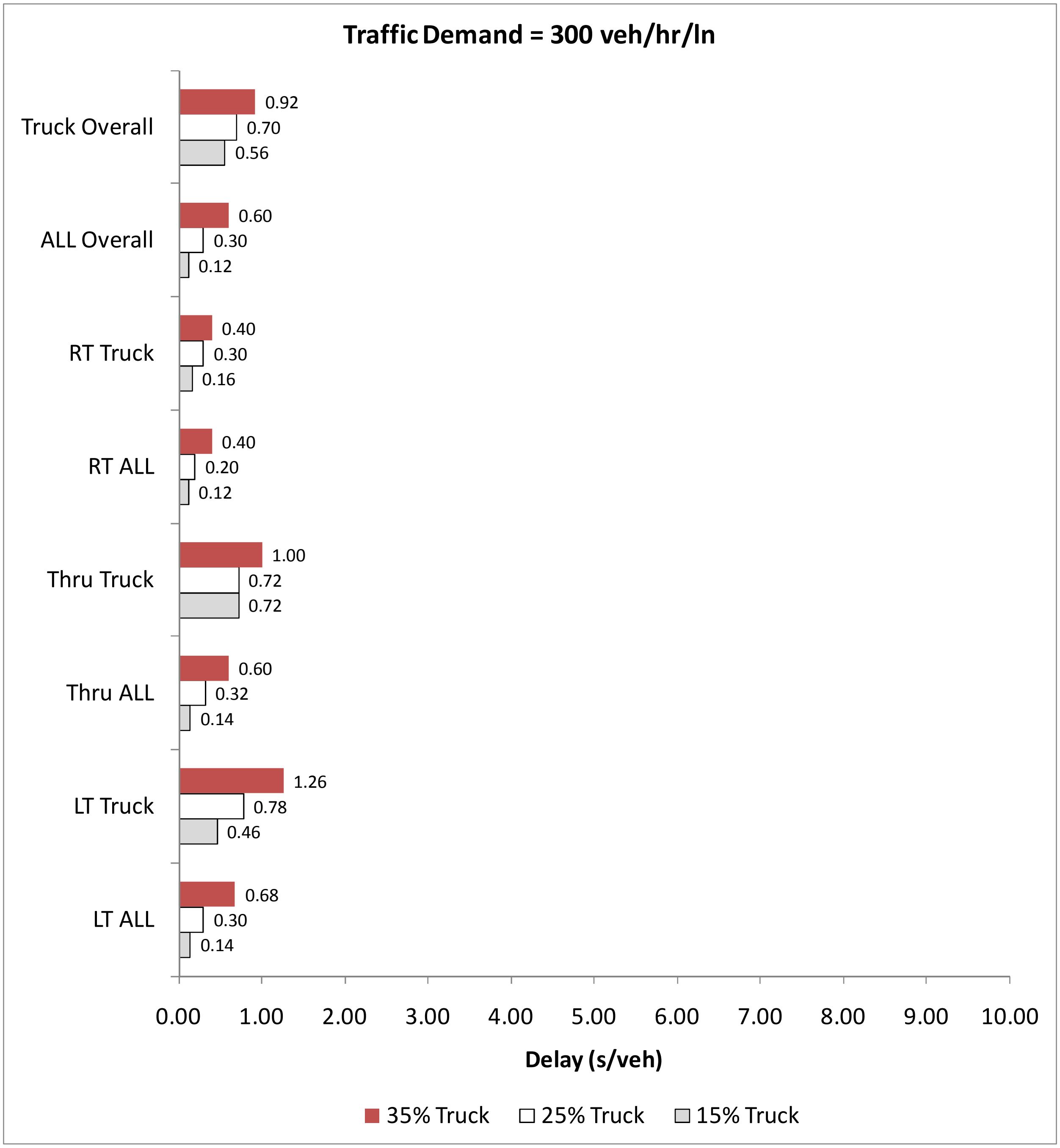

Figure 39: Delay for different movements by different heavy truck percentages for traffic demand of 300 veh/hr/ln

