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Bid-Based Priority Signal Control in a Connected Environment: Concept

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Abstract

Though the loss of time is considered equivalent to opportunity loss, little research has been conducted in the field of signal control that accounts for individual differences in subjective opportunity loss. Because bids reflect the subjective valuation of opportunity loss, this paper introduces the concept of a bid-based priority signal control that accommodates indeterministic characteristics of queue formation in a connected environment and addresses several key elements of such a concept. Within this conception, drivers can bid for their desired signal indication. Based on these bids, an algorithm extends a green interval as long as the cumulative opportunity loss observed in stopped movements remains less than the value that would be lost through the termination of that green interval. The effects of this new type of control on user benefit and queueing delay were assessed using the asymmetric simple exclusion process. Simulation results showed that the bid-based priority signal control produced a greater subjective user benefit when measured in relation to a pre-timed control with a similar green interval. In addition, the bid-based priority signal kept the average maximum queue length relatively equal to its pre-timed equivalent. The bid-based priority signal control also balanced out the expected values of user benefit in conflicting movements. Bid-based signal priority control was recommended for further study to investigate the effects of bidding distributions on effectiveness and queue length in high-fidelity microsimulations.

Time is money. Because the loss of time is considered loss of opportunity, efforts have been made in the field of transportation to minimize such losses that increase user cost.

At intersections, the level of service (LOS) has been widely used to measure the overall quality of efficiency of movements, approaches, and intersections. Varying from A, the best, to F, the worst, LOS is a function of control delay (*1*). Aside from drivers' subjective discomfort, it is also important to achieve a good LOS from an economic standpoint because drivers' time has economic value, and delay can result in opportunity loss for drivers' economic activities. In fact, for this very reason the American Association of State Highway and Transportation Officials (AASHTO) recommends that engineers consider travel time as a key factor of user benefits (*2*).

Because road networks generally have two-dimensional geometry, vehicle control comes down to effectively allocating a three-dimensional space-time (area + time) to potentially conflicting demands. At a corridor level, Wong (*3*) proposed the concept of roadway reservation, where road users can book roadways in advance based on system optimization rules that prioritize transits and high-occupancy vehicles (HOVs). Today, HOV lanes exemplify this idea. On a smaller scale, major practices to reduce opportunity loss include preemption and transit signal priority (TSP). Preemption gives emergency vehicles a right-of-way, whereas TSP offers a right-of-way to public transit, including buses and light rails because mass transits tend to have more occupants than passenger cars. A TSP prioritizes transit vehicles over other vehicles in an attempt to reduce the total amount of opportunity cost because of signal allocation. All of these concepts, though varied in their systems and approaches, share the same philosophy: signal priority should be given to vehicles whose time is more "valuable" than others. Besides these practices, some intersections have actuated signal control, which extends green intervals based on the existence of vehicles approaching the signal as a function of needs (*4*). Actuated control is philosophically different from preemption and TSP because it does not take each vehicle's difference of the value of time (VOT) into account while it gives larger right-of-way to the movements with larger

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demands. Many conventional actuated signal controls use the concept of maximum allowable headway (MAH), which refers to a headway where an actuated controller allows vehicles to "call" extended green intervals for the movements receiving green time at the point. The length of MAH gets shorter over time, making extensions more difficult if the movement has already been receiving green time. MAH, however, is not the best tool to maximize user benefit for the following reasons:

1. Each vehicle occupant's VOT does not affect headways.
2. Since multiple vehicles in a movement receive signal indications, vehicles in each movement should be treated as a group.

In reality, individual values of time are not likely to be homogeneous. Therefore, all of the aforementioned concepts do not achieve optimality in relation to individual VOT. Although some researchers have proposed methods to minimize person-based delay through adaptive signal control (*5*, *6*), it may be ideal to extend the concept of person-delay to individual differences in time valuations among vehicle occupants in signal operations because subjective user benefits contribute to individuals' quality of life. It is, in fact, quite difficult to calculate individual subjective values of travel time (SVTT) precisely because SVTT can vary among road users. SVTT can even vary for an individual road user. For example, the subjective valuation of user benefit is not necessarily proportional to the length of time saved (*7*). Rather, user benefit can be affected by various factors such as trip purpose, trip length, and surplus time and may have a non-linear relationship (*8*).

Considering the elusive nature of the individual VOT, a signal priority based on bids may be an effective tool in achieving minimum opportunity loss for individuals. Although the summation of individual willingness to pay is not always equal to the social price of time (*9*), bids can convey an individual's SVTT since money provides a unit of value (*10*). With this concept, drivers in a hurry can receive the right-of-way sooner than they would with conventional signal controls if they value their time enough to pay for a shorter delay.

