"Interchange: An Analysis of Auction Mechanics for Intersectionss"

by

Nitin Shantharam

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The Laboratory for Ubiquitous Computing and Interaction

Department of Informatics

Donald Bren School of Information and Computer Sciences

University of California at Irvine

UNIVERSITY OF CALIFORNIA,
IRVINE

Interchange: An Analysis of Auction Mechanics for Intersections

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Information and Computer Science

by

Nitin Shantharam

Thesis Committee:
Professor Donald J Patterson, Chair
Professor Bill Tomlinson
Professor Ramesh Jain

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DEDICATION

To my parents Shantharam Keshava and Rajani Shantharam, and my sister Shruti.

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ACKNOWLEDGMENTS

I would like to thank Don Patterson for his invaluable input and support. Moreover, this work could not have been completed without the support of Bill Tomlinson and Ramesh Jain. I would also like to thank Ryan Idrogo-Lam for his input and exceptional work on the simulator.

ABSTRACT OF THE THESIS

Interchange: An Analysis of Auction Mechanics for Intersections

By

Nitin Shantharam

Master of Science in Information and Computer Science

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Professor Donald J Patterson, Chair

In urban environments a large amount of effort is directed toward alleviating motor vehicle congestion including the design and implementation of complex software and hardware infrastructure. We propose a conceptually simple infrastructure that has promise for increasing performance and responsiveness of intersections to dynamic traffic conditions. The proposed system uses an auction-based mechanism at intersections to alleviate traffic congestion. We discuss the reasoning and goals of implementing auction mechanics into intersections and set empirical expectations as to how such intersections should perform. Second, we compare our simulation of a traditional intersection and an auction-based intersection and propose metrics to track and evaluate such intersections. We demonstrate that auction-based intersections perform well in single and multi-grid configurations. Finally, we present our mesoscopic simulator capable of simulating real-world topographies and show that auction-based intersections show promise in more realistic systems as well.

Chapter 1

Introduction

Steve usually starts his morning at 8am with coffee and a bagel, but today is special. It is his birthday and his destination isn't the office, it is Las Vegas, so waking up an hour early didn't seem so bad. After packing up the car, he sets up his Interchange enabled GPS Navigation System, adding stops at his friends houses' to pick up his fellow bachelors. The system maps his optimal route before asking him how much he'd be willing to spend to get to Vegas faster. Running late, Steve starts by setting his bid at its highest.

As he drives to his friends' houses, Steve's Interchange enabled GPS Navigation System automatically sends a bid to each intersection as approaches them. Since his friends live on side streets Steve has to cut across several arterial streets that when "optimized" under a traditional timed intersection would have made his trip slow driving. Luckily, the city of Irvine recently installed Interchange lights and Steve's bids are enough to win him the light as he picks up each of his friends.

With everyone now in tow, Steve begins to settle in for the 3 hour trip. No longer feeling rushed, he considers leaving his Interchange rush status where it is, but realizes that on the freeway there are no intersections anyways. So as he merges onto I-15, he leans over to his Interchange enabled GPS Navigation System and toggles his rush status down to zero and continues on his way.

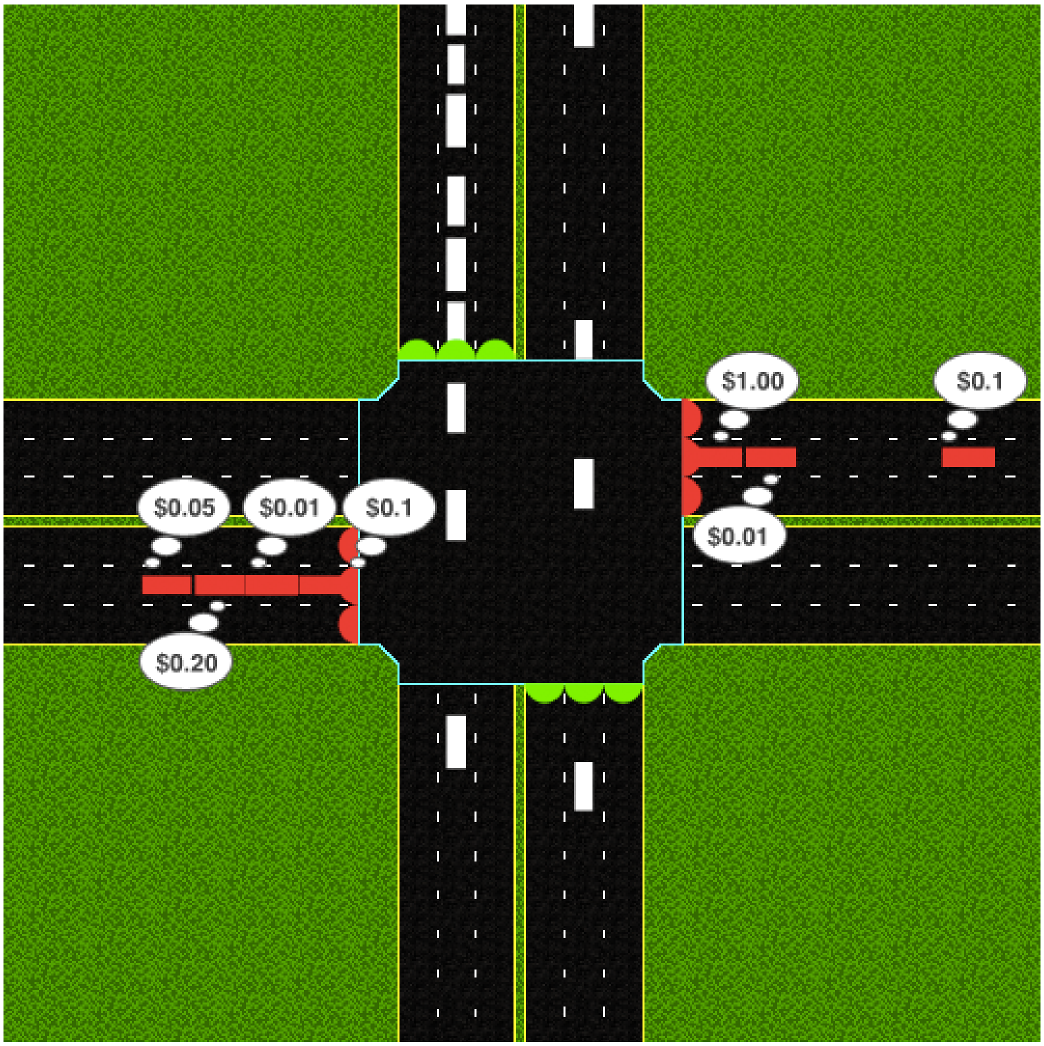

Figure 1.1: An screenshot from the Interchange version of AIM4 with vehicle bids overlaid.

"Interchange" is a system that manages traffic light cycles according to auction-based mechanics rather than through in-road loop sensors and timing (see figure 1.1). To use our system, drivers must have a vehicle equipped with a computer interface to networked navigation assistance such as that provided by Google Maps or MapQuest with an additional software component that communicates to Interchange. When a driver enters the vehicle they specify their destination and a degree of "rushedness" which is expressed in terms of a dollar-amount that they are willing to spend to turn an individual light green (w.l.g., [$0.00 - $1.00]). The navigation software plans a route, as is typical in such systems today, and sends it to Interchange which keeps track of the route progress of all vehicles participating in the system and the current individual bids. As the driver proceeds along the route, Interchange aggregates the total bid of all vehicles that are within range of an intersection and chooses the pattern of the various safe red/green light configurations that maximizes the highest current total bids. This system creates a number of dynamics:

- An individual traveling alone on a road network would have all the lights turned green for her for negligible cost.
- People who are late for appointments could bid the maximum amount to reduce wait time.
- Cost-sensitive drivers could travel in ad-hoc packs, gaining advantage without expense.
- Public service vehicles such as ambulances and police vehicles could be given the ability to bid arbitrarily high to support the public good of their trip.