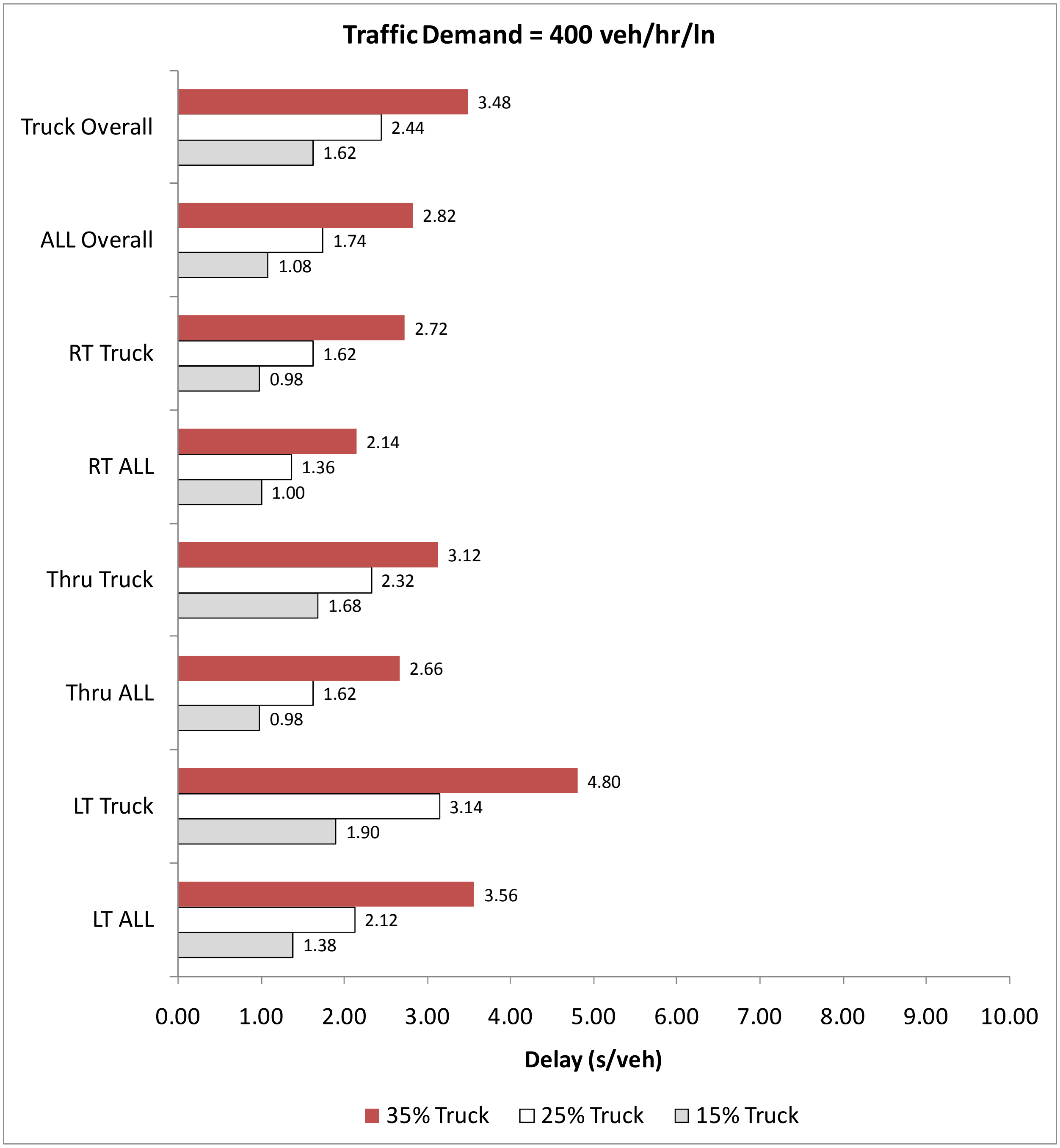

Figure 40: Delay for different movements by different heavy truck percentages for traffic demand of 400 veh/hr/ln

