Comparative Analysis of Economic Instruments in Intersection Operation: A User-Based Perspective

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Abstract—Focusing on different economic instruments implemented in intersection operations under a connected environment, this paper analyzes their advantages and disadvantages from the travelers’ perspective. Travelers’ concerns revolve around whether a new instrument is easy to learn and operate, whether it can save time or money, and whether it can reduce the rich-poor gap. After a comparative analysis, we found that both credit and free-market schemes can benefit users. Second-price auctions can only benefit high VOT vehicles. From the perspective of technology deployment and adoption, a credit scheme is not easy to learn and operate for travelers.

Index Terms—connected vehicle, economic instrument, auction, transaction, credit, intersection, operation, benefit, user-based

I. INTRODUCTION

Economic instruments are known to be powerful traffic management tools, both theoretically and in practice (e.g., dynamic tolls). Under limited road resources, economic instruments with demand management can better serve heterogeneous vehicles’ demand and improve overall social welfare. Although Pigou has numerically argued that pricing strategies are useful for improving social welfare in 1920 [1], their real-world implementation has not been possible until today. Inconvenience is one of the reasons that impede its actual deployment. Traditional tolls (e.g., toll booths) introduce delays to travelers. For example, paying for parking will result in no less than 10-60 seconds time lost to every vehicle. Thanks to RFID technology, tolling on the highway can be carried out with zero delays to travelers. RFID cards and gates can save people’s time substantially. However, tolling gates and other facilities are usually expensive, and it has yet not seen wide-spread implementation, especially in many developing countries.

Today, we are witnessing major shifts in surface transportation. Advanced information technology and connected vehicle (CV) technology allows for direct vehicle-to-vehicle and vehicle-to-infrastructure communications, while autopilot features allow the vehicles to perform driving maneuvers autonomously (e.g., in response to the controls). This has given rise to several recent papers to use tolling or auctions directly between vehicles for deciding on right-of-way (ROW) or priority [2]–[5]. Auctions can be thought of as advanced tolling schemes, whereby vehicles auction their time in ways that capture heterogeneity in value of time (VOT). Some have been used for intersection operation research and parking management research [2]–[11]. In the intersection control literature, auctions require vehicles to give prices for a priority pass, and only vehicle(s) with a higher price(s) can pay and pass with priority. There are two typical formats: open auctions and sealed bid auctions [12]. Open auctions include ascending price auctions and descending price auctions; sealed-bid auctions include first-price auctions, second-price auctions, etc. Sealed bid auctions are more suitable for traffic management without unduly burdening drivers.

Standard auction mechanisms are not revenue-neutral economic instruments: travelers always need to pay an extra amount of money to travel. It can worsen family finances, especially for the poor, and unavoidably lead to public outcry and political opposition. The credit auction schemes, which may be originated from tradable network credits theory in traffic network management [13], [14], can also be revenue-neutral [5]. The credit is similar to a new currency, which should be pre-distributed by the government freely and periodically. Citizens can use it for travel and trade it in a trading market. By controlling the amount of credit in circulation, the transport sector can also manage the generation of traffic demand indirectly.

However, credit trading is itself time consuming and it renders travel a more complex process. A recent departure from auction-based mechanisms was the free-market mechanism introduced in [11], [15]–[18], in which vehicles pay each other for right-of-way as opposed to paying a third party (the system operator). Unlike auction-based approaches, these direct transaction-based approaches have the advantage that losers are directly compensated for “giving” priority.

All above mechanisms of economic instruments, including auction, credit (credit auction), and direct-transaction (free-market), are not easy to understand for citizens. Their concerns are usually different from and more complicated than the optimal objectives of theoretical models. Investigations are showing that travelers’ major concerns include relative convenience, cost, speed, reliability, safety, comfort, environment pollution, body health, and so on [19], [20]. We suppose that different economic instruments have a similar influence on
safety, comfort, reliability, environment and health. Among other things, they may care about: 1) whether a new measure is easy to learn and operate; 2) whether it can save time or money; and even 3) whether it is equity. Improvement of social welfare (even a Pareto-improvement\(^2\)) may also widen the rich-poor gap. Focusing on the first and the second concerns, this paper comparatively analyzes the influence of different economics instruments for travelers.

The next section discusses what citizens need to do for their travel under different economic instruments. The following section analyzes citizens’ benefits under different financial instruments. We transfer the time-saving options into monetary income and use the benefit to represent the sum income (transferred and real). This is followed by the last section, which briefly discusses the rich-poor gap and concludes the paper.

