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Bid-based Signal Control with All Passive Players

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***Abstract*—In this paper, we present a realization of bid-based control strategy in which all drivers are modeled as passive players, and movement managers develop bidding strategies based on state-observer system principles. Their bidding strategies blend engineering attributes (length of dynamic queue, and number of turns since last win, which is analogous to delay) with economic attributes (the account balances of the movement managers). Movement managers bid for green time for their respective turning movements. Arriving motorists pay fees so the movement managers can bid for discharge slots. Movement managers pay the municipality what they bid when use of the intersections space is contested; otherwise, they pay a nominal fee. An intersection between two one-way streets has been used to test these ideas. To provide benchmarks against which to compare the results from bid-based control, a model of an actuated controller is employed. The results suggest that bid-based control strategy produces lower delay and cycle length distributions than those produced by actuated control strategy.**

I. INTRODUCTION

Resource allocation problems deal with the assignment of resources to activities, and the scheduling of those activities. For example, resource allocation solutions are used to allocate landing slots at airports, workstations in job shops, CPU time slices for computers, and beds and medical personnel in health-care facilities. Resource allocation techniques may also be used to manage intersection space through signal control. Signal control can be seen as a process that assigns intersection space (the resource) to vehicles by separating intersecting vehicle movements in space and time. These separations manifest in the controller's phase sequences and switching times. (Here, a phase is considered a combination of movement greens that occur simultaneously). Furthermore, vehicle flows at signalized intersections constitute a non-stationary stochastic process, and optimal control of those flows is NP-hard [1]. In order to cope with such computational complexity, traditional signal control strategies make use of offline search methods to generate signal timing plans for fixed-time operations [2], [3], [4]. The main weakness of such methods is that their plans are computed for static situations based on historical data. Such situations seldom exist in the real-world due to the highly stochastic nature of the control system.

Advances in connected vehicle technologies (V2V and V2I) and autonomous cars provide opportunities to apply artificial intelligence techniques to the fundamental problem of traffic signal control. Vasirani and Ossowski[5], [6] propose a computational market for distributed allocation of green time in an urban road network, where drivers purchase reservation slots to cross intersections by trading with infrastructure agents in a virtual market place. Similarly, Carlino et al., [7] propose a framework in which each driver in a given queue bids for the lead vehicle in that queue to be discharged.

Isukapati [8] proposed a market-based control system where intersection space is viewed as a scarce commodity, the use of which is allocated through an interactive bidding process involving vehicle and infrastructure decision agents. Here the control problem is envisioned as an auction system in which drivers pay to get responsive treatment. Any financial transactions in the game can be figurative or literal. A family of game realizations can be created using the concepts presented in [8]. A given realization of the game is defined by: 1) driver behavior, 2) the rules by which the game is played, 3) the bidding strategies, 4) the objectives being pursued by the players, and 5) the information being shared.

Driver behavior in the game can be modeled as either *active* or *passive*. If drivers are passive, they pay the movement manager to arrange a time for them to go and then wait for their appointed entry time. On the other hand, active players constantly evaluate the system, and take actions to expedite their service.

The ***rules*** determine how the bidding process takes place, the manner in which the movement managers can interact with one another, and the amount of information shared with the bidders. For instance, the municipality gets to decide whether the bidding process is single-stage or two-stage. In addition, the municipality decides how much the winning movement managers pay: two examples are their bid amount (first-price sealed bidding) or the amount bid by the second highest bidder (second-price sealed bidding).

The ***bidding strategies*** determine how the movement managers develop their bids and what information they use to do so. Movement managers might have the same or different objectives. Furthermore, bidding strategies can be developed either by using principles from *state-observer systems* or from *probability theory*. The former is analogous to a feedback loop; movement managers aim to learn the functional form of the bid equation by combining engineering attributes (e.g. length of the dynamic queue or number of turns since last win, which is analogous to delay) with economic attributes (the account balances of movement managers). In the latter instance, movement managers compute the bid amounts to be submitted using historic data (if available) and probability theory principles.