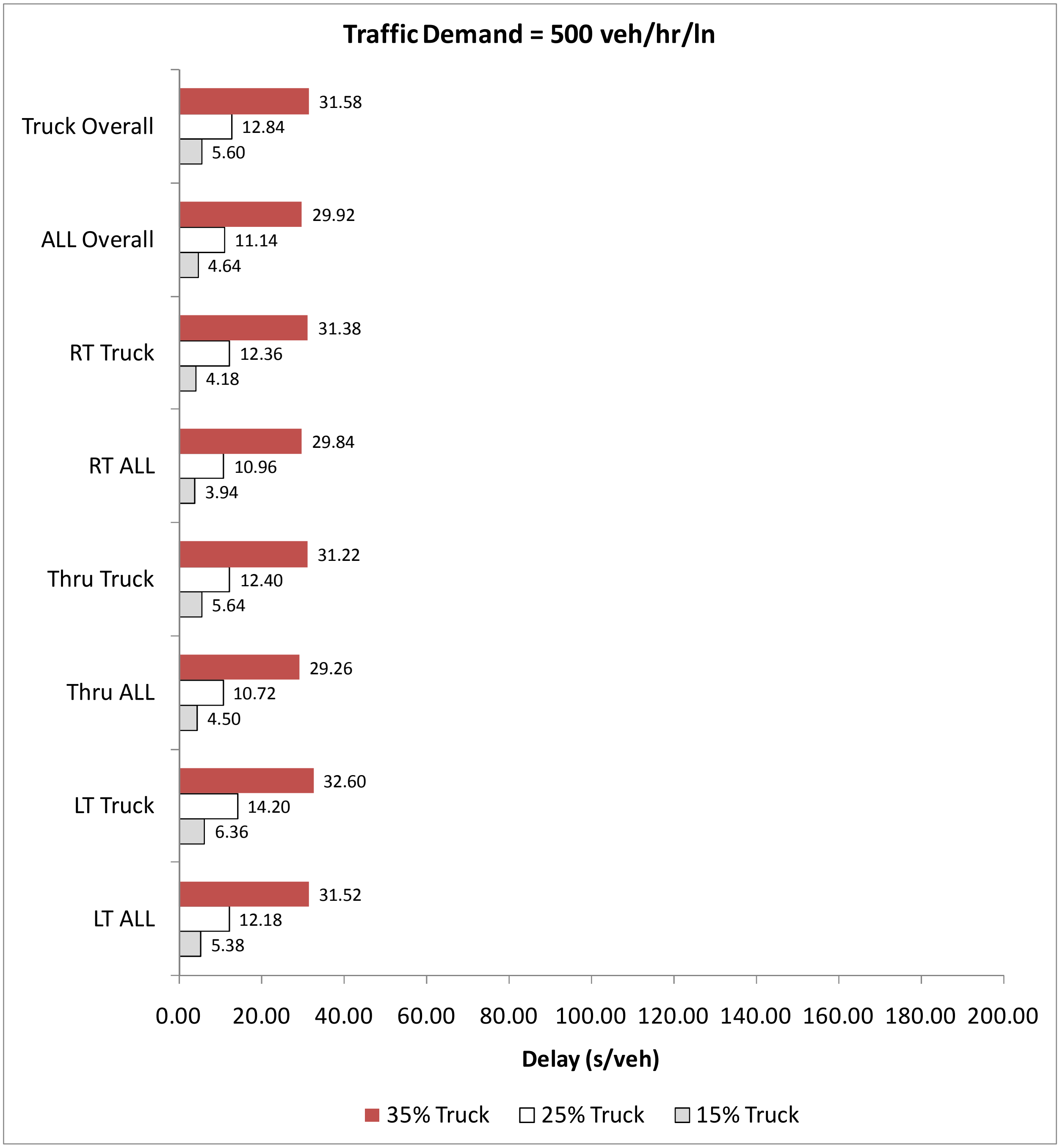

Figure 41: Delay for different movements by different heavy truck percentages for traffic demand of 500 veh/hr/ln