At intersections, some researchers have explored the feasibility of right-of-way reservation systems in a connected environment without traffic control signals. Sometimes, such procedures involved an auction to choose vehicles entering intersections. For example, Schepperle and Böhm (*11*) proposed the idea of distributing time slots for vehicles approaching an unsignalized intersection and reported reduced average waiting time with their method as compared with conventional signal control. In their framework, drivers were able to reserve the right-of-way within an intersection when their "requests" were approved in the auction which allowed one vehicle at a time per direction to request a time slot. Dresner and Stone (*12*) presented a similar method using a tile-based autonomous intersection management system without conventional traffic signals in which drivers reserved their paths within an intersection in such a way that ensured they did not occupy the same spatial tile at the same time. Because their tile-based priority control enabled more vehicles to enter an intersection at the same time, it would be extensible to intersections with larger numbers of lanes and spatial areas. Vasirani and Ossowski (*13*) on the other hand, envisioned an unsignalized intersection treated as a marketplace where vehicles could trade their right-of-way reservations based on bids. They found that higher bids, on average, resulted in shorter delays.

These studies have shown that, ultimately, intersection conflict management would not require traffic control signals in a situation in which all road users achieve perfect inter-user communications. Yet it is worth exploring signal priority control in the context of bidding because it may take decades to see completely connected signal control systems, and intersections should also manage non-motorized users. At signalized intersections, Carlino, Boyles, and Stone (*14*) simulated aggregated trip times with auction-based priority management schemes in transportation networks in four cities in the United States. In the simulation, drivers were able to place bids to receive the right-of-way, however the bidding method was not described in great detail. Their findings indicated that an auction method reduces trip time. Later, Mashayekhi and List (*15*) suggested using Q-learning to optimize bid amounts and simulated transportation network travel times. The reinforcement learning algorithm resulted in shorter average travel times as the experiment continued.

Although existing studies have demonstrated interesting implications, it remains unclear how much delay bidding would contribute at an intersection, since previous studies have compared aggregated travel times in transportation networks. In addition, existing research has assumed environments in which vehicle movements, positions, and speeds are fully predictable, though in reality this may not be the case. However, it may be possible for signal priority control to provide larger flexibility and a good degree of coordination if vehicles are permitted to place bids even before joining queues. To address these issues, this paper introduces the concept of bid-based priority signal control in a connected environment, discusses its key elements, and assesses its potential effects on user benefit and queueing delay in comparison with a traditional pre-timed signal control at an isolated intersection.

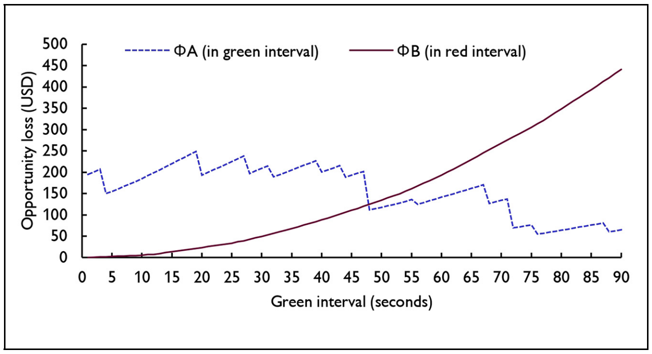

Figure 1. Opportunity loss as a function of a green interval.

Table 1. Key Variables and Settings in Bid-Based Priority Signal Control

Variable	Potential setting
Bidding horizon	Any value
Bidding type	Open/blind
Bidding timing	One time/multiple times
Expected red interval	Mean/median/mode
Minimum green interval	Any value
Maximum green interval	Any value
Bidding range	Free/in-range
Payment amount	Any value

Methodology

In this paper, the term "user benefit" refers to a subtraction of the opportunity loss—which is expressed as the "loss of value" in a bid-based priority signal control—of an alternative case from that of the base case. For example, if the opportunity loss of an alternative case is 6 and that of the base case is 8, user benefit of the alternative scenario is 2 as road users can cut the cost by 2 in the alternative case. At intersections, increasing user benefit for one movement often results in a decrease in user benefit in the conflicting movements.