II. MANUAL OPERATION FOR TRAVELERS

Compared with auctions and direct-transactions, use of credit schemes require additional credit trading work (II-A). Also, all systems need to trade for priority at the intersection (II-B), and CV technology with the support of mobile payment is also necessary. Some steps of the process can be replaced by a machine, but other steps cannot.

A. Trade of credit in virtual market

The pre-distributed credit from the government will typically not be suitable in that the budget does not correctly align with their travel needs. Trade of credit cannot be avoided.

Fig. 1 illustrates the basic process of trading credit budget. Suppose the result of the step “Estimate the budget of all trips” is almost correct. The process in Fig. 1 will be employed in two scenarios. 1) It happens at the beginning of credit refreshment (old credits are scraped, and new credits are distributed). 2) It starts if a traveler adds/cancels a trip in his/her travel schedule. It is hard to say which scenario is more likely, but it is clear that: if the period of credit redistribution is shorter, scenario one will happen more frequently; otherwise, scenario two will happen more frequently.

The color green represents the work of the step that can be replaced/assisted by a machine. For example, we can imagine that the credits in different cities are similar to different stocks\(^3\). Travelers can know the prices and easily trade credits by mobile payment.

The step “estimate the budget of all trips” is a recombined step, and it can be described by the process in Fig. 2. If there are \(n\) trips, this process in Fig. 2 should be done \(n\) times. At the beginning of Fig. 2 the input of travel information cannot be done by a machine, and travelers have to decide and provide such inputs themselves.

\(^2\)an improvement only benefit some people with the other people unchanged

\(^3\)The credits should be homogeneous within the same traffic network, such as the network of a city
and expire. Also, trading credit through an agent will result in wasted money because credit will inevitably devalue to guarantee that the credit is enough for travel, and this can lead to additional delays, they have to pay for an increase in budget. We assume to be the subject vehicle and which vehicle we consider to be the opponent. We denote by \( t_A \) the time of vehicle A (vehicle B) should they win.

The game setting in this paper is one that is played between pairs of vehicles. We consider the simple setting of an intersection of two single-lane one-way streets. That is, we consider two conflicting through movements. In our analysis we take the position of one of the two vehicles involved in a game, which we shall refer to as vehicle A, the subject vehicle, and denote their VOT by \( v_A \). We refer to the other vehicle as vehicle B, the opponent vehicle, and denote their VOT by \( v_B \). Generally speaking, the games considered here are symmetric and it, therefore, does not matter which vehicle we assume to be the subject vehicle and which vehicle we consider to be the opponent. We denote by \( t_A \) (\( t_B \)) the time saved by vehicle A (vehicle B) should they win.

Both the time and money saved are important in the implementation of economic instruments. The VOT is like a bridge used to transfer time into money, and we consider the benefit \( B \) as the sum of money earned and transferred time saved (converted to monetary units). For example, if vehicle A with VOT \( v_A = 2 \) cents/s, gets passing priority and saves \( t_A = 2 \) s, its time saved in monetary units is \( v_A t_A = 4 \) cents. But it pays 1 cent so that its benefit is \( B = 4 - 1 = 3 \) cents. Here, the return rate of the game is \( \alpha = \frac{3}{4} = 0.75 \) for vehicle A.

In brief, we analyze different economic instruments in this section:

1) **First-price auctions.** The higher bid wins and the winner delivers the amount they bid in its entirety to a third party operator in exchange for ROW or priority. Here, the return rate of game \( \alpha \) is always zero.

2) **Second-price auctions.** The player with the higher bid also wins, but only delivers the loser’s (smaller) bid to the operator. The \( \alpha \) is (this vehicle is A):

\[
\alpha_{2auc} = \begin{cases} 
\frac{v_A t_A - v_B t_B}{v_A t_A} & \text{if A wins} \\
0 & \text{if A loses}
\end{cases}
\]  

(1)

3) **Credit with second-price auctions (we refer to it as credit in this paper).** Its benefit from the game is the same as the benefit in the second-price auction (\( B_{2auc} \)). However, out of game, it still has money earned from credit distribution \( C \), and a loss because of credit trading \( L_A \). In this paper, we suppose the money earned out of game is person-equal and revenue-neutral, and its lost is about 10% of what it earns in total. The credit benefit is:

\[
B_{cre} = B_{2auc} + C - L_A.
\]  

(2)