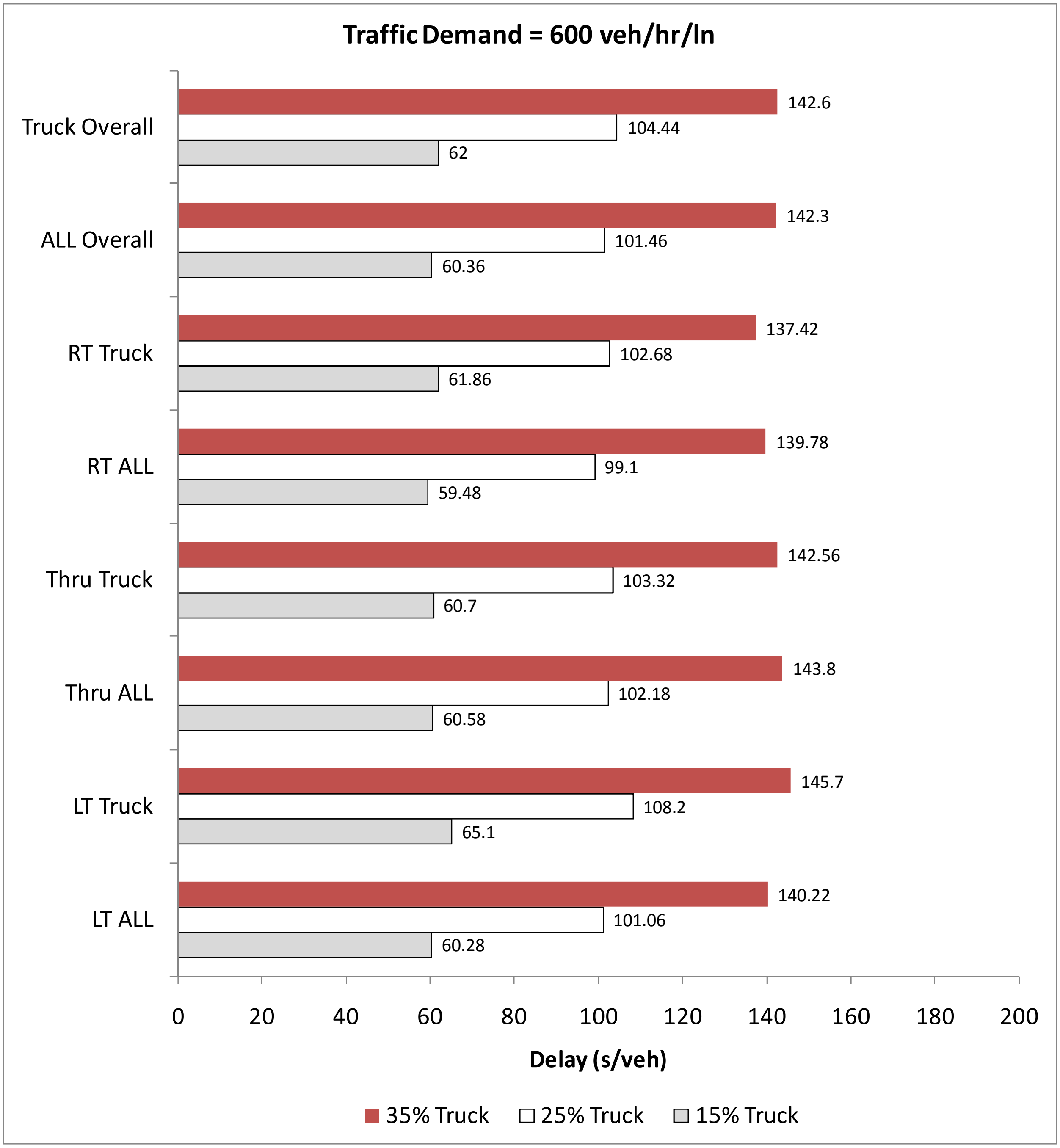

Figure 42: Delay for different movements by different heavy truck percentages for traffic demand of 600 veh/hr/ln