Since signals regulate conflicting movements, user benefits should be sought in relation to the conflicting movements at an intersection. In other words, giving green intervals to a movement can result in the conflicting movements' opportunity loss. This means that signal priority is a matter of green time allocation to each conflicting movement per unit time besides lost times. Therefore, it is reasonable to arrange green intervals by comparing the expected sum of opportunity loss borne by conflicting movement groups within bidding horizons. This method has its foundation in the idea that a green interval should be extended as long as the opportunity loss currently observed in the stopped movement is less than the value that is going to be lost by the termination of the current green interval. For example, when there are only two conflicting movements, Movement A (ΦA), a movement currently in a green interval, and Movement B (ΦB), a movement currently in a red interval, the current green interval for ΦA is extended until the cumulative loss of bidding value actually observed or was going to be observed in the next vehicle arrival in a red interval (ΦB) exceeds the expected loss of bidding values in ΦA. Figure 1 illustrates an example case of this concept. The lines are theoretical total amounts of opportunity loss when a green interval was terminated at the moment of calculation. In this case, ΦA would experience larger opportunity loss compared with that of ΦB if the current green interval ended less than 48 s ("too short"). On the other hand, the cumulative opportunity loss in ΦB would surpass that in ΦA if the green interval exceeded that ("too long"). Therefore, it is reasonable to end the current green interval for ΦA in 48 s. A green interval becomes more likely to get terminated as time goes on because bids accumulate in ΦB while they do not necessarily have an increasing trend in ΦA. In ΦA, bids are not counted once the vehicle passes through the intersection. For this reason, a green interval is likely to get terminated after a vehicle with a relatively high bid goes through the signal. The minimum and maximum green intervals can be set if necessary.

This paper discusses several key elements that should be considered when introducing bidding to priority signal control (Table 1).

Bidding Process

A bid-based priority signal control intends to provide drivers with opportunities to increase their benefits. Because it takes multiple vehicles into consideration, bids are treated as groups when signal decisions are made. The maximum influence of each bid can be proportional to its range and inversely proportional to the number of total bids. In other words, a bid can have a stronger influence when there is a smaller total number of bids compared with the person's bid. Likewise, each bid would be diluted when there are many other bidders. For instance, if someone bids \$10.00 and others bid \$2.00 in total, the person bidding \$10.00 is likely to get the desired indication. One, however, cannot bid \$10.00 if the maximum bid is limited to \$1.00 per bid even when one is willing to pay more than \$1.00.

Vehicle Detection

A bid-based priority signal control requires vehicle speeds, locations, and bids in real time. In a connected environment, these data can be acquired by vehicles themselves and transmitted to a bid clearing terminal.

Detectors can be placed on the road or on the signal itself as needed.

Bidding Horizon

Like other priority signal control methods, a bid-based priority signal control captures bids from vehicles within its bidding horizons, the area where bids are effective. The appropriate length of a bidding horizon depends on characteristics of traffic in the areas, but it should not only be short enough to predict vehicle arrivals with an allowable accuracy but also be long enough to gather information on vehicles that could arrive in the near future. While little research has been done on determining the best bidding horizons, two or three cycles may be a feasible point to start because some other priority signal control algorithms have worked well with these planning horizons (*5*, *6*).

Bidding Type and Timing

There are different types of bidding: open and blind. Open bidding refers to situations where bidders are aware of other bids whereas blind bidding keeps bids secret from other bidders. Open bidding is suitable in that it provides bidders opportunities to pay as little as possible to get what they want. Contrary to open bidding, blind bidding does not provide bidders with opportunities to adjust their bids based on others' bids.

Another classification of bidding is the number of times a bidder can place a bid: one-time and multiple-time. Although multiple-time bidding provides liquidity to bidding markets, the authors recommend one-time blind bidding at one location as a standard because it keeps signal decisions stable. If drivers can place bids multiple times, signal priority decision making can be reversed frequently. Also, one-time bids are more likely to reflect drivers' original willingness to pay because it is in ratio scale, which is a higher level of measurement compared with ordinal or interval scales used in open bidding.

Because it might not be safe for drivers to manually place a bid every time, bids should be set in vehicles before they approach a signal controlled by bids. For example, one-time open bidding can be implemented in a connected environment where signal controllers communicate with individual vehicles, which should have some reaction criteria, including a manual bid input by voice or a pre-set bidding function expressing the bidder's time valuation. In a connected environment, the bidding system may be able to provide drivers the information of the expected relationship between a bidding value and shortened time before they place bids.

Range of Bids

There are two options for the bidding range: free bidding and in-range bidding. While free bidding allows signals to achieve free markets, it can also have side effects from the potential initial queue delay caused by abnormal bids, especially in signal networks where signals are close to one another. A bidding range has a large influence on the system's stability and effectiveness. If the range is too small for the number of bids in the bidding horizons, the presence of a bid can be too small, which could make the bidding system itself less meaningful.

As long as the range is determined based on its potential effects, potential bid distributions at the location should also be investigated because they depend on each other. In addition, once a bid-based priority signal control is introduced at an intersection, the bidding value distribution may eventually converge into a certain value at the location as a result of repeated bidding attempt by drivers.

