Interchange: Bidding for Green Lights

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Abstract—In urban environments great effort is directed toward alleviating traffic including the design and implementation of complex software and hardware infrastructure. We introduce the idea of an auction-based mechanism for resolving vehicle intersections using a multi-way group auction mechanism. We propose a supporting infrastructure that has promise for increasing performance and responsiveness to dynamic traffic conditions. In order to evaluate new intersections, we propose new metrics that attempt to capture a more human aspect of vehicular transportation. We demonstrate that Interchange intersections perform well in single and multi-grid configurations, are self-adapting and are responsive to a variety of traffic loads.

I. INTRODUCTION

"Interchange" is a system that manages traffic light cycles according to auction-based mechanics when participants have a vehicle equipped with an enhanced networked navigation device (see figure 1). With this device, drivers specify their destination and a dollar-amount expressing their "rushedness" or the dollar-amount that they are willing to spend to turn an individual light green (w.l.g., [$0.00 - $1.00]). Interchange monitors all participating vehicles, their routes and current individual bids, aggregating the total bid of all vehicles that are within range of an intersection and selecting a safe red/green light configuration that matches the highest cumulative 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 speed their travel. Cost-sensitive drivers could travel in ad-hoc packs, gaining advantage without expense. Public service vehicles such as ambulances and police cars could be given the ability to bid arbitrarily highly to support the public good of their trip.

A driver's route must be known (as in [1]) so Interchange can unambiguously identify the intentions of a driver when they are approaching an intersection from beyond the range of fixed sensors. Non-participating drivers have no-cost proxy bids submitted by agents controlled by sensors located close to the intersection. In the absence of sensors or bidders, timer agents gradually increase a no-cost proxy bid causing the intersection to periodically cycle through light patterns. 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
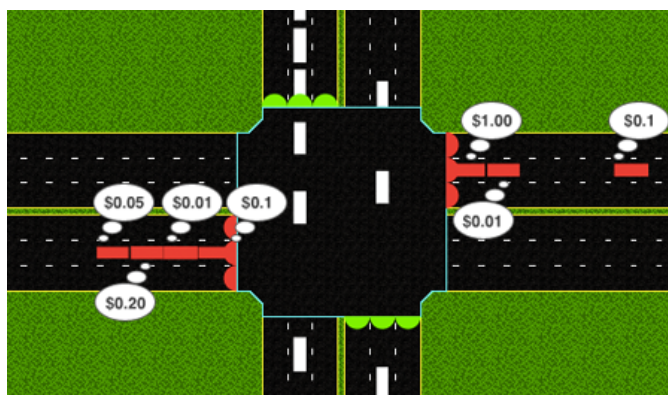

Fig. 1. Interchange UI with bids overlaid.

minimal loss of accuracy in the near-term [2], [3].

This system does not require administratively and technically complex *large-scale infrastructure coordination*, or *major changes in a driver's behavior*. Intersections must have modest additional hardware installed that supports network control of traffic light settings (with appropriate security and failsafe mechanisms). Interchange can be implemented through a centralized or decentralized architecture alongside current infrastructure. For this system to work, it is not necessary for *all* intersections to be upgraded; it can be done incrementally with correspondingly incremental benefit.

Alternatives to a simple capitalist reading of this scheme that are supported include: paying with non-currency "credits" that are distributed via an environmental incentive system; distributing the payment from auction winners to the losers so that they can trade waiting time now for future priority; allowing local government to sponsor turn lights so that it is cheap and easy for customers to turn into schools, libraries and other public services; allowing people to trade Interchange credits on an open market so that speculators can profit on events which increase or decrease traffic; allowing buses and carpools to multiply their bid by the number of passengers.

A. Related Work

Other research related to this project falls primarily into two categories: smart networked intersections, typically agent-based, and auction-based mechanisms for time/slot allocation. Typical metrics focus on system-wide performance evaluations (with a few exceptions [4], [5], [6]).