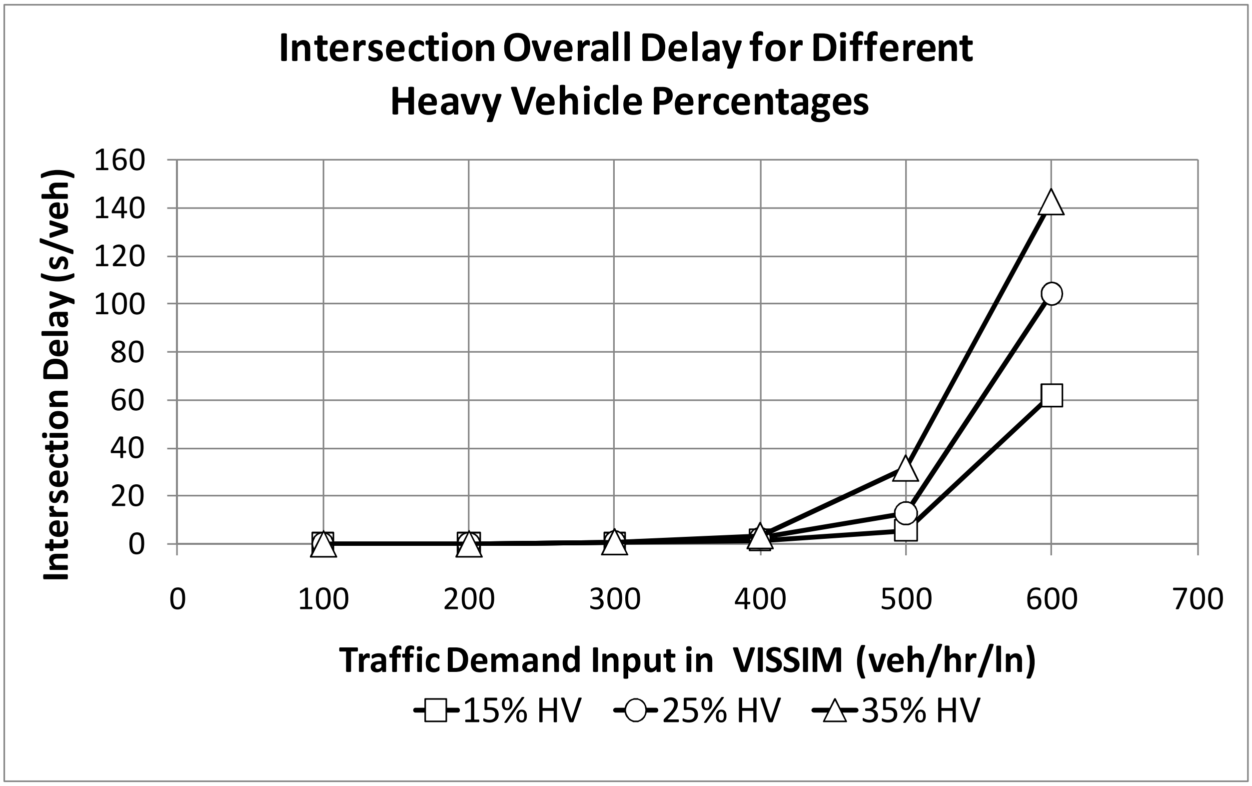

Figure 43: Overall intersection delay by different heavy truck percentages under different traffic demand conditions

Figures 37 through 42 demonstrate that heavy trucks generally experienced slightly longer delay than passenger cars under all tested traffic demands from 100 through 600 veh/hr/ln. Heavy trucks making different movements experienced similar delay. And this similarity in delay did not change with either the traffic demand or the heavy truck percentage. This indicates that the delays for different movements were balanced when increasing either the traffic demand or the heavy truck percentage. According to Tables 6 and 7, a trend of decreasing delay was observed for the right-turn trucks under traffic as the heavy vehicle percentage increased. It has to be noted that this trend was caused by the variation in simulation results, and only happened under low traffic demands of 100 and 200 veh/hr/ln, where the resulting delays were close to zero. Therefore, these numbers do not necessarily validate this trend, as an obvious trend of increasing delay was observed under higher traffic demands as indicated by Tables 8 through 11.