1.1 Preparing for the Future

Interchange does not require *large-scale infrastructure coordination*, or *major changes in a driver's behavior*. Requiring infrastructure coordination is problematic because of the complexity of urban environments and because of the administrative and political difficulties of coordinating across boundaries such as at city limits or borders. Our system is an attempt to alleviate traffic congestion in a way that is feasible starting from existing technology. To realize such a system, intersections would have to have modest additional hardware installed which would support network control of traffic light settings. Such a system would naturally need to be secured against malicious access and have a failsafe mechanism that would revert to existing behavior in the event of a network failure. Notably, however, it is not necessary for *all* intersections to be upgraded for this system to work; it can be done incrementally with correspondingly incremental benefit.

On the driver's side it is necessary for the driver to have software installed in their vehicle that specifies and communicates a desired route (similar to [14]). This knowledge is critical for the ability of the system to identify the intentions of a driver when they are approaching an intersection so that a bid can be offered for the desired transition through the intersection as there may be no other way to indicate a desire to turn. If a driver does not have such a system installed in their vehicle, then loop sensors that are present in the road could offer a no-cost proxy bid on behalf of the driver. In the absence of any loop-sensors, a collection of proxy bidders could be maintained which each wish to transition through the intersection in a different way. Over a short time interval their bid value can gradually increase causing the intersection to appear to behave as if it was operating on a simple timer mechanism. Finally, in the event that a driver changes their destination or is unable to specify their destination at the beginning of their trip, technologies that do online route *prediction* can substitute with minimal loss of accuracy in the near-term [6, 10].

Additionally, although for clarity we frame this system as functioning through a centralized coordination scheme, with subsequent threats to privacy, there isn't any technical reason that prevents the logic of the system from residing in the intersections themselves (or as is typical in the literature, in "agents") with direct-communication between vehicles and intersections. We therefore argue that although the system we propose entails technological complexity, it can be implemented within and alongside current infrastructure and will not adversely impact the existing transportation infrastructure.

1.2 The Market and Payment Methods

Key pieces of technology required for Interchange already exist and are in use. Interchange can utilize the infrastructure in place to charge toll road drivers during auctions. Although the most obvious method of implementing payments in this system involves coordination with an online debit/credit payment gateways, we only introduce our system in this way for ease of understanding. It is possible to engineer the market in this system to support a wide variety of social values. Although it is beyond the scope of this paper to explore these possibilities in depth, it is important to mention the possibilities of such a system, for example, the ability to:

- Pay with non-currency "credits" that are distributed via an incentive system and impose non-financial penalties such as longer wait times for those who violate traffic laws.
- Distribute the payment from auction winners to the losers so that they can trade waiting time now for future priority.
- Allow local businesses to sponsor turn lights so that it is cheap and easy for customers to get to their store.
- Allow people to trade Interchange credits on an open market so that speculators can profit on events which increase or decrease traffic.
- Allow buses and carpools to multiply their bid by the number of passengers.

1.3 Related Work

In the computing literature, related work falls primarily into two categories: smart networked intersections, typically agent-based, and auction-based mechanisms for time/slot allocation. We describe some notable related work in the literature below.

Roozemond et. al. propose an agent based Urban Traffic Control system (UTC) capable of adapting to traffic conditions in real time [11]. In this system intersection control ITSAs (Intelligent Traffic Signaling Agents) are complex agents that periodically receive and distribute data. In the proposed system a network of ITSAs communicate with the UTC which maintains global knowledge of the system. ITSAs receive information about the current state of traffic, information about nearby ITSA's, and are capable of analyzing and interpreting received data to make appropriate changes to their policies. ITSA's show how a pro-active and re-active system can potentially be a helpful paradigm. However, because of the global nature of the system an implementation on a wide scale would require significant investments in infrastructure.

Dresner and Stone propose a multi-agent reservation based system for increasing throughput and decreasing delays at traffic intersections [3]. In the proposed system vehicles request reservations for a specific times and lanes to pass through an intersection. The intersection manager simulates traffic based on the requested reservations faster than real-time and only confirms reservations that will not cause accidents. While such a reservation-based system outperforms traditional intersections, Dresner and Stone admit to difficulties in implementing such a system in the real world. Such a system changes the rules of the road within the intersection, by, for example, removing traffic lights. With no option for individual reactive agency, all vehicles would have to implement and always stick to the intersection control policies in place. Moreover, Dresner and Stone present their AIM4 simulator capable of simulating the reservation based system. Our single intersection and simple multi-intersection experiments build on top of AIM4 to simulate Interchange.

In a time/slot reservation system vehicles need to adhere to confirmed reservations to an accuracy that, while appropriate for autonomous driving, would be unfeasible for human drivers. Dresner and Stone propose new light models that allow for autonomous driver use in conjunction with human drivers [2]. In the all-lanes model every lane in a given direction will go green while all other lanes stay red. As time progresses the intersection would give all lanes in another direction greens and set all others lanes to red. In their single-lane light model only a single lane would be green at any given time. In turn, green lanes would rotate through all possible directions of the intersection. In our light model for Interchange we allocate specific time for left turns while other lanes react similarly to Dresner and Stone's all-lanes model.

Balan et al. [1] evaluate fairness as opposed to efficiency when dealing with traffic control systems. Fairness, they argue, is often neglected because of the difficulties in implementing a "fair" system in traditional static traffic controllers. Their proposed system, based on historical fairness, awards credits to vehicles waiting at red lights. By storing credits in vehicles, traffic controllers are able to base their decisions on the credits vehicles have stored. In turn, traffic controllers make decisions based on vehicles' historical wait times and show preference to vehicles who have waited longer than others. Results from their experiments showed that history-aware traffic controllers were not only more fair, as they had expected, but that under some circumstances were more efficient than traditional traffic controllers.

Le et.al, describe utilizing auction systems to optimize a multi-faceted system for assigning aircraft landing slots in crowded airports [8]. They propose simultaneous multiple round and package auctions and, importantly, they argue that the bid price is only one determining factor among many that should be taken into account in the market: "Auction rules determining the winners for each round are made public. The amount of bid is only one of the six factors that constitute the scores of airlines for each round, the other fives are 1) number of seats; 2) flight OD pair; 3) prior airline infrastructure investments to insure financial investment equity; and 4) historic slot occupancy rates to insure schedule stability [8]."

Finally, Vasirani and Ossowski propose a market-inspired approach to traffic management at intersections using a time-slot mechanism [12]. In such systems a vehicle makes a request for a reservation to cross an upcoming intersection for a specific space-time. These reservation requests can also include details regarding the price to cross the intersection. Intersections calculate all potential crossing patterns and grant reservations to a subset of vehicles. Vehicles that are unable to get a reservation must stop when they reach the intersection and request a new reservation. Further work by the authors show that maximizing intersection profit also shows significant reduction in average vehicle travel times [13].

1.4 Contributions

Our hypothesis is that auction-based intersection management will be more efficient than systems based on timing cycles or loop sensors and that this efficiency will hold in more complex multi-intersection topologies. Although the concept of auction mechanics at intersections is not novel in and of itself, we extend upon prior work to further evaluate the potential for such a system. Moreover, we introduce our mesoscopic simulator capable of simulating real-world topologies and evaluate the potential benefits of Interchange. Our contributions are as follows: We expand on prior work evaluating the idea of an auction-based mechanism for resolving vehicle intersections using a multi-way group auction mechanism. We propose new metrics to evaluate intersections that attempt to capture a more human aspect of vehicular transportation. Previous metrics have focused on system-wide performance evaluations (with a few exceptions [5, 7, 9, 13]). Finally, we simulate a complex multi-intersection system using real world data to confirm our hypothesis.