Expected Red Interval and Certainty Function

With a bid-based priority signal control, the cycle length is not fixed, but an expected red interval should be determined as an input variable for movements receiving green indications. Unlike the opportunity loss of vehicles in a red interval, the fluctuations in vehicle speed may change the opportunity loss in the movement currently receiving a green interval. For example, if a red interval is the length of R seconds, a vehicle stopped at the beginning of the red interval is likely to lose R seconds, whereas a vehicle stopped 10 s later is likely to wait only for R–10 s in addition to decelerations and the start-up lost time. In other words, bids from vehicles closer to the signal are more crucial than those from vehicles further away.

Wolput, Christofa, and Tampère (*16*) have developed formulas for optimal cycle length with TSP at intersections. Although they may be useful, it is not possible to set the exact waiting time length since green intervals are subject to change in a bid-based priority signal control. While this paper uses an arbitrary value as the expected red interval in simulations, engineering studies should be conducted to find feasible expected red intervals to use.

Minimum and Maximum Green Intervals

It is important to consider any existing pedestrians since they require a certain amount of the minimum green time to cross the streets.

The maximum green interval can be introduced if road operators want to limit the flexibility of a bid-based priority signal control.

Payment Amount

Determining the payment amount as a result of bidding would play a key role in the concept. In a bid-based priority signal control, the outcome is not necessarily a dichotomy of "success" or "failure," but can be gradient because high bidders sometimes will have to stop or slow down until the vehicles in front of them get discharged.

In a case of free-riding, vehicles could receive the desired indication because of others' bids. For example, Vehicle a_1 in ΦA could receive an extended green interval not because of a $1.00 bid it placed, but because Vehicle a_2, a vehicle closely following Vehicle a_1, placed $10.00. In this case, it might not be clear whose bid obtained the desired indication, especially when the conflicting movements bid a close value.

Although this situation does not happen when bids are only placed in a semi-actuated intersection, successful bids accompanying a stop may also be debatable. If 20 vehicles (Vehicle b_1—Vehicle b_{20}) with no bids in ΦB are in the queue receiving a red indication and an arriving vehicle, Vehicle b_{21}, places $10.00 to get a green indication, the signal could start discharging the queue in ΦB until new bids from ΦA exceed the expected opportunity loss of ΦB. This means Vehicle b_{21} possibly receives a red indication again before it gets discharged. In such a case, Vehicle b_{21}, however, still received some benefits from its bid regardless of how the driver would feel because the bid still made the vehicle proceed. Some road users might not want to pay when situations like this happen.

Overall, the paying scheme should be as simple as possible so that every user can easily understand how the system works; otherwise, the market penetration rate would remain low. It might be possible to calculate the degree of contribution for each bidder so that they can pay based on their "influence." This idea, however, may not be feasible for real implementation unless the majority of bidders can intuitively understand how the calculation works.

A practical solution to this problem is making bidders pay regardless of the results since all bids are more or less woven into calculations. This "all-in" policy is not only simple but also has the potential to keep the computational load of a clearing system low as it discourages drivers to place less important bids.

Potential Effects

A bid-based priority signal control potentially generates turbulence in traffic and affects drivers' bidding behaviors.

Traffic. It has not been known how a bid-based priority signal control affects the existing traffic. With a bidding signal control, signal timing decisions are made based on bids, thus it may cause turbulence in traffic especially when the bidding value distribution deviates to a large extent from that of the arrival distribution without bidding control. This might not be a big problem at an isolated intersection, but this effect should be taken into consideration when introducing a bid-based priority signal control to intersections that are close to one another.

There is a possibility that drivers rarely place bids on a daily basis, but road operators should be aware that traffic turbulence can frequently be caused on roads with a high volume of traffic even if bidding is a rare behavior for individual drivers. For example, the likelihood of placing a bid is as follows, when each driver is likely to place a bid at once out of a hundred opportunities:

$$P(A) = \frac{1}{100} \quad (1)$$

Yet, the probability that an intersection dealing with 100 vehicles per cycle experiences at least one bid in a cycle is expressed as follows:

$$1 - P(\bar{A})^{100} = 0.63 \quad (2)$$

This means the signal is more likely to experience at least a bid per cycle than having no bids in a cycle.

Bidding Behaviors. Bidding behaviors are worth researching not only because people may change their bidding motivations and tactics based on their experiences, but also because bidding distributions can influence the effects of a bid-based priority signal control.

Bidders may be able to expect the probability of getting the desirable signal indication as a function of bids after a certain time period. A driver who goes through an intersection every day may develop a sense of the confidence interval of a bidding value that is likely to result in the desired signal indication. Because bidders will try to place the lowest bid that obtains the desired signal indication, bidding values at each intersection can get closer to what a fixed-value priority control offers, but little study has been conducted into this possibility.