The ***objectives*** determine what the players are trying to do. Drivers might be trying to minimize travel times or delays. Movement managers might be interested in minimizing average delays for their drivers at as low a cost as possible. The municipality might be interested in equity or it might be interested in receiving a revenue stream that pays for the cost of the intersection and its maintenance.

Information exchanges also heavily influence how the game is played. For example, drivers might or might not want to reveal where they are going, what turning moves they want to make, when they will arrive at the intersection, how much they are willing to pay to be serviced, and whether they are interacting with other travelers or not. The movement managers might or might not know what bids were submitted by the other movement managers. The movement managers might or might not be able to share information.

Using this framework Isukapati and List [9] created a realization of the game in which drivers are modeled as active players and moment managers prepare bids using historic data and probability principles. Isukapati and Smith [10] extended the framework to a simple network. Our previous research demonstrated that market-based control strategy outperformed actuated control strategy on a simulated network of simple two-phase intersections.

In this paper, we present a different realization of the game, in which all drivers are modeled as passive players, and movement managers develop bidding strategies based on state-observer system principles. The rest of the paper is organized as follows: Section 2 presents game terminology; Section 3 presents details on the realization of the game; Section 4 presents details of the experimental design; Section 5 presents results from several simulation experiments, and Section 6 presents conclusions and recommendations.

II. Game Terminology

As with any game, there is a set of rules about how the game is played, and there are relationships among the players. These ideas are described below.

In this game, a ***time step*** is the increment by which the game proceeds. In the context of this discussion, the time step is 0.1 seconds. The state of the game is updated every 0.1 seconds.

A ***discharge slot*** is the time allocated for discharging the lead-vehicle(s) in queue; in this case equal to 2.1 seconds. This value is chosen because it is the typical average headway between vehicles being discharged at the stop bar.

An ***initial fee*** is the amount paid by arriving motorists to their respective movement managers upon their arrival.

A ***nominal fee*** is the minimum cost for using the intersection.

Financial transactions occur between movement managers and travelers or movement managers and the municipality. Movement managers charge an initial fee to the travelers and sometimes collect a secondary-fee. When movement managers discharge their vehicles, they either pay the municipality the amount of their winning bid (if they won) or a nominal fee if there was no competitive bid because no other movement manager had vehicles wanting to use the facility in a particular discharge slot. The financial transactions occur during each turn, subsequent to the bidding process and prior to the completion of vehicle discharges. Funds are transferred between movement managers and travelers and movement managers and the municipality.

Each movement manager has a bank ***account*** into which it deposits the fees paid by the drivers and from which it pays for use of the intersection. Each movement manager monitors its account balance to ensure that it has sufficient funds to pay for bids that are won.

A ***secondary fee*** can be assessed to drivers in the queue to ensure that the account balance remains positive. These secondary fees are then distributed ex-post facto among all the drivers for a given movement manager to ensure equity is preserved.

Events are the actions that take place during the game. Two ***events*** might take place in each ***time step***. The first event is the bidding. Bidding determines how the intersection is used in the next discharge slot. The second event is the execution of financial transactions. Effectively, time stands still while these two events take place. The third event is the vehicle releases, and it takes place once the discharge slot is allocated to a specific movement manager(s). This is the point in the game when vehicles pass through the intersection. As indicated above, one vehicle per lane can be released on any given movement during a single discharge slot.

A ***turn of the game*** encompasses bidding followed by financial transactions, and the resulting vehicle discharge(s). Each turn of the game ends when the business of the turn is completed: the transactions between the winning movement manager(s) and municipality are finished, the winning movement manager(s) have discharged their first vehicles in queue; the system information is updated, and the players are ready to participate in the next turn of the game. This process continues until the game ends (which is the end of the analysis period).

A ***performance metric*** is a measure used to assess the quality of the games outcome. Although many metrics might be used to evaluate signal performance, delay is used here. Early ideas about delay were developed by Wardrop, [11] and analytic expressions for the delays were later presented by Webster [12], [13]. More recently, Newell [2] provided additional thoughts about the manner in which delay should be studied. In current realizations of the game, the movement managers endeavor to minimize the average delay for their drivers by submitting winning bids and charging sufficient fees (to the drivers) so that the bid payments can be covered subject to an expectation that their account balance will always be nearly zero.