4) **Direct transactions.** The winner transfers a fraction of their winnings to the loser and nothing to a third party operator. We consider two rules for the value of \( \alpha_{tra} \), the first rule is \( \alpha_{tra} = 1/2 \), which has analytical support as a side payment in a transferable utility game [11], [15]. The second rule is that vehicle A keeps a fraction of their bid equal to the proportion of their personal benefit to the total personal benefit in the system: \( \alpha_{tra} = \frac{v_A t_A}{(v_A t_A + v_B t_B)} \). The two rules can be amalgamated using a binary variable \( \chi \), which applies the first rule when set to zero and applies the second rule when set to one:

\[
\alpha_{tra} = \frac{(v_A t_A - 1)\chi + 1}{(v_A t_A + v_B t_B - 2)\chi + 2}.
\]  

(3)

In a sealed bid, vehicles do not know each other’s VOTs, so from the perspective of each vehicle, the other vehicle’s VOT is a random variable. We will also consider heterogeneity in traffic conditions, so that time savings can also be treated as random variables. We will quantify and analyze expected net personal benefits and use these expectations to perform comparisons between the different game types. Use of expected values is motivated by the law of large numbers; it represents the benefits realized after playing a large number of games.

**B. Input of calculation**

In the calculations below, we assume that the probability distributions of VOT and time saving (across the driving
population) are given. In this section, we pick a typical distribution, log-normal distribution for both VOT and time saving. We borrow the investigation results of VOT by Brownstone, et, al in San Diego for $f_v$ [22]. As shown in Fig. 4, median VOT is $30$ per hour (0.8 cent per second). The upper quartile is $43$ per hour (1.2 cent per second), and the lower quartile is $23$ per hour (0.6 cent per second). In addition, considering a mean discharging time of 2 second per vehicle at the intersection, we design $f_t$ shown as in Fig. 5.

![PDF of VOT](image)

**Fig. 4: PDF of VOT.**

![PDF of time saving](image)

**Fig. 5: PDF of time saving.**

### C. No abandonment and honest VOT reporting

The net personal benefits of the game are summarized in Table I for the case when player A wins, and in Table II for the case when player A loses. Because this is symmetric for A and B, we just focus on vehicle A in the analysis. We define:

\[
\beta \equiv 1 - \alpha. \quad (4)
\]

**TABLE I: Benefit of game when vehicle A wins**

| Game                        | Net Benefit |
|-----------------------------|-------------|
| First-price auction         | $\alpha_A v_A t_A$ | $\beta_A v_A t_A$ |
| Sec.-price auction          | $\alpha_A v_A t_A$ | $\beta_A v_A t_A$ |
| Dir. transaction            | $\alpha_A v_A t_A$ | $\beta_A v_A t_A$ |

The situation is trivial in this case for a first-price auction: $B_{1auc} = EB_{1auc} = 0$ with probability 1. For a second-price auction, vehicle A knows their own VOT, but not B’s, so the latter is random. The time savings shall also be assumed to be random to represent variability in traffic conditions. From Table I the benefit of the game for A in a second-price auction is

\[
B_{2auc}(v_A, V_B, T_A, T_B) = 1_{\{v_A T_A \geq V_B T_B\}} \alpha_A v_A T_A, \quad (5)
\]

where $1_{\{\cdot\}}$ is an indicator function that returns 1 if \( \cdot\) is true and returns 0 otherwise. The expected benefit in the game to A is given by

\[
E B_{2auc}(v_A, V_B, T_A, T_B) = E\{1_{\{v_A T_A \geq V_B T_B\}} \alpha_A v_A T_A \} = E\{\alpha_A v_A T_A | v_A T_A \geq V_B T_B\} P(v_A T_A \geq V_B T_B). \quad (6)
\]

The expected benefit for credit can be based on the expected benefit of second-price auctions in Eq. 2:

\[
EB_{cre} = EB_{2auc} + C - EL_A. \quad (7)
\]

In the case of a direct transaction game, there is a non-negative net personal benefit to vehicle A whether they win or lose. The net personal benefit is given by

\[
B_{tra}(v_A, V_B, T_A, T_B) = 1_{\{v_A T_A \geq V_B T_B\}} \alpha_A v_A T_A + 1_{\{v_A T_A < V_B T_B\}} \beta_A v_B T_B \quad (8)
\]

and the expected personal benefit is

\[
E B_{tra}(v_A, V_B, T_A, T_B) = E\{\alpha_A v_A T_A | v_A T_A \geq V_B T_B\} P(v_A T_A \geq V_B T_B) + E\{\beta_A v_B T_B | v_A T_A < V_B T_B\} P(v_A T_A < V_B T_B). \quad (9)
\]

When a pair of vehicles cross a single-lane one-way intersection, there is a basic scenario that both vehicles have equal opportunity to pass with priority. That is similar to a two-equal-phase control scenario. The Expected benefit in this traditional environment is the expected basic benefit $EB_b$ in this section.