Chapter 2

Model

In a simulated intersection in our system, i, an auction works as follows: When vehicles approach within 10sec (distance varies based on vehicle speed) of i on a route in which they are being confronted with a red light they make a bid via Interchange for a green light and begin decelerating to a stop. A bid is formally a 3-tuple specifying the lane of origin, $o \in O_i$, the destination lane, $d \in D_i$, and a bid value $v \in [\$0.00-\$1.00]$, $b = \{o, d, v\}$. A vehicle may only bid once per intersection. Interchange maintains a database of bids and first, aggregates across those that begin and end in the same lanes, $B_{o,d} = \sum_{b \mid b.o=o, b.d=d}(b.v)$. Each intersection, based on the lane and road configuration, has a set of traffic patterns, $\bar{P}$, that are consistent with safety. Each pattern, $p \in \bar{P}$, allows multiple transitions of the form $o \rightarrow d$. As time progresses Interchange monitors the aggregation of bids, $\bar{B}$, and then further aggregates for each p, the total bid for a light pattern: $T_p = \sum_{(o,d)\in p}(B_{o,d})$.

When any pattern bid, T_p, becomes higher than that of the current winning pattern the lights smoothly and intelligently switch to the pattern with the new highest bid, with yellow lights assigned to lanes whose setting is changing from green to red. To prevent undesired behavior, bids from slowing and stopped vehicles are only subtracted from the aggregates as they leave the intersection, not when the lights switch. If n vehicles participate in the winning bid, and the second highest bid *at the time of the last pattern switch* was, T_p', then individuals are charged T_p' distributed *in proportion* among the winning vehicles as they leave the intersection. This is consistent with the lowest price that could have been offered to win the auction.

Furthermore, we've instituted a minimum time period (10 seconds) and maximum time (60 seconds) that a light configuration remains stable. This prevents lights from switching too rapidly, preventing vehicles which need time to accelerate, from leaving the intersection. It also prevents vehicles which are not participating in Interchange from not being allowed to transition through the intersection. Vehicles which pass through the green light after the auction resolution are not charged.

For our first evaluation we simulated single and multiple intersections. Our single intersection simulation consisted of 8 total lanes in a North/South and East/West configuration. We simulated vehicles traveling straight through the intersection to ease the interpretation of our data.

We implemented our simulation for single-intersection and simple multi-intersection grids by extending the Autonomous Intersection Management (AIM4) simulator because of its ease of use and adaptability [4]. We extended the AIM4 simulator by implementing a new kind of intersection request handler capable of accepting bids from vehicles, running an auction, and establish light patterns for the intersection. Moreover, we implemented functionality for vehicle drivers to detect Interchange-capable intersections and send bids appropriately. Our later work uses a new mesoscopic simulator we have developed capable of simulating real world topologies.

2.1 Evaluation Metrics

There are numerous ways used in the literature to evaluate intersections such as average speed, probability of stopping, emissions level, etc. [1] Most evaluations focus on "hard" metrics. These metrics are indicative of overall intersection performance from a non-humanistic point of view. However, we argue that transportation is a human-based task and can be better understood and evaluated with metrics that capture "soft" driver-related parameters. Drivers, for example, are engaged in a process of going from their origin to their destination. However, not all drivers need to reach their destination at a set time. Some drivers may be in a rush to reach their destination, others may not be concerned with minor delays. We aim to take these factors into account in our evaluation to show how such metrics can be used to better understand a socio-technical system like this and to show the potential gains that would otherwise be missed.

2.1.1 Hard Metric: Wait Time

The primary metric we use to measure performance is wait time. We track wait time by simulated drivers from the moment the vehicle comes to a stop until they begin accelerating again to clear an intersection.

2.1.2 Soft Metric: Driver Rushedness

Intuitively, a driver agent that is more rushed might be willing to bid higher to pass through more green lights. "Driver Rushedness" represents how rushed a driver agent is at any given moment directly represented as a value in the arbitrary range of 0 and 100, inclusively. We make the assumption that drivers will bid a corresponding amount in the auction in the range of \$0.00 and \$1.00. Driver Rushedness is treated as an independent variable in our evaluation.

Chapter 3

Single Intersections

We based our evaluation on a set of traffic scenarios: the traffic conditions along each road, and the amount of driver rushedness. For each traffic profile we ran our modified AIM4 simulator on both traditional and auction-based intersection models. For all of the results that we present we collected enough data such that with 95% confidence, the measured mean wait time is within 20sec of the true mean wait time.

For our single intersection model two roads, N/S and E/W, each have one lane in each direction. Vehicles enter the simulation according to a Poisson distribution, with the parameter, λ_{NS} and λ_{EW} which are the "introduction rates" that represents the probability that a new vehicle will be instantiated on a given incoming road at each simulator tick. Intersection saturation occurs at approximately $\lambda = 0.5$.

3.1 Baseline

As a baseline we first established that our auction-based intersection does no worse than a traditional intersection in comparable circumstances which also verified the

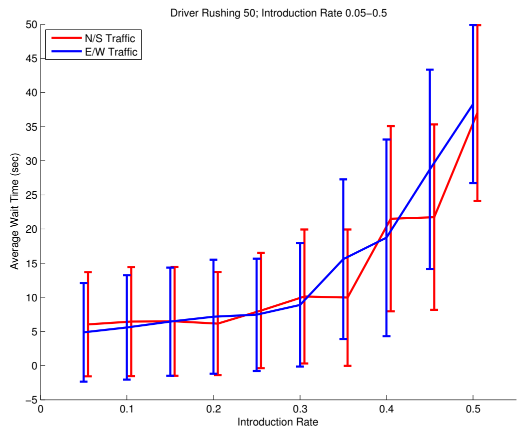

Figure 3.1: A timed intersection with gradual increasing traffic.

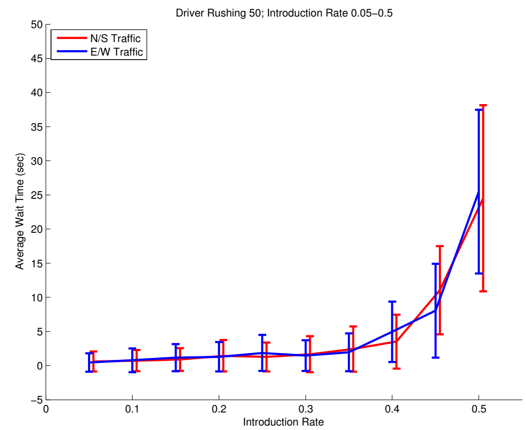

Figure 3.2: An Interchange intersection with gradual increasing traffic.

correctness of our implementation. We established our first traffic profile as one in which traffic along both roads was equal and λ varied from 0.05 to 0.5. We expected vehicle wait time to increase along with λ in both cases. Moreover, we expected the auction-based intersection to be equivalent to the traditional intersection since all drivers would be bidding the same constant amount in equal traffic. We collected statistics separately for each road for consistency with later experiments. As expected, both the traditional and auction-based intersections reacted similarly to this traffic profile as shown in figures 3.1 and 3.2. As the traditional timed intersection always makes some vehicles wait even under light load, there is some wait time even at very low, λ. This is not the case for an auction-based mechanism which had no wait time under light load and slightly lower wait times under high load. The timed intersection also had greater variability in the wait time as the lights did not adapt well to randomly induced surges in traffic.

