Proceedings of the 2014 Winter Simulation Conference
A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.

SIMULATING UNSIGNALIZED INTERSECTION RIGHT-OF-WAY

Jessica Mueller
David Claudio

Department of Mechanical and
Industrial Engineering
Montana State University
Bozeman, MT 59717-3800, USA

ABSTRACT

Right-of-way prioritization at unsignalized intersections has been largely unexplored. Drivers do not always use consistent methods to determine who has the right-of-way to enter the intersection at unsignalized intersections. Problems with right-of-way assumptions include that not all drivers engage in one set algorithm to assess intersections priority, and issues of yielding can occur when drivers arrive at an intersection simultaneously or near-simultaneously. A discrete event simulation model was built to emulate a 4-way stop-signed intersection; and different prioritization rules were instated to determine which lane has right-of way. First-in-first-out and yield-to-right prioritization methods were found to differ in terms of time spent waiting and traveling through the intersection, as well as intersection throughput for different intervals of high traffic volume. The first-in-first-out prioritization algorithm provided superior service to drivers arriving at an intersection, compared to the traditional yield-to-right approach, in both low- and high-traffic volume conditions.

1 INTRODUCTION

Right-of-way prioritization at unsignalized intersections has been largely unexplored. With the recent advancements in vehicle-to-vehicle communication capability, there is an opportunity to focus on different methods to allocate vehicle right-of-way. Currently, drivers follow a few different prioritization methods. At completely unsignalized intersections featuring no signage and intersections featuring signage instead of lights, drivers tend to adopt one of two main methods to determine right-of-way. The legally accepted prioritization in the United States and several other countries requires drivers to yield to their right; however some drivers tend to adopt a 'first-in, first-out' method of assigning priority to enter the intersection. Problems with these systems are that not all drivers engage in one set algorithm to assess intersections, and also that issues of yielding can occur when drivers arrive at an intersection simultaneously or near-simultaneously.

By assuming that a system can be placed in all vehicles that would accurately notify the driver about what lane or direction of traffic has priority, uncertainty can be largely removed from the intersection-navigation system so that the driver can focus on other attention-demanding tasks related to driving. This project aims to determine what prioritization algorithm can provide optimal service to people arriving at an intersection, both in terms of time waiting in line, as well as for the number of vehicles that can be processed through the intersection in times of heavy use. This problem is different from past literature in that it focuses on unsignalized intersections, and intends to use an in-vehicle system to relay prioritization information to drivers in an effort to reduce the uncertainty caused by drivers' unclear right-of-way assumptions.

The intent of this simulation was to assess two different prioritization methods for vehicles passing through an intersection, at low and high levels of traffic volume. By modeling the intersection and changing only how prioritization is assigned, these experiments can demonstrate how driver time in the intersection and the queues leading up to the intersection can be minimized.

Discrete event systems simulation is useful here due to its nature—these models relied on logically applied methods for determining vehicle prioritization order, and a simple restructuring of how those logical algorithms work can be easily applied to a single intersection system.

2 BACKGROUND

2.1 Unsignalized Intersections

Many different types of traffic intersections have been referred to as "unsignalized," including intersections of a minor and major road, intersections with two-way stop control, intersections with all-way stop signage, and roundabouts (Torbic et al. 2004). While these are all fairly different road layouts, they all fall under the "unsignalized intersection" umbrella. An analysis of crashes in California found unsignalized intersections show an average of 1.5 crashes per year in rural areas, and 2.5 crashes per year in urban areas (Bauer and Harwood 1996). The same study showed that urban signalized intersections average 4.6 crashes per year. When unsignalized intersections become signalized, the trend generally results in higher crash rates; although those crashes are less severe and the type of crashes change to result in fewer angle or turning crashes, with more rear-end crashes. The finding of increased crash rates is supported by earlier work in Israel, where a study investigating the increase in the level of traffic control at intersection found that any increase in traffic control level tended to result in higher crash rates (Polus 1984).