Figure 43 indicates that the intersection delay was maintained at close to zero level when the traffic demand was at 400 veh/hr/ln or lower. For the traffic demands higher than 400 veh/hr/ln, the intersection delay increased as the heavy truck percentage increased. Specifically, under the traffic demand of 500 veh/hr/ln, the intersection delay could still be maintained at the 10 s/veh level for heavy truck percentages of both 15% and 25%. Under the same traffic demand (500 veh/hr/ln) the intersection delay reached near 30 s/veh for the heavy truck percentage of 35%. However, this was still a reasonable delay for such a high heavy truck percentage under such a high traffic demand. Under the near capacity traffic demand of 600 veh/hr/ln, the 15%, 25%, and 35% heavy truck percentages resulted in intersection delays of around 60, 100, and 140 seconds. In summary, under the traffic demand of 600 veh/hr/ln, the ACUTA system approximately reached its capacity when heavy vehicle percentage was equal to 15%, and operated at oversaturated conditions when heavy vehicle percentage was greater than 15%.

5.3 Corridor Extension of the ACUTA Algorithm

The mobility performance of the ACUTA algorithm when implemented at an isolated intersection has been extensively investigated from various perspectives in the previous sections. This section aims at exploring solutions for extending the ACUTA to a corridor level, where adjacent intersections are located with a certain distance.

The ACUTA algorithm is designed to manage traffic for an isolated intersection. The algorithm is generic across different intersections when the geometric information of the intersection is known. The deployment of the ACUTA at an isolated intersection only requires configuring the ACUTA with the specific geometric information pertaining to that particular intersection. Therefore, a simple approach for extending the ACUTA to the corridor level is to treat each intersection along the corridor as isolated intersections and directly deploy the isolated-intersection-based ACTUA at each intersection of that corridor. The concept of this approach is illustrated by Figure 44.