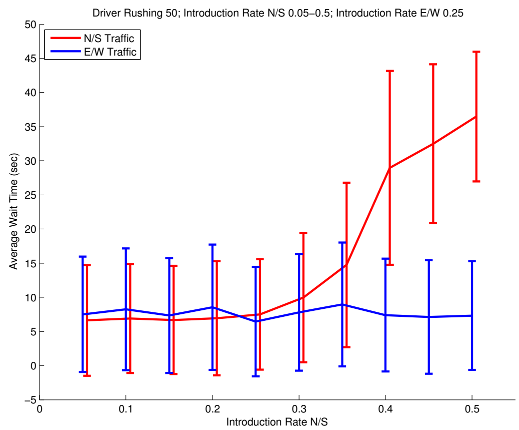

Figure 3.3: A timed intersection where only N/S traffic progressively becomes heavier.

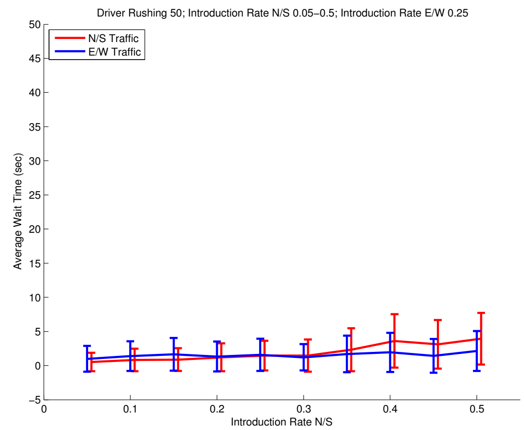

Figure 3.4: A Interchange intersection where only N/S traffic progressively becomes heavier.

3.2 Heavy Traffic Along One Road

The second simulation we ran was to test the effectiveness of the intersection when traffic along one road becomes heavily congested. To simulate this, λ_{NS} on the N/S road increased, the E/W road kept a steady, $\lambda_{EW} = 0.25$. The results of this traffic profile are shown in figures 3.3 and 3.4. In the timed intersection, wait time along the N/S road is slightly lower until the $\lambda_{NS} = \lambda_{EW}$ and then it increases above that of the E/W road. Vehicles begin to back up and wait time along that road dramatically increases. When simulated with the auction-based intersection the higher λ_{NS} equates to, on average, a higher bid, via aggregation, along the N/S road and the intersection switches more frequently to allow N/S traffic to pass. Nonetheless a slight transition is also noticeable when $\lambda_{NS} = \lambda_{EW}$. Under this profile Interchange gives N/S traffic approximately 4 more seconds than E/W traffic per green light for vehicles to pass.

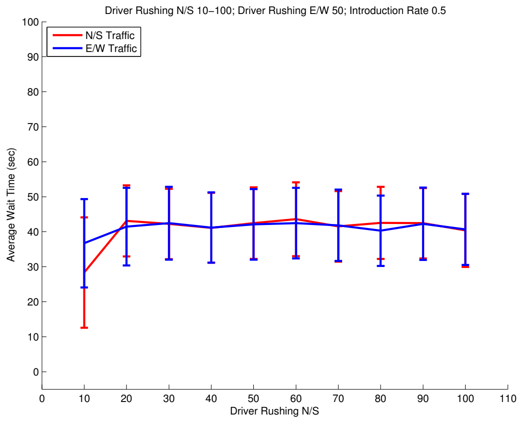

Figure 3.5: A timed intersection where N/S traffic progressively becomes more rushed while E/W traffic remains constant.

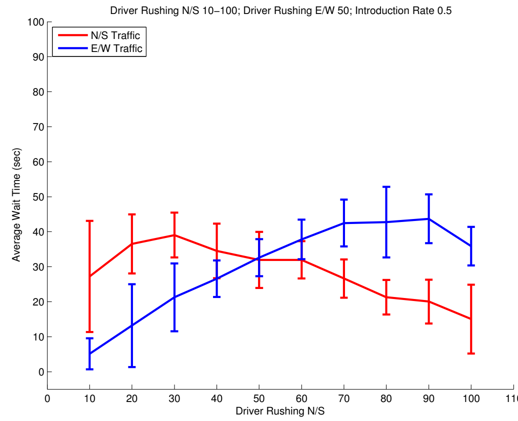

Figure 3.6: An Interchange intersection where N/S traffic progressively becomes more rushed while E/W traffic remains constant.

3.3 Rushed Drivers Along One road

In our third profile, we kept both introduction rates steady, but at a relatively high level $\lambda_{NS} = \lambda_{EW} = 0.5$. We varied the rushedness to evaluate the effect of bidding on wait time. E/W drivers were set to bid \$0.50 while N/S drivers bid between \$0.10 and \$1.00. The results are shown in figures 3.5 and 3.6. Under a traditional intersection without auction mechanics, bidding never took place, and the intersection performed normally unable to react to the human concerns. When simulated using the auction-based intersection we see that N/S wait time drops below E/W wait time when rushedness drops below E/W rushedness at 50. At the point when both roads are equally rushed the performance is approximately equal to figure 3.2 at rushedness of 50. The Interchange intersection adapted to give preferentially longer green lights to the N/S traffic.

Chapter 4

Simple Multi-Intersection Grids

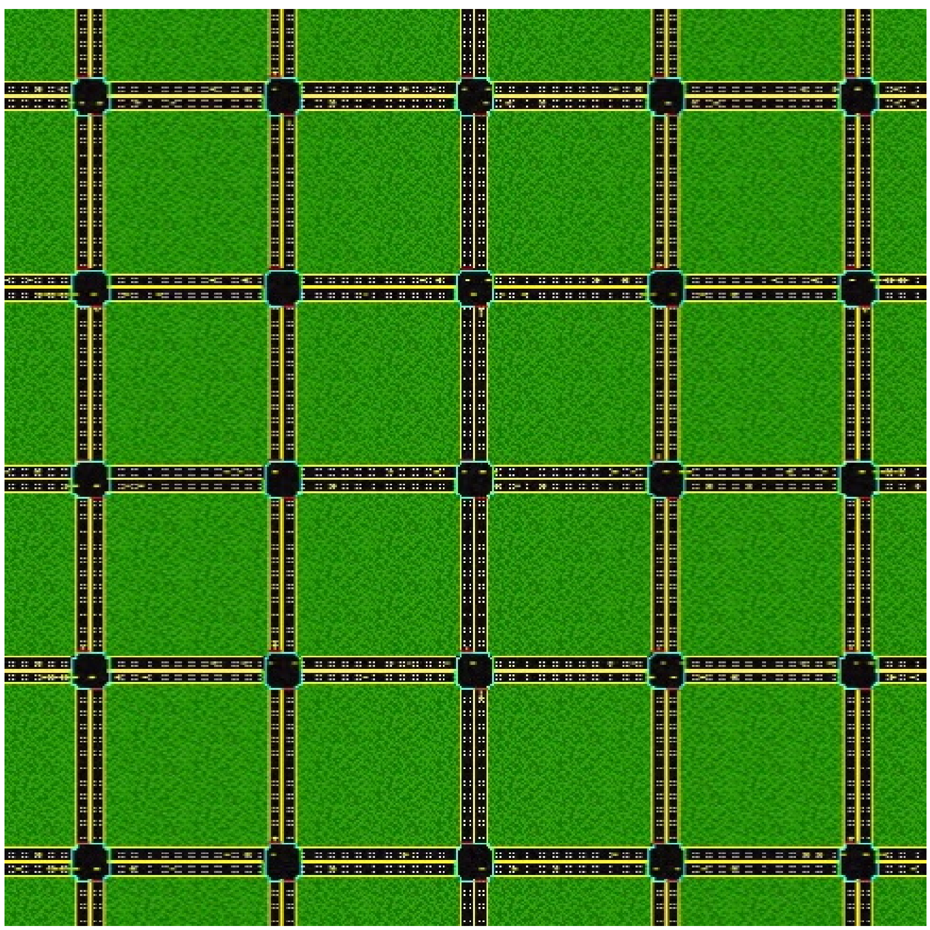

Figure 4.1: 5x5 grid of Interchange intersections

While single intersection traffic simulations are essential in understanding the feasibility and interactions between the Interchange system and vehicles, they provide little insight into the complexities of more realistic multi-intersection city grids. Although any one intersection could be shown to perform better under specific circumstances, neighboring intersections could be timed such that these benefits become negated or amplified. When simulating a traditional multi-intersection grid we expect to see baseline performance to be worse than Interchange for these reasons. We expect the adaptive nature of Interchange intersections to allow for lower wait time for vehicles traversing across multiple intersections.