If people change their behavior based on their experiences, there is a possibility that a bid-based priority control loses its benefits without a constant variable optimization.

Findings

This paper aimed to introduce the concept of bid-based priority signal control and discuss its key elements; thus, the authors decided to use the asymmetric simple exclusion process (ASEP), a plain method to simulate directional traffic flows (*17*) as a simulation tool to assess the effects of bid-based priority control on user benefit and

x-axis (seconds)		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Vehicle number		1				2				3				4				5	
Bid (USD)		1				1				1				1				1	
Time (seconds)	t	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0
	t + 1	2	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0
	t + 2	3	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
	t + 3	4	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1
	t + 4	5	2	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0
	t + 5	6	3	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0
	t + 6	7	4	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
	t + 7	8	5	2	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1
	t + 8	9	6	3	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0
	t + 9	10	7	4	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0
	t + 10	11	8	5	2	0	0	1	0	0	0	1	0	0	0	1	0	0	0

Figure 2. An example of the ASEP simulating queueing delay.

delay. This model simplifies vehicle movements while keeping the moving trends and was thought to be suitable for early-stage discussions. In the simulations, the maximum queue length in a stopped movement (ΦB) and opportunity loss were compared between the bid-based control and pre-timed control, whose green interval was arranged to be that of the average green interval in the bid-based control.

Settings

In the simulations, vehicle locations and speeds are assumed to be known in real time. Vehicle movements, an example of which is shown in Figure 2, were governed by the following rules:

1. Each number referred to the state of a vehicle in the cell (0: vacant; positive numbers: vehicle existence and bid).
2. The horizontal (x-) axis gave vehicle locations (left: downstream; right: upstream) and vehicles moved to the left cell every second unless the left cell already had filled up with another vehicle or the vehicle received a red indication at the origin of the x-axis, which was an intersection.

Although the simulations did not precisely illustrate variables such as vehicle lengths, gaps, the effects of queue spillback, and deceleration, the ASEP was still thought to be a feasible simulation tool, considering that the purpose of this paper was to introduce a conceptual framework of the bid-based signal priority control and that other variables can vary depending on the situations. The authors considered the number of stopped vehicles as a queue length. This practice was reasonable since vehicle arrival was assumed to be uniform in this experiment.

The following algorithm was performed:

$$G = G_{\min}(E(\mathrm{LV}_A) < \mathrm{LV}_B) - 3 \qquad (3)$$

$$E(\mathrm{LV}_A) = \sum_{i=1}^{n} b_i t_i f_{\mathrm{certainty}_i} \qquad (4)$$

$$t_i = E_{\mathrm{red}} \qquad (5)$$

$$\mathrm{LV}_B = \sum_{i=1}^{n} b_i d_i \qquad (6)$$

where

G = green interval (seconds),

$G_{\min}(x)$ = minimum green interval that satisfies x (seconds),

$E(x)$ = expected value of x,

LV_Φ = loss of value in Movement Φ (USD),

n = number of vehicles within a bidding horizon,

b_i = bid from the vehicle i (USD),

t_i = individual weighed time for the vehicle i (seconds),

$f_{\mathrm{certainty}_i}$ = certainty function,

E_{red} = expected red interval ($0 \leqslant E_{\mathrm{red}} \leqslant 62$) (seconds),

d_i = delay of the vehicle i at the time of calculation (seconds).

Other settings were as follows:

- The intersection had two conflicting movements: Movement A (ΦA) and Movement B (ΦB) without pedestrians.

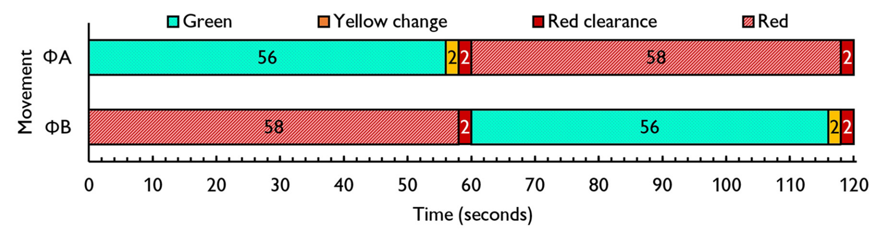

Figure 3. Typical phase settings.

Table 2. Bidding Value Distributions

Bid (USD)	0.00	0.50	1.00	1.50
Frequency	70.00%	10.00%	10.00%	10.00%

Note: USD = United States dollar.