III. GAME DETAILS

The realization of the game discussed here has three types of players: 1) drivers; 2) movement managers, and 3) the municipality. Here, all drivers are modeled as passive players i.e., upon their arrival, they pay their respective movement managers' an initial fee to arrange a time for them to go and then wait for their appointed entry time. Movement managers negotiate for use of the intersection on behalf of drivers making a specific turning movement. Movement managers interact with drivers, prepare bids, and communicate with the municipality regarding financial transactions and the bidding process. The municipality receives bids, makes decisions about control assignments, and passes decisions back to the movement managers. The municipality also conducts financial transactions with movement managers.

A. How The Game Progresses

Drivers use wireless telemetry to report their arrival. The movement manager then collects an initial fee. The movement manager updates its account balances, adds the new arrival to its service queue, and stores information about the vehicle until it is serviced.

The bidding process determines which movement managers can use a given discharge slot (green time), and movement managers can submit bids every time step (0.1 seconds) until there is a winner. Once a winner is declared, the bidding process is ceased for a pre-specified duration equivalent to either minimum green or saturation headway (2.1 seconds). The bidding process also determines how much the movement managers pay. If there is ever a situation where only one movement manager has a non-zero queue, then that movement manager wins automatically and a nominal fee is paid for using the intersection space. The vehicles in queue are discharged at saturation headway. When more than one movement manager has a queue, use of the discharge slot (green time) is determined by submitting bids. The highest bidders (one or more) are the winners; the winning movement managers pay what they bid (or some other amount like the second-highest bid) depending on the rules set by the municipality. One vehicle is then discharged by each winning movement manager.

B. Bidding strategies

Movement managers develop bidding strategies based on state-observe system principles. Their bidding strategies blend engineering attributes (length of dynamic queue, number of turns since last win, which is analogous to delay) with economic attributes (the account balances for the movement managers).

The variables in the bidding equation that capture attributes of the system are referred as system variables. Queue lengths, account balances, and the number of turns since last win are all examples. The bidding system described here has two essential features: First, the agent uses values of system variables that exist at the end of every turn of the game. These values are inputs for computing bid prices in the next turn of the game. Second, a bid price to be submitted is computed using estimates of system parameters from the previous turn, and known preset input parameters. The bidding equation formulated based on these principles takes the following general form:

$$bid_i^k = f(q_i^k, bb_i^k, w_i^k / (\alpha_i, \beta_i, \gamma_i)) \tag{1}$$

It can be seen from the equation above that the bid submitted by a movement manager representing approach i in the k^{th} turn (bid_i^k) is a function of service queue length on approach i (q_i^k), the account balance for agent i (bb_i^k), and a parameter indicating the number of turns since last win (w_i^k). Also, it should be noted that input parameters $\alpha_i, \beta_i, \gamma_i$ are constant for a given approach. This means that these parameters are static, and the bidding system does not have the ability to learn and adjust these values from historic data. In other words, in this realization, the movement managers do not change the functional form of the bid equation. Therefore, the bid value in any turn of the game is the value of the bid function for the given system variable for that turn of the game. One such bidding strategy is:

$$bid_i^k = p_{min} + \alpha_i * q_i^k + \beta_i * bb_i^k + \gamma_i * w_i^k \tag{2}$$

Where

- bid_i^k = bid submitted by movement manager i in turn k
- p_{min} = nominal fee for buying discharge slot (green time)
- q_i^k = length of the queue for movement manager i in turn k
- bb_i^k = account balance for movement manager i in turn k
- w_i^k = number of turns since last win for movement manager i in turn k
- $\alpha_i, \beta_i, \gamma_i$ = bidding equation parameters for movement manager i

To maintain solvency, the agents can collect secondary fees. (These secondary fees are then distributed equally among all the movement drivers ex post facto.) The logic presently used to determine if a secondary fee will be collected is as follows: If

$$w > f_{min}, s_i = w - f_{min} \tag{3}$$

- w = winning bid
- s_i = surcharge for approach i
- f_{min} = initial fee for approach i

Secondary fees are effectively a simulation convenience. That is, instead of creating logic that allows a higher fee to be collected from some or all drivers initially, secondary fees are only collected to ensure that the account balance remains positive. Hence, at the end of the game it will be at or near zero. Ex post facto, these secondary fees are then allocated among all the drivers serviced by the movement manager.