Looking specifically at fatal crashes, intersection-related crashes are estimated to account for 21% of all fatal crashes; and 42.9% of the fatal intersection crashes occur at unsignalized intersections. These fatal crashes are generally angle-crashes (Torbic et al. 2004).

One problem with unsignalized intersections may be that drivers may be unaware of local driving standards or laws. Summala (1998) studied American drivers on-road in Helsinki, and found that all drivers showed unsafe driving behaviors at the unsignalized intersections. The drivers showed improved and safer behaviors after training, but found that the different signage policies and varying traffic laws in different parts of the world may be leading to more crashes at these types of intersections.

2.2 Traffic Conflicts at Unsignalized Intersections

Typical traffic intersection simulation models try to include variables that drivers use to assess their own decision of whether or not to enter the intersection. The widest accepted definition of traffic conflicts is "an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged." (Amundsen and Hyden 1977). Due to this definition of traffic conflicts, many studies focus on metrics like time-to-collision (TTC). TTC describes the amount of time it would take for a crash to occur if both vehicles continue on their present speed and heading. Minimum and maximum values of TTC have been identified in virtual simulations and on-road studies; and these findings result in many intersection simulations using variables like TTC or gap acceptance as quantifiers for whether or not drivers will preempt or yield to other vehicles at intersections (Sayed et al. 1994).

Li et al. (2011) specifically examined characteristics of unsignalized intersections, looking at conflict angle at hypothetical collision points (frontal, wide-angle lateral, vertical lateral, small-angle lateral, or rear-end conflict) as well as the crash type (head-on, angle, or rear end) for several different types of unsignalized intersections. They were able to develop intersection crash severity classifications based on these parameters, with the intention of using the classification predictions in future unsignalized intersection crash prevention driver support systems.

2.3 Simulated Traffic Flow in Literature

A great deal of literature exists describing simulated traffic systems, worldwide. Depending on the traffic characteristics relative to the study intersection, different elements are specifically included in the model. A paper from India separated incoming vehicles into types, including pedal cycle, motorcycle, autorickshaw, car, or heavy vehicle, and was focused on the traffic conflicts encountered in the study intersections (Rao and Rengaraju 1998). Rao and Rengaraju were primarily concerned with finding conflict rates given different levels of traffic volume on the minor and major roads composing the intersection.

In more recent years, the topic of driver trait characteristics has been explored to examine how this may affect driver behavior at intersections. Kaysi and Abbany (2006) modeled aggressive driver behavior based on the idea that gap acceptance was a critical part of modeling driver activity in unsignalized intersections; and that aggressive drivers have fundamentally different basic levels of gap acceptance than the 'average' driver used in past research.

An Indonesian study focused on using simulation to establish intersection capacity for 3-segment unsignalized intersections, based on the potential conflict points and taking into account mixed vehicle types, and the ambient speeds (Prasetijo et al. 2011). The simulation states that it ignores priority rules, due to the local tendency to ignore common prioritization methods. Prasetijo et al. use their simulation as a method to assess intersection capacity.

One study focused on the interactions between pedestrians and traffic at a signalized intersection (Suh et al. 2013). Suh et al. noted that pedestrian behavior has a fairly significant interaction with similar characteristics that are seen in unsignalized intersections with gap acceptance—and noted that it is a mistake to assume pedestrian crossings are always in compliance with pedestrian signals. The integration of pedestrians into an intersection shows how pedestrians can actually influence traffic behavior; pedestrians crossing irrelevant to signals can alter vehicle time through the intersections and general traffic flow.

Liu et al. (2012) studied U-turns in simulation, and was able to calibrate and verify that simulation models were able to provide acceptable intersection capacity estimates. In this case, the simulation was used to expand the study capability of an existing traffic simulation software and confirm that it could be effectively used to study an irregular traffic maneuver once sufficiently calibrated.