Table 3. Descriptive Values in Bid-Based and Pre-Timed Control

Item	Timing	M	SD	Min.	Max.
Green interval for ΦA (seconds)	Bid-based	52.38	74.64	22.00	102.00
	Pre-timed (G = 52 s)	52.00	76.86	52.00	52.00
Expected lost value in ΦA (USD)	Bid-based	95.35	53.55	0.00	269.00
	Pre-timed (G = 52 s)	109.77	68.56	0.00	358.80
Lost value in ΦB (USD)	Bid-based	128.60	106.29	18.50	769.50
	Pre-timed (G = 52 s)	145.98	141.21	0.00	927.00
Vehicles passed in ΦA (vehicles)	Bid-based	14.14	4.19	7.00	27.00
	Pre-timed (G = 52 s)	14.00	0.00	14.00	14.00
Maximum queue length in ΦB (vehicles)	Bid-based	18.20	5.60	8.00	35.00
	Pre-timed (G = 52 s)	18.00	0.00	18.00	18.00

Note: n = 50; M = mean; SD = standard deviation; Min. = minimum; Max. = maximum; USD = United States dollar.

- A simulation started when a green time for ΦA began.
- Bidding horizon = 2,640 ft/each.
- Simulation period = a green interval.
- Approaching driving speed = 40 mph.
- Arrival headway = 4 s/veh for each movement (assumed a uniform distribution).
- Minimum green time (G_{min}) = 0 s.
- Maximum green time (G_{max}) = ∞ s.
- Yellow change interval = 2 s.
- Red clearance interval = 2 s/time.
- The expected typical red interval for a movement = 58 s (Figure 3).
- The bidding value distribution in the bid-based control is shown in Table 2.

Bids from ΦA were multiplied by a certainty factor ($f_{certainty}$) to introduce the probabilistic nature of the expected typical red interval for a movement. The factor was 1.00 for 0–924 ft (0–63 s); 0.75 for 939–1,775 ft (64–121 s); and 0.50 for 1,789–2,640 ft (122–180 s).

With bid-based priority signal control, green time for ΦA was extended until 3 s before the loss of value in ΦB, the movement receiving a red indication, exceeded the expected loss of value for ΦA. This setting made ΦB experience the maximum loss of value at the last second before it received a new green indication. In the bid-based control, the same bidding distribution was applied to ΦA and ΦB. Simulations were repeated 50 times in each condition on Microsoft Excel 2016.

Results

The mean green interval for ΦA was 52.38 s. Table 3 shows descriptive statistics in each condition. Figure 4 pictures the user benefit with the bid-based control

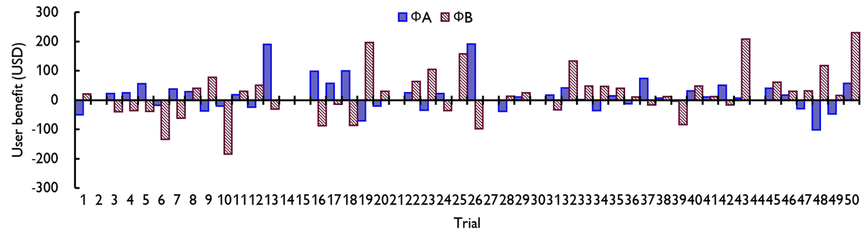

Figure 4. User benefit with bid-based control throughout trials.
Note: G = 52 s.

Table 4. User Benefit per Green Interval with Bid-Based Control

Movement	M	SD	Min.	Max.
ΦA	$14.42	$53.23	–$101.20	$191.90
ΦB	$17.38	$80.23	–$184.50	$230.50
ΦA + ΦB	$31.80	$80.43	–$204.20	$287.80

Note: n = 50; M = mean; SD = standard deviation; Min. = minimum; Max. = maximum.

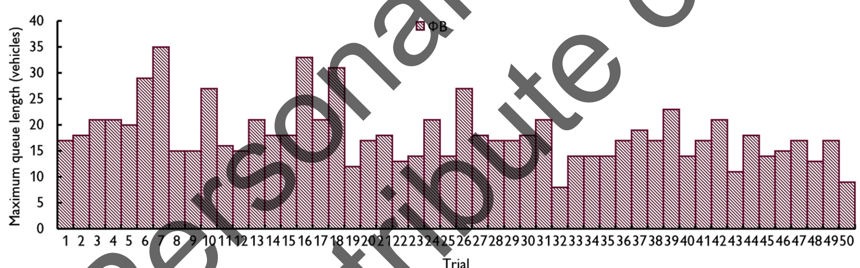

Figure 5. Maximum queue length in ΦB with bid-based priority control.

throughout trials. Table 4 shows the user benefit per green interval with the bid-based control. Figure 5 shows the maximum queue length in ΦB with the bid-based priority control.