Secondary fees simply ensure that movement managers have sufficient funds to cover their bids.

IV. Test-Case Illustration

The objective of test-case illustration is two-fold: 1) to create a bid-based control strategy based on the ideas presented above, and 2) to compare the performance of bid-based control (bids drive control decisions) to that of actuated control (gap-timers drive control decisions). An intersection between two one-way streets has been used to further explore these ideas; and the model realization was programmed in Python. The attributes of the game are as follows: 1) Each approach has one lane; and 2)First-in-First-out (FIFO) is preserved in the queues.

A. Control Structure of the Simulation Model

Algorithm 1 presents the pseudo code for bid-based control strategy. Movement managers representing the NB and EB approaches perform two main tasks during every time step (δ_t = 0.1 seconds).

First, they check to see if there are any new arrivals. If there are, the agent collects an initial fee from each new driver and adds the vehicles to its FIFO queue. Second, the movement managers develop a way to provide acceptable service green times for their respective customers. In a given turn of the game, if only one of the queues (either NB or EB) is non-zero, then the movement manager representing that approach is declared to be the winner; and is allowed to use the intersection space for a duration equivalent to minimum green time. The movement manager pays a nominal fee (per vehicle discharge) to the municipality and discharges the lead vehicles at saturation headway.

On the other hand, if both the NB and EB queues are non-zero, then allocation of green time is determined by bidding. The NB and EB movement managers submit bids and the highest bidder is the winner. The winner is allowed to use the intersection space for a duration equivalent to minimum green time. The winning movement manager then pays the municipality what he/she bid per discharge. However, before this monetary transaction between the agent and the municipality takes place, the moment manager collects a secondary-fee from the driver being discharged.

At the end of minimum green movement managers submit bids (if necessary) for intersection control. If the movement manager who currently holds the intersection control now submits a winning bid, the manager is allowed to use the intersection space for another 3 seconds, or else a clearance interval of 4 seconds is imposed before shifting intersection control to the new winner.

Algorithm 1: Control Logic

```
δ_t = 0.1 (initialize time step);
t = 0 (initiate simulation time);
h_d = saturation headway;
g_min = minimum green;
c = clearance interval;
while t ≤ T do
    t += δ_t;
    if new arrivals = True then
        collect f_min;
        add new arrivals to service queue
    end
    if only one agent has a service queue then
        declare that agent as a winner for t = t + g_min;
        agent pays municipality an amount p_min;
        discharge vehicles in queue at h_s
    end
    if more than one agent has a service queue and
      φ = 0 then
        movement managers submit bids for control;
        highest bidder wins and given control for
          t = t + g_min;
        collect secondary fee is winning bid is greater
          than nominal fee;
        secondary fee (s) = w_bid − f_min discharge
          vehicles in queue at h_s
    end
    if t > t + g_min then
        movement managers resubmit bids for control
    end
    if current winner = previous winner then
        extend green by 3 seconds
    end
    else
        Impose clearance interval;
        allocate intersection control to new winner for
          t = t + g_min
    end
end
```

B. Playing the game

Conceptually, the processing capacity of a signalized intersection is around 1,700-1,800 vehicles per hour. In order to test the robustness of the proposed frame work, the intersection was subjected to processing a total of 1,500 vehicles (the sum of the volumes on both approaches) but under three different scenarios

- $Scenario-1$: equal volumes on each approach (v_N = 750, v_E = 750)
- $Scenario-2$: slightly higher volume on North bound (v_N = 900, v_E = 600)
- $Scenario-3$: significantly higher volume on North bound (v_N = 1200, v_E = 300)

To test the robustness of the control strategy, a 9,000-second-long simulations were performed for each scenario described above. Vehicular traffic on each approach was generated from a shifted negative exponential distribution with a minimum headway of 2.1 seconds. Here are the parameter values used for computing bids α = 0.02, β =

0.015, γ = 0.05.