We extended our prior single-intersection simulation to support a grid of two-way streets. At each intersection the Interchange intersection was simulated and vehicles were introduced at all edges of the grid. Among the simplifications made compared to real cities:

- The 5x5 grid pattern was simulated with two-way streets, there are no curved, angled, or other kinds of roads.
- Vehicles were only introduced at the 20 edges of the grid
- Vehicles only traversed the street they were introduced on, a vehicle did not make left or right turns while crossing the 5x5 grid.

The following are preliminary results for multi-intersection simulations. In a 5x5 city grid we simulated traffic profiles similar to those from the single intersection.

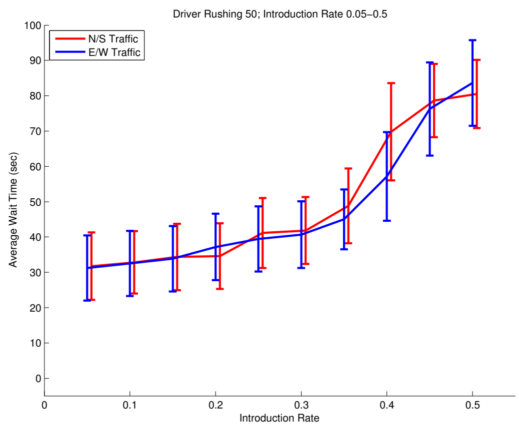

Figure 4.2: A 5x5 grid of timed intersections where traffic progressively becomes heavier.

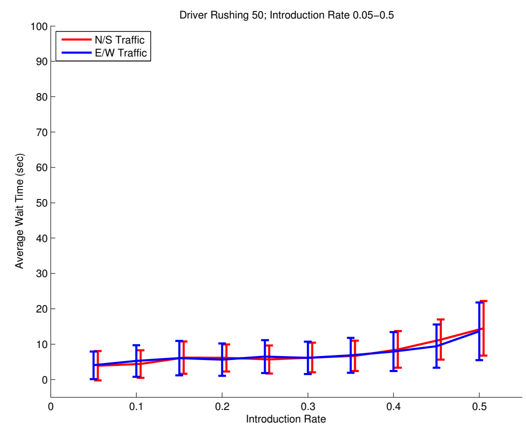

Figure 4.3: A 5x4 grid of Interchange intersections where traffic progressively becomes heavier.

4.1 Multi: Baseline

In the baseline traffic profile, the introduction rate was increased from 0.05 to 0.5 in 0.05 steps. Vehicles were introduced randomly at any edge on the grid and navigated directly across the grid, no left or right turns were allowed. Results are shown in figures 4.2 and 4.3. The baseline Interchange-based city grid performed better at all introduction rates showing over fifty percent less wait time for vehicles that were initially introduced into the system. Although individual intersections had no knowledge about global system state or communicated with neighboring intersections vehicles, when little traffic was present, vehicles were able to pass directly through the grid without stopping. The timed intersections were about 5 times slower in light traffic and about twice as slow under heavy traffic.

4.2 Multi: Heavy traffic Along One Road

In the second traffic profile λ_{NS} was progressively increased from 0.05 to 0.5 while λ_{EW} was held steady at 0.25. Results are shown in figures 4.4 and 4.5. As N/S

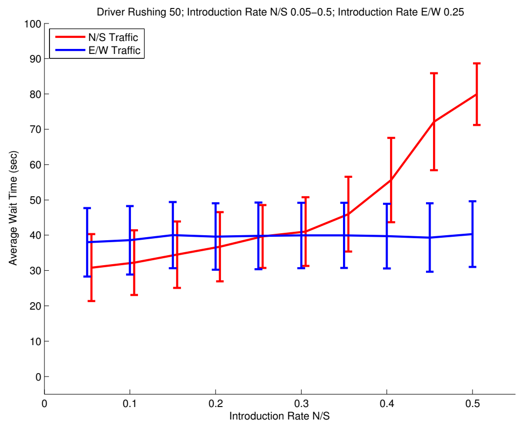

Figure 4.4: A 5x5 grid of timed intersections where N/S traffic progressively becomes heavier while E/W traffic remains constant.

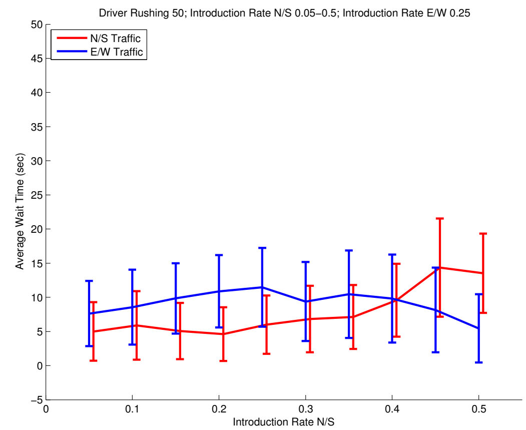

Figure 4.5: A 5x5 grid of Interchange intersections where N/S traffic progressively becomes heavier while E/W traffic remains constant.

traffic progressively increased the grid become saturated with vehicles. At a certain traffic density vehicles traveling along the N/S streets began to experience significantly longer wait times. Results from our simulation show that the point at which this occurs (0.3 for a traditional intersection, and 0.4 for Interchange) is at a higher introduction rate. In turn, the Interchange system allows for a higher influx of vehicles before vehicles being to suffer from significantly higher wait times.

4.3 Rushed Drivers Along One road

In our third traffic profile λ_{NS} and λ_{EW} was held steady at 0.5 while driver rushedness for NS traffic was varied 20-80. Driver rushedness for EW traffic was held steady at 50. Expectedly, we show in 4.6 that traditional intersections show no preference for rushed traffic. As intended in 4.7 we see that Interchange gives preference to N/S rushed drivers as they begin to bid higher than the E/W average.

Results show that dynamic intersection controllers that do not have global system

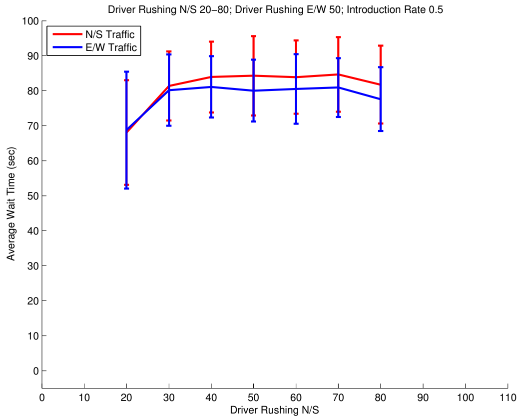

Figure 4.6: A Traditional 4-way intersection where N/S traffic progressively becomes more rushed while E/W traffic remains constant.