User Benefit. In relation to the pre-timed condition with a 52-s green interval, user benefit per green interval was increased by $31.80 on average with the bid-based priority signal control, where the green interval ranged between 22 and 102 s. This is because the bid-based priority signal control had room for adjustment whereas the pre-timed control had "zero-tolerance" on the flexibility of green time interval.

The large variances (SD/M = 3.69 for ΦA; 4.62 for ΦB; and 2.53 for ΦA + ΦB) in user benefit indicated that there were trials where the bid-based control could not provide user benefit in relation to the pre-timed control. Yet, the bid-based control brought user benefit per green interval in 38 (74.00%) out of 50 trials.

Figure 6 illustrates the average user benefit in the two movements with the bid-based control in relation to different green intervals for ΦA with pre-timed control. In the simulations, bid-based adjustment found an optimal green interval (52.38 s). With the bid-based priority signal control, both movements were likely to experience almost the same degree of user benefit because the algorithm prevented unreasonable opportunity loss for the entire intersection. The figure indicates that vehicle users in ΦA would not have benefited when a pre-timed control had a relatively short green interval and vice versa.

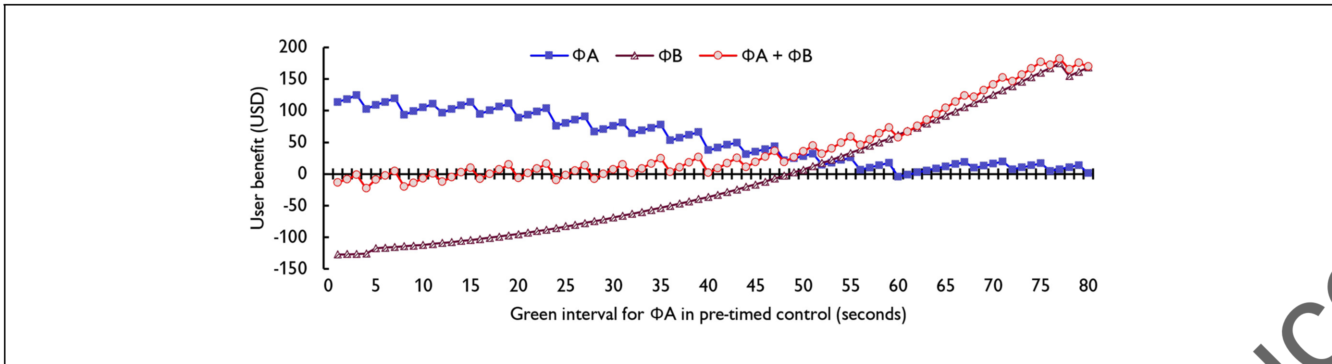

Figure 6. Average user benefit with bid-based control in relation to the green interval for ΦA in pre-timed control.
Note: n = 50 for every point.

Queue Length. This study considered queue length as a function of queueing delay since vehicles arrived uniformly. The average maximum queue length in ΦB with the bid-based control was 18.20 vehicles, which was close to that of the pre-timed control (18 vehicles). The value ranged from 8 to 35 along with a green interval for ΦA.

When the queue length in ΦB reached 35, 33, and 31 vehicles in Trial 7, 16, and 18, respectively, the total user benefit was –$22.70, $11.60, and $13.80. Because long queue lengths can generate initial queue delay once it exceeds a threshold, the effects of bid-based priority signal control on queue length in multiple cycles should be investigated further before on-site implementation.

Conclusion

The simulations with the ASEP revealed that the bid-based priority signal control was capable of achieving increased user benefit on average in relation to a pre-timed control with a similar green interval while keeping the average maximum queue length largely the same as the pre-timed equivalent. In other words, a bid-based signal priority control increased the frequency of subjective user benefits. In addition, it balanced out the expected values of user benefit in the two conflicting movements.

Limitations and Recommendations

To consider a bid-based priority signal control, both its advantages and potential side effects should be analyzed. Therefore, the research in this paper was conducted within certain limitations that suggest recommendations for future research.

First, it is recommended that further study be conducted into high-fidelity microscopic simulations. Although the ASEP model was useful to observe the moving trends of each vehicle as a particle in an initial observation, microsimulations should be conducted to investigate the effects of a bid-based control because they show more realistic results based on more inputs, such as decelerations, accelerations, and queue spillback with stochastic vehicle arrivals.