Roozemond et al. propose an agent based Urban Traffic Control system (UTC) capable of adapting to traffic conditions in real time [7]. 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 [8]. While such a reservation-based system outperforms traditional intersections, Dresner and Stone admit to difficulties in implementing such a system in the real world because vehicles need to adhere to confirmed reservations with a precision that, while appropriate for autonomous driving, would be unfeasible for human drivers. Balan et al. [9] evaluate fairness as opposed to efficiency when dealing with traffic control systems. Le et al. describe utilizing auction systems to optimize a multi-faceted system for assigning aircraft landing slots in crowded airports [10].

II. MODELING A SINGLE INTERSECTION

To model an intersection, i, our simulation 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, $b = \{o, d, v\}$, specifying the lane of origin, $o \in O_i$, the destination lane, $d \in D_i$, and a bid value $v \in [\$0.00 - \$1.00]$. 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, $B_{o,d} = \sum_{b \,|\, b.o=o, b.d=d}(b.v)$. Each intersection, based on the lane and road configuration, has a set of traffic patterns, $\bar{P}$, that when followed, would not result in collisions. Each pattern, $p \in \bar{P}$, allows multiple simultaneous non-colliding transitions of the form $o \to d$. 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 switch to the pattern with the new highest bid, with yellow lights assigned to lanes whose setting is changing from green to red. Bids from slowing and stopped cars are only subtracted from the aggregates as they leave the intersection, not when the lights switch. After a light change, the *second* highest bid *at the time of the last pattern switch* was T_p'. Individuals that benefit from the switch are charged the equivalent proportion of T_p' that they bidded for in T_p. This is consistent with the lowest price that could have been offered to win the auction. Vehicles that pass through the green light after the auction resolution are not charged. Additionally, appropriate minimum switching times are enforced.

III. EXPERIMENTS

The primary metric that 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. Our independent variables are traffic conditions and the rushedness of the driver. For each traffic profile, we ran a modified AIM4 simulator [11] 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 parameters, λ_{NS} and λ_{EW} which are the "introduction rates" that represents the probability that a new car will be instantiated on a given incoming road at each simulator tick. Intersection saturation occurs at approximately $\lambda = 0.5$.

A. Single Intersections

As a baseline, figure 2 shows that the wait time of an auction-based single intersection does no worse than a traditionally timed intersection with average driver rushedness. As the traditionally timed intersection always makes some cars wait even under light load, there is some delay 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 delay time as the lights did not adapt well to randomly induced surges in traffic.

Figure 3 shows the results of the second simulation we ran to study 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, $\lambda_{EW} = 0.25$. In the timed intersection, wait time along the N/S road is slightly lower until $\lambda_{NS} = \lambda_{EW}$ and then it increases above that of the E/W road. Cars 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 cars to pass.

Figure 4 show the results of our third simulation. 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 delay time. E/W drivers were set to bid \$.50 while N/S drivers bid between \$.10 and \$1.00. In the Interchange 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 2 at rushedness of \$.50. The Interchange intersection adapted to prefer longer green lights for the N/S traffic.