Wu et al. (2013) developed a collision avoidance system for unsignalized intersections that focused on completely unsigned intersections and thus, if a driver approaching from one direction was at risk of hitting a potentially obscured driver arriving from a different approach, the system would warn the driver approaching from the minor stream of traffic that his path was not clear. This system was tested and verified to work with simulated drivers using PreScan simulation software, but not validated on-road.

2.4 In-Vehicle Driver Warning Systems

As one objective strategy for improving safety at unsignalized intersections, the National Cooperative Highway Research Program (NCHRP) recommends improving driver awareness of intersections (Torbic et al. 2004). While their suggestions for increased awareness include improved signage, rumble strips, or guidance lighting; one opportunity for this increased awareness involves in-vehicle driver alert systems.

Driver warning systems to date have focused primarily on either accessory systems (GPS) or crash warnings. Crash warning systems have found encouraging results; heavy truck drivers have shown increased headway in dense traffic; and responded to traffic conflicts faster with warning devices in use (Bao et al. 2012). This shows that driver warning systems are working, and they are becoming more prevalent as technology advances in cars.

A driver support system designed to provide gap information to drivers at intersections was tested in driving simulators. Drivers consistently used the displays and were consequently more likely to stop at the intersection stop signs, they waited longer to cross, and they were less likely to cross in small or critical gaps (Becic et al. 2012). The same type of system could be used to inform drivers about priority in intersection navigation. The findings in related driver warning systems show that at least in pilot simulator studies, drivers are using these displays and adjusting their behavior toward the safer driving habits that the displays try to elicit.

While critical gap estimation and crash warning plays a large component in much of the past research using driver warning systems, this research is novel in that it suggests using similar systems within driver vehicles: an on-board dynamic indicator of priority. This should eliminate the need for drivers to individually assess intersections for preempting or yielding behaviors.

3 METHODS

3.1 Models

The models were created using Arena v. 14.0. First, each lane of a 4-way intersection was modeled separately (North, East, South, and West). Each lane has its own arrival rate, calculated based on discrete observations of a similar intersection in South Bozeman, MT. Once in the queue for the lane, each arriving vehicle is assigned a direction to turn, based on percentages from the same discrete vehicle observations. The actual overhead of where the lanes meet was divided into four resources; with vehicle requiring a certain combination of those resources in order to complete their desired driving maneuver. For example, a vehicle from the east lane who was turning left into the South lane would need to use resources 1, 2, and 3. An estimated time to complete the driving maneuver was assigned (4 seconds), and once the vehicle completed travel through the intersection, the vehicle exited the simulation. A diagram of the proposed system is shown below in Figure 1.

For all models, two different arrival rates were used for all lanes. First, the arrival rates observed from a local intersection were used in calculating the rates; and a second more dense arrival rate was also used that is intended to be reflective of a similar intersection with higher traffic flow. The data that were used were manually recorded discrete numbers of vehicles arriving at each lane, as well as the direction that each vehicle turned. The time period used to calculate arrival rates was between 4:30PM and 5:30PM, which was the highest traffic flow rate observed for all lanes in the entire intersection, shown below in Figure 2.