In addition, it is recommended that future studies investigate the effects of a bid-based priority signal control for multiple cycles. Although the ASEP did not consider queue spillback precisely, there may be real situations where queue spillbacks should be maintained under a certain value. A bid-based priority signal control has the potential to discharge relatively long queues automatically because bids from a longer queue are likely to be larger than those from the shorter conflicting movements. The bid-based priority signal control is flexible and robust in this context. If this is always the case, long queues observed in the ASEP (e.g., Trials 7, 16, and 18) might not be a big problem over cycles. However, excessive queue spillbacks could cause initial queue delay at the intersection or adjacent portions of the road over multiple cycles. If a bid-based priority signal control often creates long queues that result in severe delay, effective methods to control the effects of queue spillback should also be discussed. For instance, the length of queue spillback could be limited by installing some sort of queue length detection systems or setting a maximum green time, whose value may depend on intersection geometries.

Another future interest lies in optimizing bids in a transportation network. As long as green time is controlled by bids at each intersection, intersections may release movements that conflict with each other at the subsequent intersections. Thus, it would be interesting to assess the possibility that road users can bid for multiple intersections.

Furthermore, the effects of many independent variables should be investigated. Such variables would include vehicle arrival types, bidding distributions, traffic volume, degree of saturation, signal phasing, and the technology penetration rate. Since road users using different modes of transportation meet at intersections, it

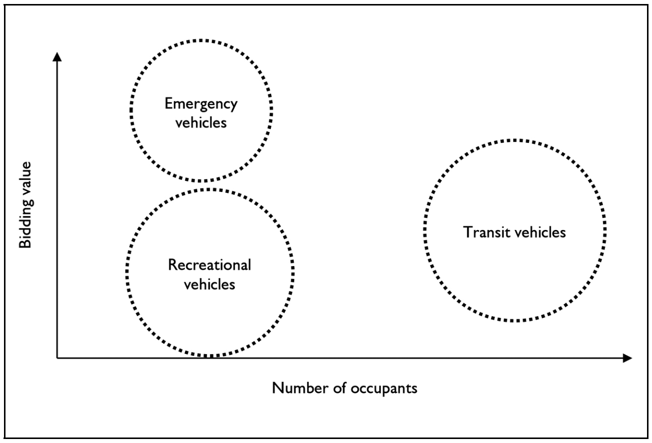

Figure 7. Concepts of signal priory control.

would also be of great value to investigate the effects of those variables in mixed flow environments. For example, a minimum green time should be implemented when there is a pedestrian crossing. In addition, future work should be done on the bidding infrastructure that can address VOT associated with different numbers of vehicle occupants.

As well as these variables, the initially expected red interval should be optimized when a bid-based priority signal control is actually installed because the value was merely arbitrary and largely affected the calculation in this study. The representative value can be the average, median, mode, or some other, but how to determine the fittest value has yet to be established. At the same time, it is important to note that there may be no "absolutely right" settings at real intersections because the meaning of optimality can vary from situation to situation.

Besides engineering studies, social studies should be conducted from a policy-making standpoint because bid-based priority control will not work if there is significant opposition to the system. The individual's ability to pay is not likely to be proportional to the individual VOT when the payment source is each driver's disposable income; thus, some people may think "the rich" would be favored and might not support the idea of bidding itself. Others could raise a question if vehicle users without any connected environment should be ignored in the bidding process. At the same time, it is also questionable how "equal" it would be to assume the homogeneous VOT for the right-of-way allocation that sacrifices some users' VOT. These perspectives add up to philosophical arguments and should be discussed in the future. Although some communities might like the idea, it may well be difficult to reach a global consensus on this issue as long as people have different opinions.

Theoretical and Practical Implications

In addition to the matters discussed above, a bid-based priority signal control has several implications.

Above all, a bid-based priority signal control can be an integrated form of priority control because preemption, TSP, and other signal priority control methods share the same ideology. If the system is introduced on transit vehicles, it can work as TSP whereas it can provide preemptions if it is put on emergency vehicles (Figure 7). Since these concepts are qualitatively the same, the only thing vehicle operators would be required to do would be to adjust bids. Such an integration will allow manufacturers to provide the infrastructure at reduced costs.

Also, it may be interesting to assess the effects on safety of the bid-based priority signal control because road users may begin to buy green indications rather than speed when they are in a hurry. Furthermore, a bidding scheme could be a good source of revenue for road authorities or other governmental organizations operating signalized intersections if the payment system is designed properly.

This paper introduced and discussed several key elements of a system of bid-based priority signal control. At this point, this research is merely theoretical because it is currently not easy to introduce special devices at real intersections, but it is worth exploring the possibilities associated with the bid-based priority signal control because the new type of control has the potential to give a vehicle society ways to enrich its quality.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: KI, YZ; data collection: KI; analysis and interpretation of results: KI; draft manuscript preparation: KI, YZ, LQ. All authors reviewed the results and approved the final version of the manuscript.

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