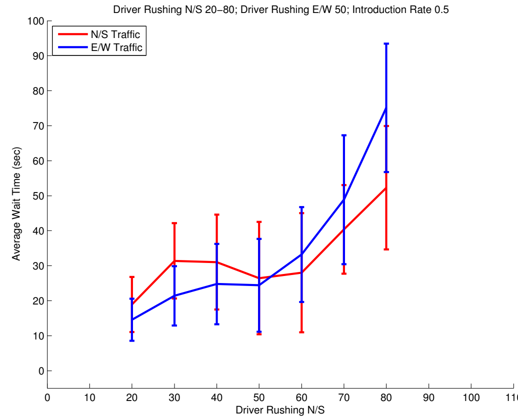

Figure 4.7: Interchange 4-way intersection where N/S traffic progressively becomes more rushed while E/W traffic remains constant.

knowledge or communicate with other intersections can produce patterns that resemble multiple coordinated intersections when necessary without historical data or pre-programmed scheduling.

Chapter 5

Real World Topologies

To simulate more complex topologies we developed a mesoscopic simulator capable of simulating vehicles on real world infrastructure. We expand on our prior work by resolving many of the limitations of our prior experiments such as the following:

- Use OpenStreetMap data to simulate a large graph of ways and intersections.
- Simulate individual agents from a origin to destination along the shortest possible route. (A* path)
- Handle 3-way and 4-way intersections with common lighting patterns.
- Handle 3-way and 4-way intersections with loop sensors.
- Driver agents appropriately handle lane-changing and adhere to the rules of the road.
- Vehicles keep track of their route, wait times, and other important statistics on their journey
- Driver agents follow local speed limits.

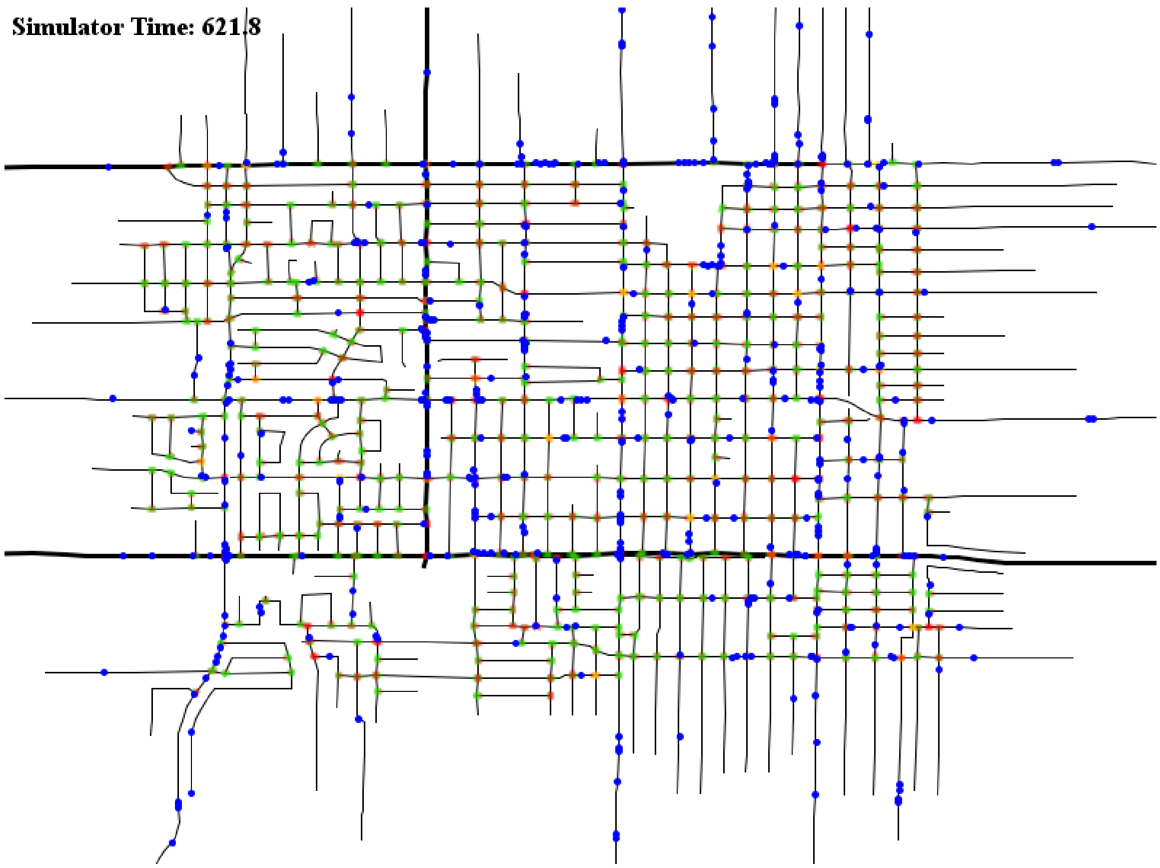

Figure 5.1: A screenshot of our mesoscopic simulator running an experiment around 33.72,-117.89. The thickness of streets represent the number of lanes. Intersection state is represented by green, yellow, and red lines along intersections and vehicles are represented by blue dots.

5.1 Simulation Area

We selected a 10 km^2 gridded area near the University of California, Irvine (figure 5.1) as our simulation area because of our local knowledge of the infrastructure and speed limits. Due to a lack of speed limit and intersection configuration information in OpenStreetMap data we developed tools to augment OpenStreetMap data with speed limits and intersection timing information appropriate for our simulated area. For clarity, vehicle and intersection interactions were simulated with the same parameters as with our AIM4-based experiments. In the following experiments traditional intersections maintained through-way green lights for 30 seconds and yellow lights for 10 seconds. Left turns were green for 10 seconds with 5 seconds of yellow. All right turns were implemented as yields and all left turns were protected turns. Vehicles bid when they were within 250 ft of entering an intersection and, as in our AIM4 model, were charged after crossing the intersection.

5.2 Experiments

In all of the following experiments the simulator precomputed a pre-defined number of routes (1000), r, for vehicles to travel in the simulation. A route is formally a 2-tuple specifying the origin, $o \in O$, and destination, $d \in D$. These routes were chosen randomly between any two nodes on the graph using A* search. We further restricted these routes such that all generated routes were at minimum 3 km long to prevent vehicles from traversing paths that were too short. Whenever a vehicle was generated during the simulation we randomly chose from one of our precomputed routes ($r \in R$) and placed the vehicle at the origin node. Vehicles were generated with a Poisson distribution at varying rates based on the experiment being run. Each tick of the simulator was 1/5th of second and intersection saturation occurs at approximately $\lambda = 0.2$, or 1 vehicle per second.

Similar to our prior experiments we based our evaluation on a set of traffic scenarios: the traffic conditions along each road, and the amount of driver rushedness. For each traffic profile we ran our mesoscopic simulator and collected enough data such that with 95% confidence, the measured average wait time is within 10sec of the true average wait time. Figures show standard error bars.

Since vehicles traveled varying distances involving a different number of lefts, rights, and throughs, we simplified our dataset by calculating the total wait time at throughs (when a vehicle was not making a turn) divided by the total number of throughs made during a vehicles journey to get the Average Wait Time per Intersection. Vehicles were considered to be waiting if they were stopped at an intersection.