Lastly, to provide benchmarks against which to compare the results from the bid-based control, a model of an actuated controller is employed. The traffic stream generator used for the bid-based control model is also used for the actuated control model to ensure that the arriving headway sequences are the same for any comparative evaluation. Detectors are placed at the stop-bar. The minimum green is set to the same value used in the bid-based control. The gap is set to the same maximum pause duration used in the bid-based control and it is held constant (i.e., no volume-density control)

V. Evaluation and Analysis

As mentioned earlier, this study has two objectives: 1) to compare the performance of bid-based control to that of actuated control, and 2) to glean any additional economic insights from the control strategy. The first two metrics gathered during the simulation (the cumulative density functions (CDFs) of individual vehicle delays, and cumulative density functions (CDFs) of cycle lengths) are used to evaluate the first objective, while the next two metrics (average cost of service per vehicle, and total income transferred to the municipality) are used to evaluate the second objective. The subsequent sections present the results of these evaluations.

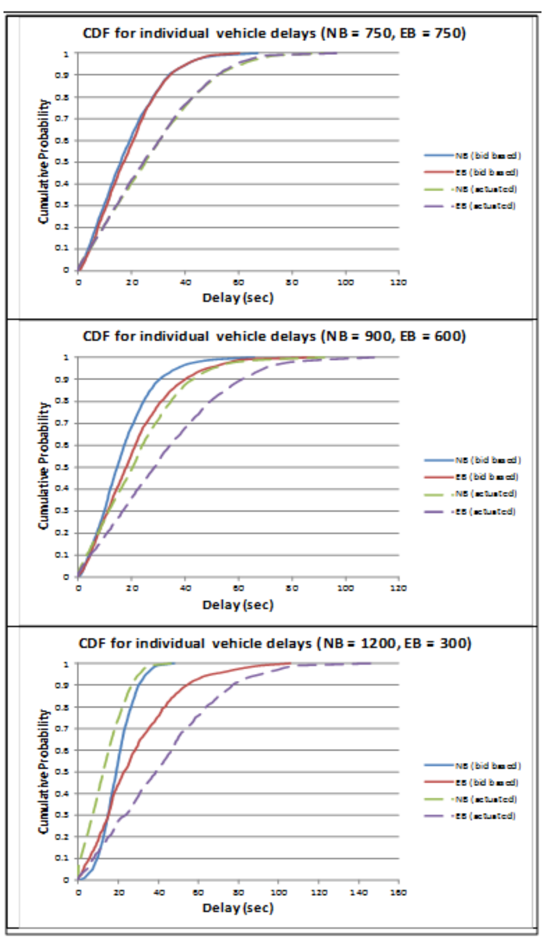

Fig. 1. *CDFs of individual vehicle delays in each of 3 flow combinations*

A. CDFs of individual vehicle delays

Figure 1 presents the CDFs of individual vehicle delays in each of three flow combinations. The best performance is reflected by the curve furthest to the left. That curve always has a distribution of delays that are smaller than the others. Each subplot contains the CDF of individual vehicle delays for both bid-based (solid line) and actuated (dashed line) control strategies on NB and EB approaches. There are several insights that one could glean from these plots. First, 90th percentile delays are significantly lower in the case of bid-based control as opposed to actuated control except in the third flow condition (v_N = 1200, v_E = 300), in which case NB delays are slightly lower in the case of actuated control. Second, vehicles on minor movements (EB) are experiencing significantly higher delays in the case of actuated control (delays in the order of 70-80 seconds) as opposed to 45-50 seconds in the case of bid-based control. Third, with regard to alleviating individual vehicle delays, bid-based control stochastically dominates actuated control, except during the third flow condition for the NB approach.