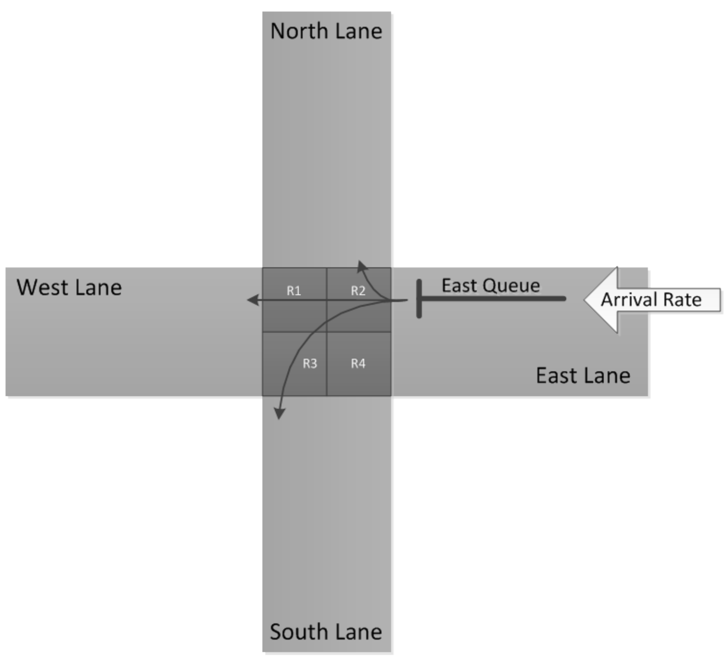

Figure 1. Intersection diagram, with paths of travel highlighted for the East Lane

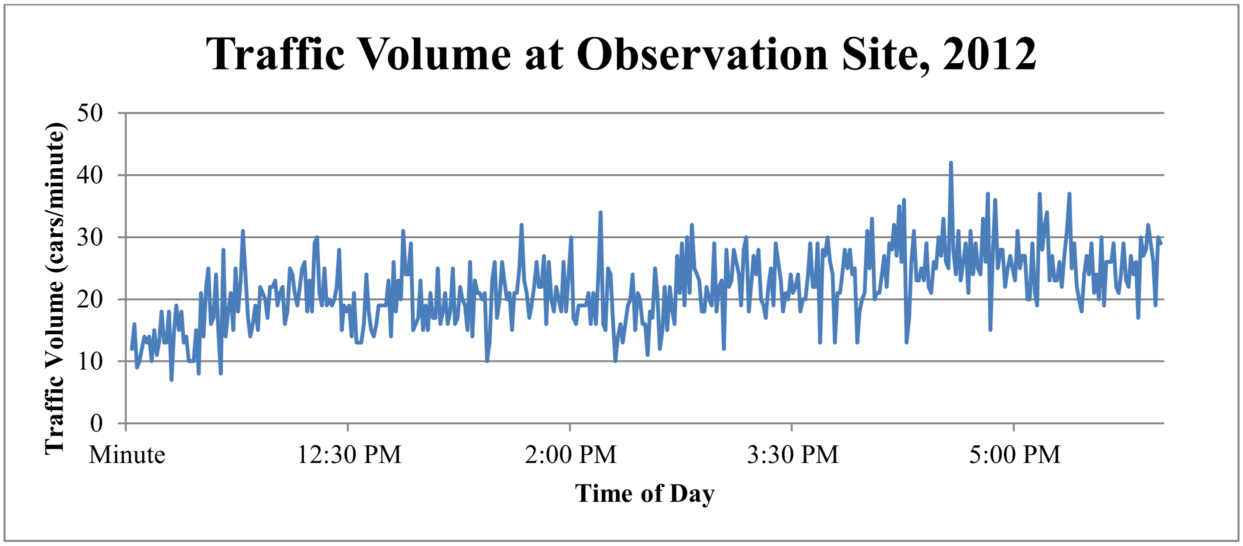

Figure 2. Traffic volume used to calculate rush hour lane arrival rates

To calculate arrival rates from these files, each lane was separately evaluated into intervals and tested to fit Poisson distributions for the "rush hour" between 4:30 and 5:30PM. Since all lanes fit a Poisson distribution, the entire data set was shown to follow a non-stationary Poisson process; meaning that the inter-arrival times were exponentially distributed. The calculated inter-arrival times are shown below in Table 1.

Table 1. Inter-arrival times used in Arena Models

Lane	Rush Hour Inter-arrival Time (min/car)	Average Inter-arrival Time (min/car)
North	EXPO(1/5.03)	EXPO(1/4.3)
East	EXPO(1/6.75)	EXPO(1/4.85)
South	EXPO(1/8.66)	EXPO(1/5.18)
West	EXPO(1/6.18)	EXPO(1/5.62)

Arrival rates were calculated using Arena's Input Analyzer. Simulations length was one hour each; to model both "rush hour" and a comparable hour of normal traffic. Some of the assumptions associated with all of the models include (i) once vehicles enter a lane, they cannot leave the queue; (ii) the lanes here have unlimited capacity; (iii) vehicle cannot enter the lanes from any other source, such as if there were driveways or parking spaces adjacent to the intersection; (iv) there are no balking vehicles; (v) vehicle paths requiring exclusive resources are able to travel simultaneously; and (vi) no pedestrians are interfering with traffic patterns.