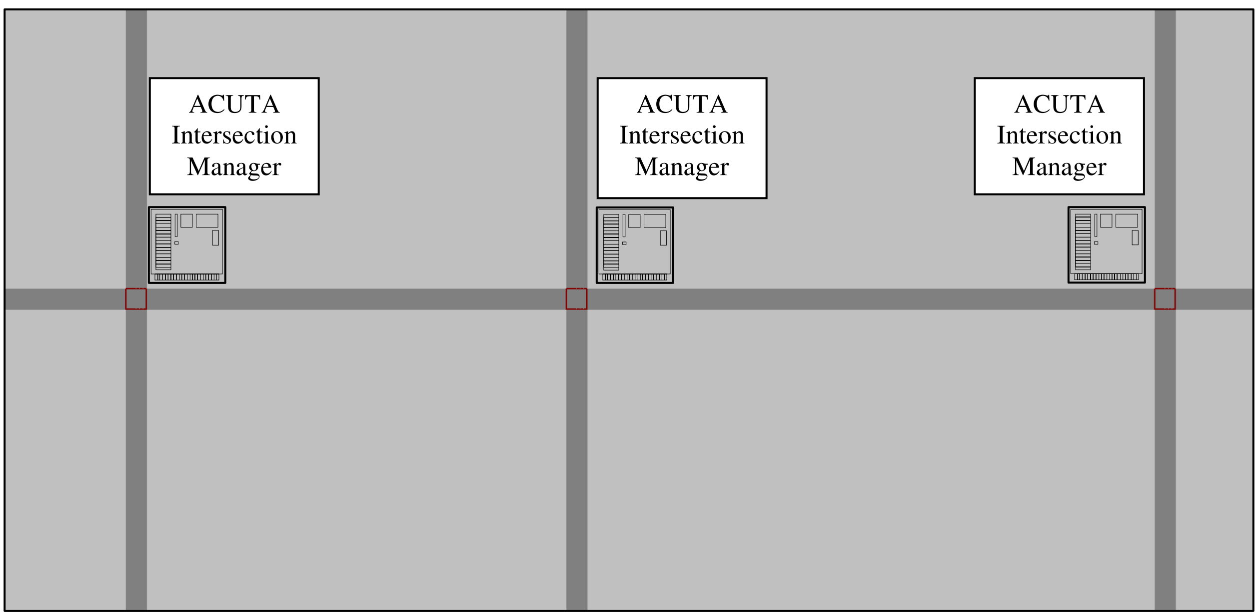

Figure 44: Extension of the ACUTA to Corridor Level

As shown in Figure 44, each intersection along the corridor has a separate ACUTA intersection manager deployed. There is no communication or coordination between these adjacent intersection managers. Each intersection manager independently processes the reservation requests from the approaching vehicles that enter the communication range of its managed intersection. Although the Highway Capacity Manual recommends signal coordination for adjacent intersections located less than 3600 feet apart (*22*), the coordination is not necessarily required between the ACUTA intersections for autonomous vehicles. For signalized intersections, the absence of coordination between two closely-spaced intersections may cause unfavorable quality of signal progression. In that case, a vehicle that clears an intersection during the green time has the possibility to immediately receive a red signal at the downstream intersection, and unnecessary delay would be incurred. Therefore, coordination is of great importance for closely-spaced signalized intersections.

Unlike signalized intersections, there are no traffic signals to regulate the approaching vehicles' right of way at the ACUTA intersections. When a vehicle clears an ACUTA intersection and enters the communication range of the downstream ACUTA intersection, its right of way is regulated by the intersection manager of the downstream intersection based solely on the traffic demand of that particular intersection. Therefore, the mobility of the intersection is determined only by the traffic demand and the efficiency of the ACUTA algorithm. The mobility analysis of the isolated-intersection-based ACUTA discussed in the previous sections has proven that the ACUTA can efficiently manage the autonomous vehicles even under high traffic demand of 620 veh/hr/ln. Therefore, deploying the isolated-intersection-based ACUTA at intersections along a corridor is a theoretically sound option for achieving reasonable efficiency, even for closely spaced and uncoordinated intersections. Simulation of the corridor-wide implementation of the ACUTA algorithms is beyond the scope of this project.

On the other hand, coordination of closely spaced ACUTA intersections could improve mobility because the approaching vehicles' speed and location information would be received by the downstream intersection manager from the upstream intersection manager before the vehicles would enter the communication range of the downstream intersection. In this case, the reservation request would be pre-placed by a vehicle before the vehicle enters the communication range of the downstream intersection. Optimization strategies could also be applied to achieve a minimized system delay with the intercommunication mechanism between the intersections. The corridor-based coordination and optimization will be investigated in future research.

CHAPTER 6: CONCLUSIONS

The major contributions of this research lie in (1) the development of the enhanced reservation-based autonomous intersection control system ACUTA with the incorporation of multiple operational improvements; and (2) the successful implementation of the ACUTA system on a standard simulation platform, VISSIM.

ACUTA was successfully implemented in VISSIM, a standard simulation platform. Although implementation of reservation-based autonomous intersection in VISSIM was widely discussed by researchers, the feasibility was always doubted and such implementation was not undertaken in previous studies. The key steps necessary to implement ACUTA in VISSIM are discussed in this report, which will benefit both future researchers implementing their autonomous intersection control algorithms and existing researchers wishing to implement their autonomous intersection algorithm in VISSIM. By using a standard simulation platform, measures of effectiveness for different control algorithms can be unified, and simulation results are more reliable compared to various customized simulation environments developed by different researchers themselves. Most importantly, results from different studies, particularly for operational performance, can be compared to each other using standard simulation input and output.