5.3 Overall Performance of the Simulator

Our first experiment was to evaluate the performance of interchange against traditional timed intersections and timed intersections with loop sensors. We extended our timed intersections to include basic loop sensors such that intersections would switch to allow waiting traffic if no opposing traffic was present. Moreover, our implementation included loop sensors for left turns such that intersections were able to detect vehicles waiting for left turns and switch when no opposing traffic was present. We simulated the system varying the introduction rate between 0.05 (1 vehicle every 4 seconds) to 0.2 (1 vehicle every second) on traditional timed intersections for timed intersections with loop sensors, and Interchange-based intersections. Data collected is shown in figure 5.2. Results showed that for traditional timed intersections as the

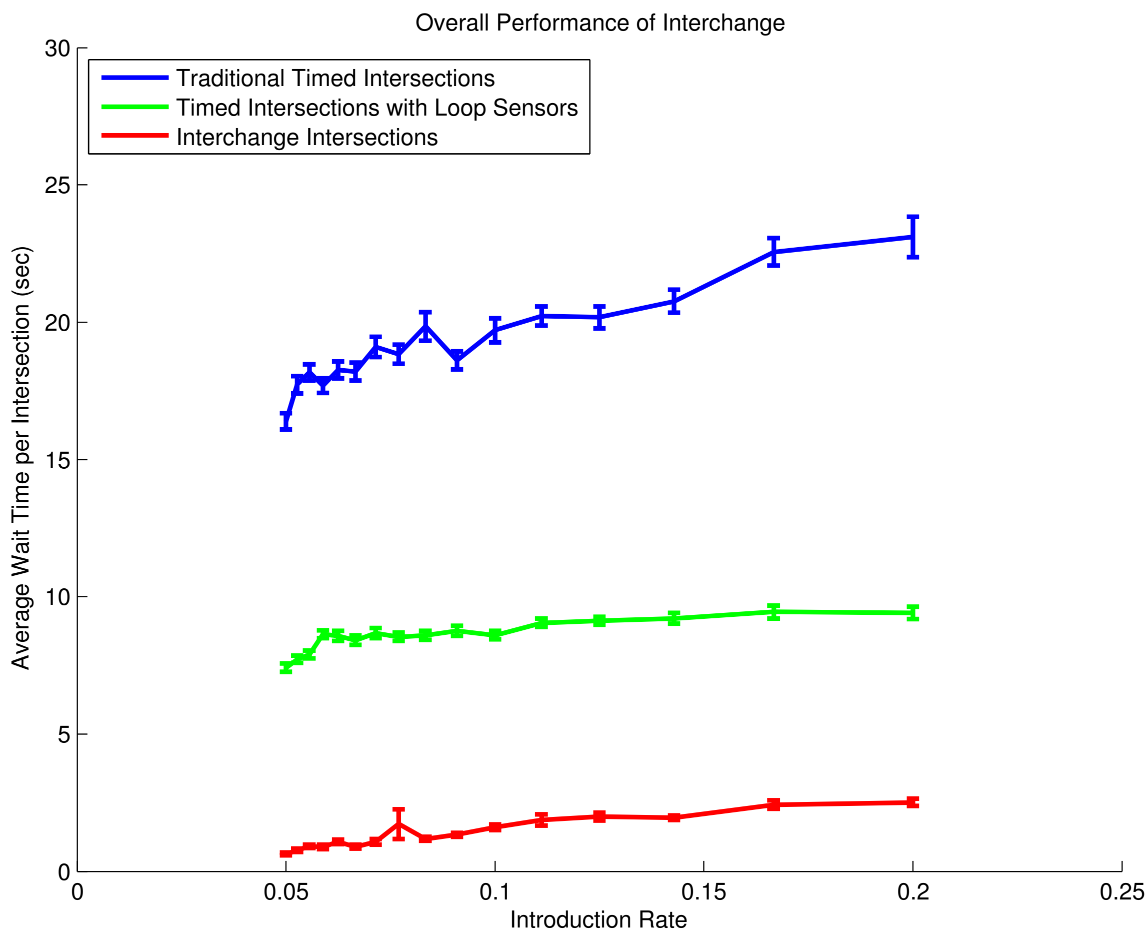

Figure 5.2: Three simulations showing the performance of three kinds of intersections as the vehicle introduction rate increases.

introduction rate increased vehicles experienced longer wait times per intersection. At the highest introduction rates vehicles waited on average 23.5sec per intersection while at the lowest introduction rates vehicles waited 16sec per intersection. As expected, timed intersections with loop sensors performed substantially better with wait times, at worse, around 10sec. Interchange-based intersections proved to have the best performance having average wait times below 5sec.

5.4 Percent of Rushed Drivers in the System

We expected the percentage of rushed drivers in the system at a given point to have a large impact on the overall performance of the system. With few rushed drivers we expect a large difference between average wait times per intersection. As the percentage of rushed drivers increases, we expected many non-rushed drivers to see benefits from neighboring drivers bidding high. At very high percentages of rushed drivers we expect the benefits of auction mechanics to lessen. In our second experiment we increased the percentage of rushed drivers in the system that would bid high ($1.00) from 5 to 95. Non-rushed drivers would bid randomly ($0.00-$0.25). See results in figure 5.3.

5.5 Driver Rushing

Our final experiment shows the change in average wait time a small portion of drivers (here 10%) experience as their bid goes from below the average bid of the population of vehicles to significantly higher than them. The population of vehicles bid $0.25 and as expected the small subset of vehicles cross over and experience reduced average wait time after bidding higher than $0.25. Moreover, we see that for 10% of drivers to experience one second less in wait time other drivers must wait, on average, less than 1/3rd of a second more per intersection. Since this value depends on the introduction rate and other factors of the simulation, more work is necessary to determine the optimal percentage of drivers to reduce the wait time on those who bid less. Still, these results show that it is possible to prioritize a small subset of drivers willing to pay more while preventing large wait times for drivers who do not. See results in figure 5.4.