3.1.1 First-In-First-Out (FIFO) Model

The FIFO model was designed to reflect the pattern of behavior displayed by drivers in which the lead vehicle in each lane's queue decide who gets to go based on who has been there the longest. In addition, if one vehicle begins a maneuver and a second vehicle is able to pass through the intersection (even if it is not that vehicle's turn), it is able to do so. This would happen if for example, the lead vehicle in the East lane had priority to enter the intersection travelling West, while simultaneously the lead vehicle in the West lane was travelling East. They would both complete their maneuvers, even though it may not have been West's turn to enter the intersection.

To accomplish this priority scheme, a variable was set up to record the time that the lead vehicle in each lane assumed the lead vehicle position. This variable was then compared across all four lanes, and the vehicle with the earliest time of arrival was assigned a higher priority to travel through the intersection than the other lanes. If any vehicles were in queue behind the first vehicle, their time to assume the lead position was given as the time that the previous vehicle entered the intersection.

3.1.2 Yield-To-Right (YTR) Model

The YTR model reflects the legal rules for yielding in unsignalized intersections, in many parts of the world. While not always used, this method of vehicle prioritization means that if two vehicles arrive to an unsignalized intersection simultaneously, then the right-most vehicle has priority to enter the intersection first. Likewise, as all four lanes form queues, the priority cycles through the lanes in a clockwise direction. Similar to the FIFO method, if there is potential for two vehicle to enter the intersection and complete their maneuvers simultaneously, they will do so.

The YTR model was built using global variables that demonstrate priority for each lane. One particular lane has the highest priority to enter the intersection; and as that vehicle leaves the system, the highest priority is then passed to the next lane in the clockwise cycle.

4 ANALYSIS AND RESULTS

To assess the average time in system, as well as vehicles passing through the system, the desired number of replicates of each model were calculated to give a 95% confidence with a half-width less than or equal to 2% of the time in the system. The half-width of 2% was selected as the time in the system ended up being fairly small for each vehicle; a 2% half-width would give a precision of within the nearest second. For calculations using the rush-hour arrival rates and simulation lengths of 15 minutes, the FIFO system required 320 replicates to arrive at this precision; the YTR system required 241 replicates. Because the FIFO model required more replicates, both systems were run for 320 replicates. For calculations comparing overall average arrival rates with simulation lengths of 8 hours, the FIFO system required 98 replications, and the YTR system needed 140 replications, so 140 replications were used for both systems in those specific calculations.

4.1 Time in the Intersection System

The FIFO method results in a statistically significant lower interval of time in the system when using the higher rush hour arrival rates; a 95% confidence interval on the difference in mean time in system showed that time in system for YTR cars was (30.7, 41.1) seconds longer than the time in system for the FIFO cars. For the simulation using the overall average arrival rates, the FIFO method of prioritization also shows a significantly lower time in the system; a 95% CI on the difference in mean total time in system is (1.85, 2.76) seconds. System specific characteristics are shown below in Table 2.