Various simulation experiments were conducted to evaluate operational performance of ACUTA. Results show: (1) operational enhancement strategies including Advance Stop Location (ASL), Non-Deceleration Zone (NDZ), and Priority Reservation (PR) for Queuing Vehicles are effective in reducing intersection delay; (2) multi-tile ACUTA has significant operational superiority over optimized signal control under high traffic demand conditions; (3) single-tile ACUTA shows promise in replacing four-way stop control for managing autonomous vehicles at low volume intersections; and (4) ACUTA successfully resolves minor-road starvation and slow-speed reservation issues identified in previous related studies. Key findings from performance evaluations are summarized as follows:

- Both single-tile and multi-tile ACUTA systems have balanced delays for left-turn, right-turn, and through movements under any balanced traffic demand conditions.
- Enabling ASL strategy can result in a 95% reduction (compared to no ASL) in overall intersection delay under a high traffic demand of 550 veh/hr/ln.
- Enabling the NDZ strategy can result in a 90% reduction (compared to no NDZ) in overall intersection delay under a high traffic demand of 550 veh/hr/ln.
- Enabling the PR strategy can result in a 7% reduction (compared to no PR) in overall intersection delay under a near capacity traffic demand of 600 veh/hr/ln, if the parameter "maximum speed to be considered a queuing vehicle" (MSQV) is set to 15 mph.
- Overall intersection delay for multi-tile ACUTA system can remain under 5 s/veh when traffic demand is 550 veh/hr/ln or lower. However, delay starts to increase rapidly when traffic demand is higher than 600 veh/hr/ln, and ACUTA intersection's capacity is approximately 625 veh/hr/ln.

- Multi-tile ACUTA's superiority in delay over the signalized intersection is only marginal under extremely high traffic demands of 800 and 950 veh/hr/ln.
- Single-tile ACUTA operates with a zero intersection delay under traffic demand of 50 veh/hr/ln, outperforming four-way stop control by 37.22 s/veh.
- Single-tile ACUTA operates with a reasonable delay of 27.16 s/veh under traffic demand of 100 veh/hr/ln when four-way stop control already reaches its capacity with a long delay of 103 s/veh.
- Delay for single-tile ACUTA increases dramatically when traffic demand exceeds 100 veh/hr/ln.
- Minor-road starvation issue does not occur when traffic demands of major and minor roads are unbalanced. The magnitude of major-road delay is always higher than minor-road delay due to the larger demand on major road. As minor-road demand increases, both minor-road and major-road delays increase. The magnitude of delay for a traffic movement is positively correlated to traffic demand of that specific movement only, and increases as demand of that movement increases.
- In order to evaluate the possibility of optimizing ACUTA's operational performance, sensitivity analyses were conducted on ACUTA's configurable parameters, including (1) granularity, (2) number of internal simulations, (3) minimum speed to allow fixed-speed reservation (MINSAFSR), (4) advance stop location (ASL), (5) end boundary of non-deceleration zone (EBNDZ), (6) minimum queue length (MINQL) to activate the priority reservation, and (7) maximum speed to be considered a queuing vehicle (MSQV). Analyses show that intersection delay is sensitive to granularity, MINSAFSR, ASL, EBNDZ, and is slightly sensitive to MINQL and MSQV under certain conditions.

Considering that heavy trucks are an essential element of an urban transportation network, ACUTA's capability of accommodating heavy trucks was also evaluated. Results show that ACUTA can efficiently accommodate heavy trucks for up to 35% heavy truck percentage under traffic demand of 500 veh/hr/ln. Key findings for trucks are:

- Heavy trucks generally experience slightly longer delay than passenger cars under all tested traffic demands from 100 to 600 veh/hr/ln.
- Heavy trucks making different movements experience similar delay. This similarity in delay does not change with either traffic demand or heavy truck percentage.
- When traffic demand is 500 veh/hr/ln and lower, intersection delay remains at a near perfect level of no delay for both heavy truck percentages of 15% and 25%, and at a decent level of 30 s/veh for heavy truck percentage of 35%.
- Under the traffic demand of 600 veh/hr/ln, the ACUTA system approximately reaches its capacity when heavy vehicle percentage is equal to 15%, and operates at oversaturated conditions when heavy vehicle percentage is greater than 15%.

In conclusion, ACUTA developed in this research is promising for future applications of accommodating autonomous vehicles at intersections under various conditions. ACUTA's operational performance still has potential to be optimized by fine-tuning the configurable parameters of the system.

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