B. Multiple Intersections

We extended our prior single-intersection simulation to support a grid of straight 5x5 two-way streets. At each intersection the Interchange intersection was simulated and
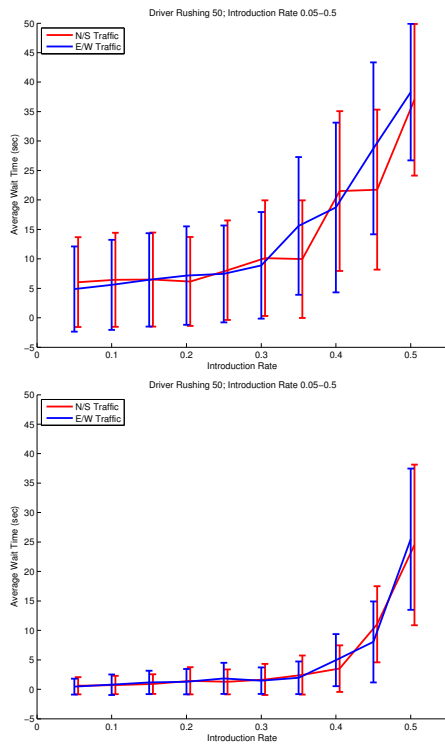
Fig. 2. A timed intersection (top) and an Interchange (bottom) intersection with gradual increasing traffic perform comparably.
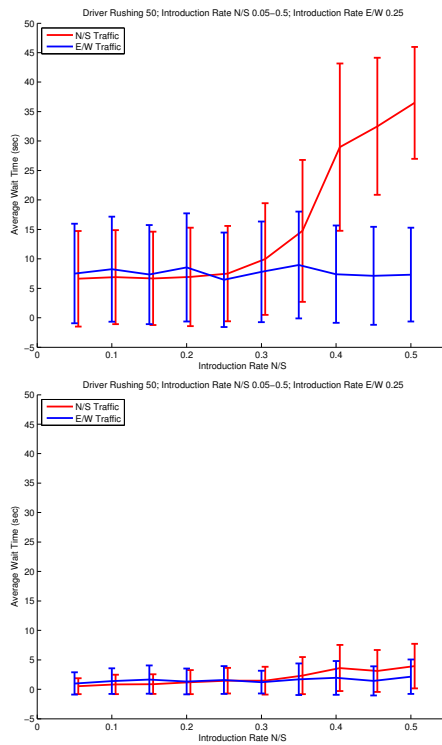

Fig. 3. A timed intersection (top) and an Interchange intersection (bottom) where only N/S traffic progressively becomes heavier.
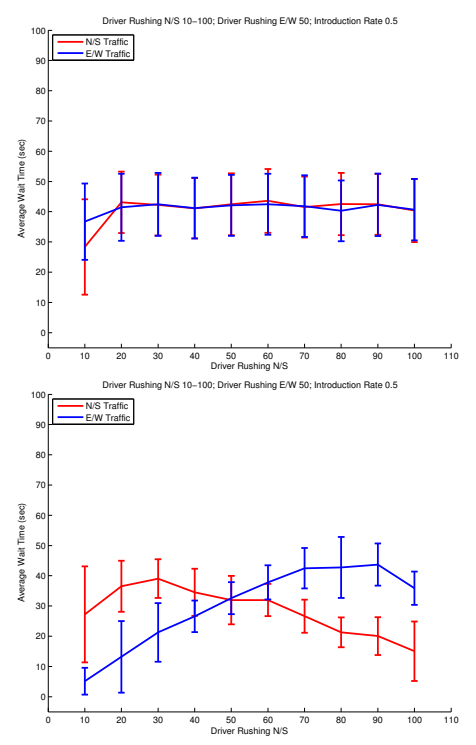

Fig. 4. A timed intersection (top) and an Interchange intersection (bottom) where N/S traffic progressively becomes more rushed while E/W traffic remains constant.
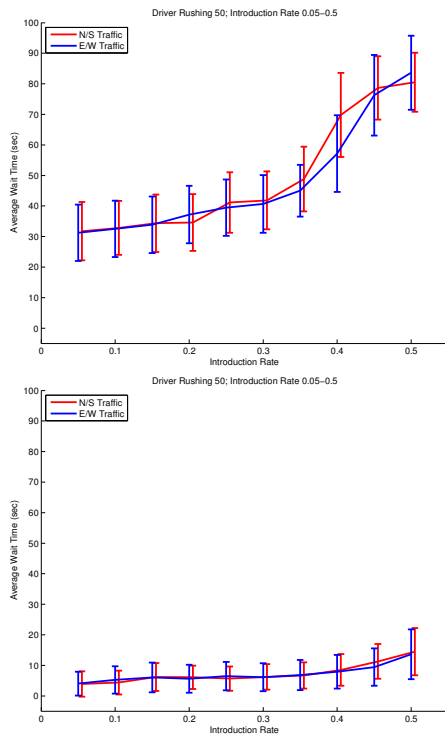