Table 2. System comparisons between FIFO and YTR Intersections for Time in System

Arrival Rates used in Simulation	Prioritization Method	Replications	Time in System	Variance
Rush Hour arrival rates	FIFO	N=320	2.994 ± 0.0597 minutes	0.2969
	YTR	N=320	3.593 ± 0.0628 minutes	0.3282
Overall average arrival rates	FIFO	N=140	0.2870 ± 0.0044 minutes	0.0007
	YTR	N=140	0.3254 ± 0.0062 minutes	0.0014

4.2 Number of Cars Through System

The FIFO method results in a statistically significantly higher number of cars passing through the system when the simulation uses the rush hour arrival rates; a 95% confidence interval on the difference in mean number of cars exiting the system is (30.9, 37.4) cars. Analysis for the simulations using the overall arrival rates over a longer period of time do not show any significant difference between the YTR and FIFO systems in the number of cars that pass through the system; the 95% confidence interval is (-28.30, 16.6) cars. System specifics are shown below in Table 3.

Table 3. System comparisons between FIFO and YTR Intersections for No. of Cars Through Intersection

Arrival Rates	Prioritization Method	Replications	Number of Cars through Intersection	Variance
Rush hour	FIFO	N=320	1428.3±2.32 cars	448.5
	YTR	N=320	1394.2±2.23 cars	414.0
Overall average	FIFO	N=140	9556.61 ± 16.05 cars	9197.16
	YTR	N=140	9562.46 ± 16.16 cars	9174.06

5 DISCUSSION AND CONCLUSION

While the YTR system is more reflective of current traffic laws, this simulation shows that if a method can be put in to place that safely enables a FIFO algorithm to establish priority, then time spent navigating through intersections could be reduced, simultaneously increasing the number of cars that could travel through the intersection system. Even with lower arrival rates—when the overall arrival rates were used to find the difference in mean time in the system—the FIFO system still shows superior average time in the intersection system.

It is also worth noting that these arrival rates were calculated for an intersection in a semi-rural community; busier intersections and urban areas would benefit much more than this simulation shows. While the time savings seem slight—if the change to a FIFO system results in a 36-second reduced time at the intersection per vehicle in a 1-hour interval characterized by rush-hour traffic; the effects in an urban area with higher traffic volume would result in longer ‘rush hour’ periods—thus the time savings would be additive in busier systems. The same small gain in average system time is also seen in the longer (8-hour) simulation with lower arrival rates—this shows that the biggest opportunity for benefit due to a prioritization method more similar to FIFO lies with high-volume intersections; which will be primarily found in more urban or populated areas.

The biggest assumption to implement an intersection prioritization system described above would be that all vehicles are expected to have inter-vehicle communication capability. While this is certainly not the case with current technology, it is a possibility that could be kept in mind as in-vehicle systems become more advanced in newer vehicles. While much of past literature is focused on simulating traffic to identify conflict rates; an in-vehicle system would reduce much of the guesswork in navigating through unfamiliar roadways or vague signage. Another assumption which bears recognition is that this iteration of the simulation did not include any delays associated with checking for and potentially waiting on pedestrians. Suh et al. (2013) used simulation with pedestrians to show that they had a definitive impact on traffic flow at signalized intersections, it is reasonable to assert that they could have a similar effect on unsignalized intersections as well.

Other system prioritization methods should be examined, to see if there is a clearly superior option. In this research only the two most common priority methods seen in the US were examined; other geographic areas or cultures may have alternative native methods that are commonly in use. In the meantime, the safety implications of this type of an intersection priority assignment should be investigated as this type of prioritization is a long term strategy.

ACKNOWLEDGMENTS

Thanks are due to Dr. Claudio's past students for collecting intersection data.

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AUTHOR BIOGRAPHIES

JESSICA MUELLER is a Ph.D. Candidate in the Department of Industrial and Mechanical Engineering at Montana State University. Her research interests lie primarily in transportation research using driving simulation and instrumented vehicles to study driver behavior. She is a member of IIE, and HFES. Her email address is jessica.mueller@coe.montana.edu.

DAVID CLAUDIO is an assistant professor of industrial engineering in the Department of Mechanical and Industrial Engineering at Montana State University, Bozeman, Montana. He received his Ph.D. in Industrial Engineering from the Pennsylvania State University. His research interests include Human Factors, Service Systems, Healthcare Engineering, and Decision Making. His email address is david.claudio@ie.montana.edu.