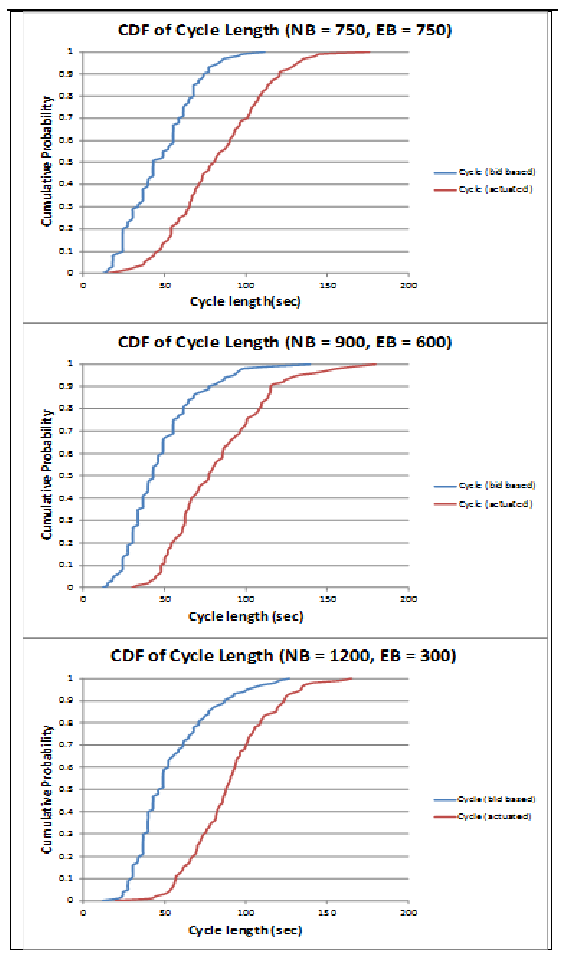

Fig. 2. *CDFs of Cycle lengths in each of 3 flow combinations*

B. CDFs of cycle lengths

Figure 2 presents the CDFs of cycle durations in each of three flow combinations. The best performance is reflected by the curve furthest to the left. That curve always has a distribution of cycle lengths that are smaller than the others. Each subplot contains the CDF of cycle length distributions for both bid-based (blue line) and actuated (red line) control strategies. It is evident that bid-based control produces significantly lower cycle lengths than those of actuated control. Please notice that the 90th percentile cycle length produced by bid-based control is around 65-70 seconds, whereas it is around 120-140 seconds in the case of actuated-control.

C. Average cost of service per vehicle

Table 1 summarizes the average cost of service for each of three flow combinations, and several insights can be gleaned from this data. The cost of service on a Minor Street is higher; on average, drivers on minor movements paid a higher price for service than those on major streets.

TABLE I
AVERAGE COST OF SERVICE ($)PER VEHICLE

Average cost of service	NB	EB
Sce - 1	$1.496	$1.493
Sce - 2	$1.478	$1.508
Sce - 3	$1.455	$1.726

D. Total income transferred to the municipality

Table 2 summarizes the average cost of service for each of three flow combinations, and like Table 1, offers several insights. In principle, one could set nominal fee for using the intersection in such a way that it covers various costs (for example, marginal costs of operation or capital costs, etc.)

TABLE II
TOTAL FUNDS TRANSFERRED ($)

Total Income Transferred	NB	EB
Sce - 1	$2,807	$2,883
Sce - 2	$3,372	$2,283
Sce - 3	$4,399	$1,378

VI. CONCLUSION

In this paper, we presented a realization of bid-based control strategy in which all drivers are modeled as passive players, and movement managers develop bidding strategies based on state-observe system principles. Their bidding strategies blend engineering attributes (length of dynamic queue, and the number of turns since last win, which is analogous to delay) with economic attributes (the account balances for the movement managers). An intersection between two one-way streets has been used to test these ideas. To provide benchmarks against which to compare results from the bid-based control simulation, a model of an actuated controller was employed. The following six observations were made in the analysis section:

1) The 90th percentile delays are significantly lower in the case of bid-based control as opposed to actuated control
2) Vehicles on minor movements (EB) are experiencing significantly higher delays in the case of actuated control
3) Bid-based control stochastically dominates actuated control in terms of individual vehicle delays, except during the third flow condition for NB
4) Bid-based control produces significantly lower cycle lengths than those of actuated control
5) On an average drivers on minor movement paid a higher price for service than those on major street
6) In principle, one could set nominal fee for using the intersection in such a way that it covers various costs (for example, marginal costs of operation or capital costs, etc.)

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