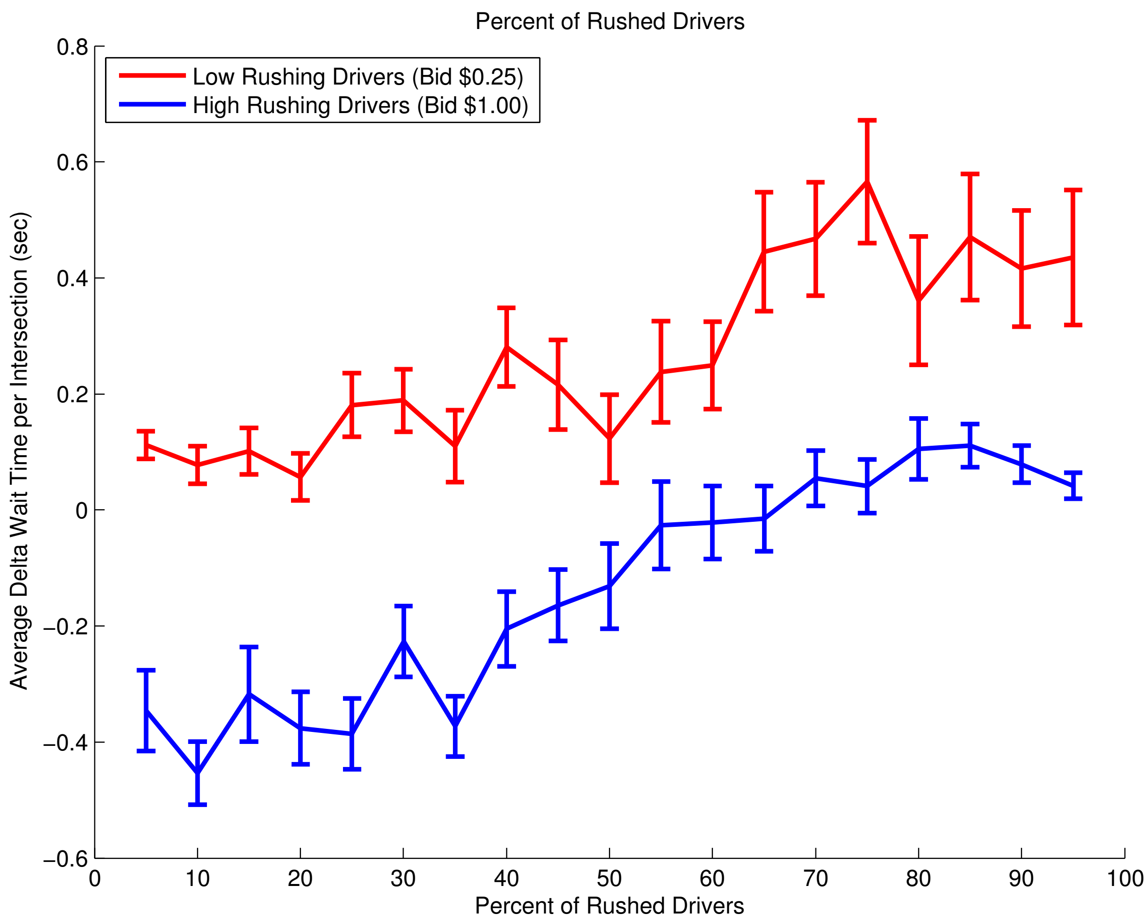

Figure 5.3: A simulation where the percentage of rushed drivers in the system increases decreasing the benefits of using auction-mechanics for intersections. Introduction rate was set to 0.1.

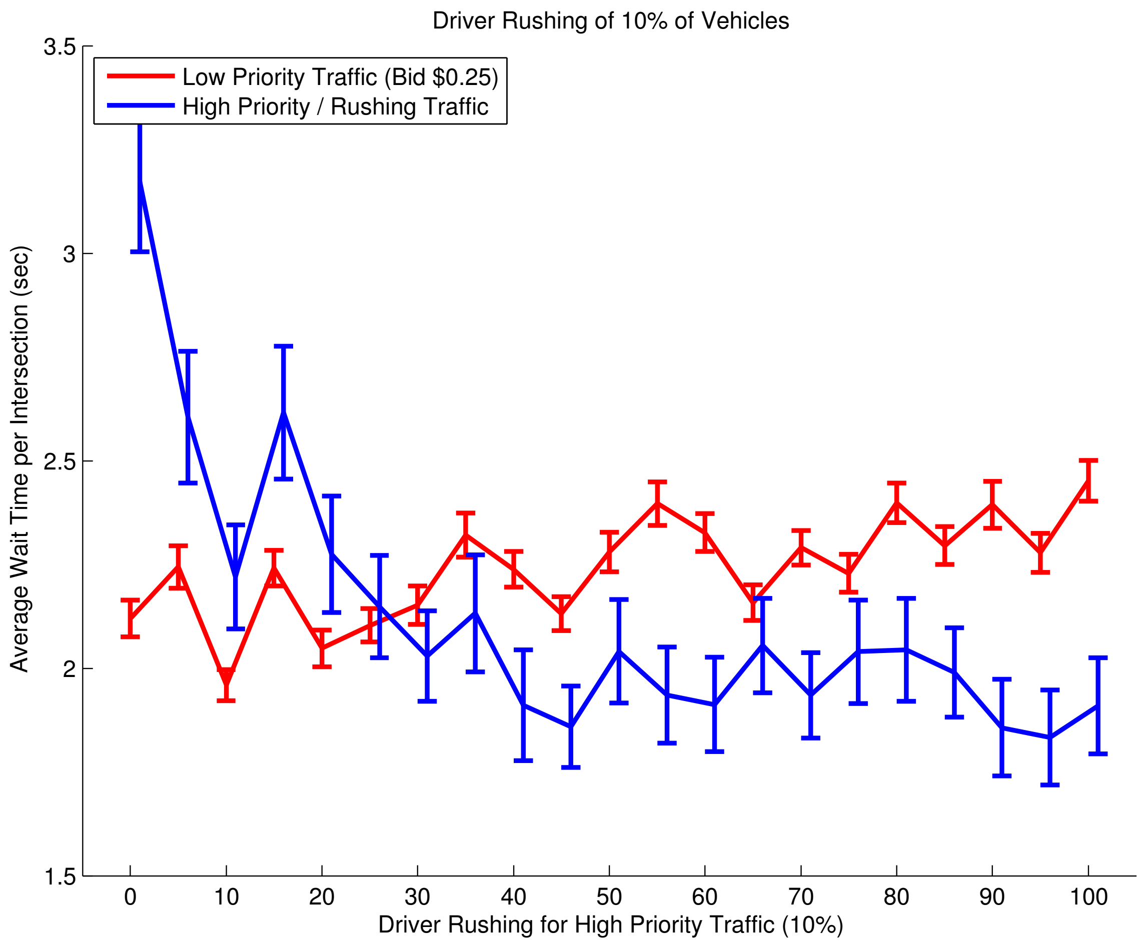

Figure 5.4: A simulation of a percentage (10%) of drivers progressively bidding higher while non rushed drivers bid randomly up to \$0.25. Introduction rate was set to 0.1.

Chapter 6

Conclusion

In this paper we have evaluated the benefits of using auction-based mechanics in intersections. We have presented Interchange, a system of independent auction-based intersections. Vehicles bid to turn lights green, the intersection controller aggregates vehicle bids among all possible lighting patterns and selects the winner based on the highest aggregate bid and minimum and maximum light switching times. Drivers need not alter their driving behavior and traffic rules are not altered within the Interchange system.

We have shown that Interchange-based intersections can be utilized to favor certain vehicles such as rushed drivers who can choose to bid higher or emergency vehicles that can bid infinitely high. By utilizing such a system not only is vehicle wait time optimized, but we can also optimize for other factors such as how rushed drivers are. Single-intersection and simple multi-intersection experiments have shown that auction mechanics can substantially improve on the performance of simple timed intersections.

Furthermore, we presented a simulator we have developed capable of simulating real world topologies by importing data from OpenStreetMap. Using this simulator we ran experiments to analyze the performance of auction based intersections vs traditional intersections and intersections with loop sensors. Results indicate that auction mechanics can provide substantial benefits on both traditional timed intersections as well as timed intersections with loop sensors by self-optimizing for traffic volume as well as driver rushedness. We argue that an auction based intersection system can therefore not only optimize for throughput but also optimize for more soft-metrics such as driver happiness.

Chapter 7

Future Work

Results from our simulations show potential for the Interchange system. Our single intersection and multi intersection experiments make a number of simplifications to make simulations easier to run. The mesoscopic simulator we have developed addressed a number of limitations. The experiments we have run using the simulator have shown that auction mechanics show promising improvements even in real world topologies. However, due to the complexities in simulating varying routes and vehicles we have had to make a number of simplifications when analyzing data from the simulator.

Results using our simulator only evaluate wait time when vehicles are not making left and right turns due to the increased variability in the data. Moreover, vehicles are configured to travel long distances over the shortest possible route. Further work is necessary in determining better ways to incorporate and analyze vehicular data. Furthermore, more work can be done to make driver agents drive routes along atrial streets as well as incorporate other common driver behaviors.

We also intend to simulate the effects of disasters in multi-intersection grids and how

Interchange could be used to alleviate common pitfalls of existing infrastructures. We aim to further enhance our simulator to support the simulation of even larger areas through optimizations as well as cluster-based simulations. Moreover, we intend to incorporate a variety of other data sources to better represent existing systems. Future work can include the evaluation of other more complex intersection systems such as multi-intersection coordination schemes at different times of the day.

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