Fig. 5. Results from a 5x5 grid of timed intersections (top) and Interchange intersections (bottom) where traffic progressively becomes heavier.
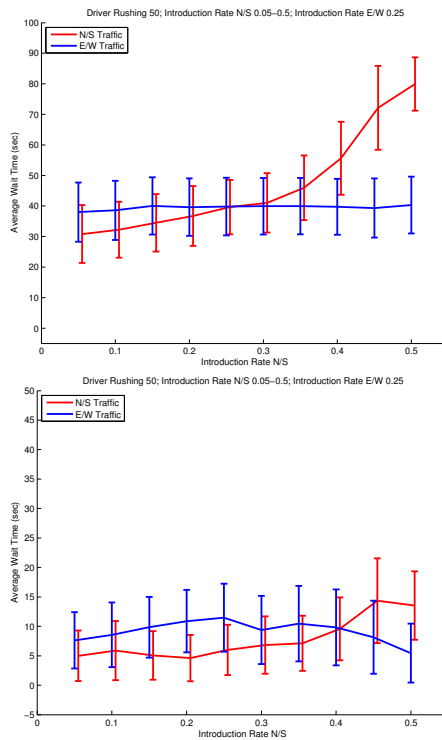

Fig. 6. Results from a 5x5 grid of timed intersections (top) and Interchange intersections (bottom) where N/S traffic progressively becomes heavier while E/W traffic remains constant.
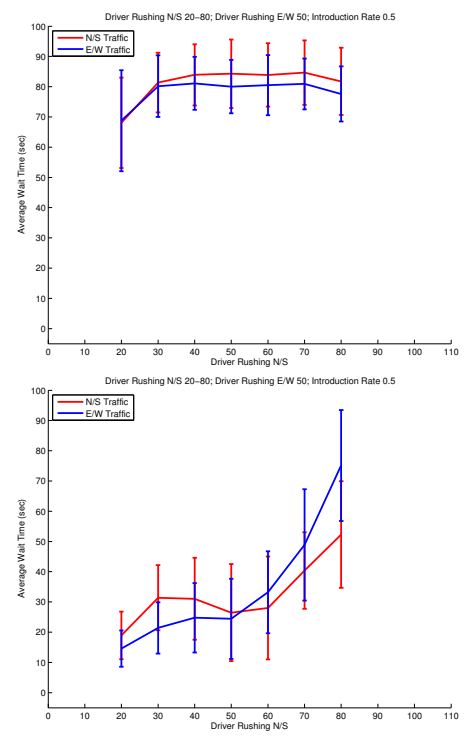

Fig. 7. Results from a 5x5 grid of timed intersections (top) and Interchange intersections (bottom) where N/S traffic progressively becomes more rushed while E/W traffic remains constant.

vehicles were introduced at all edges of the grid that travelled straight across the entire grid. Baseline results are shown in figure 5. The Interchange-based city grid performed better at all introduction rates, showing over fifty percent less delay for vehicles that were initially introduced into the system. The timed intersections were about 2 times slower in light traffic and about 5 times as slow under heavy traffic.

In figure 6, λ_{NS} was progressively increased from 0.05 to 0.5 while λ_{EW} was held steady at 0.25. As N/S traffic progressively increased the grid become saturated with vehicles. At a certain point, vehicles traveling along the N/S streets began to experience significantly longer delay times. The Interchange system allows for a higher influx of vehicles before vehicles being to suffer from significantly higher delays.

Finally in figure 7, N/S driver rushedness was progressively increased from \$.20 to \$.80 while EW rushedness was held steady at \$.50. Overall traffic was heavy. The timed intersection remains stuck in gridlock. The interchange system however, degrades gracefully, gradually shifting a greater proportion of the wait time from N/S traffic to E/W traffic as the N/S bids increase. At all times the overall wait time is less than the time intersection.

IV. Conclusions

Taken as a whole, these results show that auction-based intersection controllers that do not have global system knowledge nor use explicit coordination among other intersections can produce patterns that resemble highly coordinated systems without using historical data or pre-programmed scheduling.

These experiments make a number of simplifications that need to be relaxed before we argue for real-world trials. We are expanding upon the current simulations with non-grid topologies and support for more complex roads. To strengthen our argument for Interchange further, we plan to incorporate real maps and traffic data.

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 higher. By utilizing such a system not only are metrics such as throughput and delay improved, but we can also optimize for other factors such as how rushed drivers are.

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