We define expected extra benefit as any expected benefit minus expected basic benefit. If it is larger than 0, travelers can benefit from the economic instrument. Otherwise, travelers cannot benefit from it.

Fig. 6 shows the expected extra benefit for different VOT vehicles. The background shows the accumulated distribution of VOT. Obviously, in a first-price auction system, people can gain nothing and the extra benefit in just $-EB_b$. They will be indifferent to receiving right-of-way (ROW) or not. A system that uses the second-price auctions is a system that only benefits the rich. Vehicles with VOTs at and below the median VOT will dislike the auction game and prefer the traditional fairness control. The transaction game with
$\chi = 0$ is rewarding the low VOT vehicles. They earn much more benefit in a transaction game than under traditional control. For these top VOT vehicles, they can still gain some additional benefits. The transaction game with $\chi = 1$ is rewarding to the high VOT vehicles. At the same time, the credit scheme is similar to a balance between the two transaction cases.

In this part, we suppose that the traditional traffic system and the market-inspired system will both exist. A vehicle predetermines whether to abandon the market-inspired system and the market-inspired system will both exist. If either vehicle does not wish to play the game, then $\gamma = 0$. When this is the case, there is a probability that a vehicle will receive priority and a probability that they will not. Let $p_A$ denote the probability that vehicle A receives priority when $\gamma = 0$ and $p_B = 1 - p_A$. If $\gamma = 0$ and $v_{A,t}A \geq v_{B,t}B$, in a first-price auction vehicle A's net personal benefit is $v_{A,t}A$. Similar arguments can be made for vehicle B, other types of games, and when $v_{A,t}A < v_{B,t}B$. The (mean) net personal benefits of the game are summarized in Tables III and IV.

**Table III: Net personal benefits when $v_{A,t}A \geq v_{B,t}B$**

| Game      | Net Benefit                                      | Operator |
|-----------|--------------------------------------------------|----------|
| First-price | $(1 - \gamma)p_A v_{A,t}A$                        | $\gamma v_{A,t}A$ |
| Sec.-price | $\gamma_2auc v_{A,t}A + (1 - \gamma)p_A v_{A,t}A$ | $\gamma v_{A,t}A$ |
| Dir. trans | $\gamma_3auc v_{A,t}A + (1 - \gamma)p_A v_{A,t}A$ | 0        |

After all travelers’ choices are stable, the expected extra benefits will be all equal or larger than zero shown as in Fig. 7. We use credit (0) to represent the policy that credits are distributed to all travelers, and credit (1) to represent the policy that credits are only distributed to joiners. Fig. 7 indicates that, under 1st-price auctions, 2nd-price auctions, and normal credit distribution (combined with 2nd-price auctions), all travelers will inevitably abandon the market-mechanism. The problem is that once some travelers find that abandonment can benefit them, they will leave. And then these leavers will lead to further abandonment of the other travelers. Note that credit (1) is much harder to implement and costs a lot for the government because it requires the exact knowledge of traffic users every day.

**Table IV: Net personal benefits when $v_{A,t}A < v_{B,t}B$**

| Game      | Net Benefit                                      | Operator |
|-----------|--------------------------------------------------|----------|
| First-price | $(1 - \gamma)p_A v_{A,t}A$                        | $\gamma v_{B,t}B$ |
| Sec.-price | $\gamma_2auc v_{A,t}B + (1 - \gamma)p_A v_{A,t}A$ | $\gamma v_{B,t}B$ |
| Dir. trans | $\gamma_3auc v_{A,t}B + (1 - \gamma)p_A v_{A,t}A$ | 0        |

**Fig. 6: Benefit in honest scenario.**

**Fig. 7: Benefit in leaving scenario.**

**D. Honest VOT reporting with abandonment**

In this part, we suppose that the traditional traffic system and the market-inspired system will both exist. A vehicle predetermines whether to abandon the market-inspired system before traveling. To this end, the binary variable $\gamma$ represents whether they choose to play the game ($\gamma = 1$) or not ($\gamma = 0$). If either vehicle does not wish to play the game, then $\gamma = 0$. When this is the case, there is a probability that a vehicle will receive priority and a probability that they will not. Let $p_A$ denote the probability that vehicle A receives priority when $\gamma = 0$ and $p_B = 1 - p_A$. If $\gamma = 0$ and $v_{A,t}A \geq v_{B,t}B$, in a first-price auction vehicle A’s net personal benefit is $v_{A,t}A$. Similar arguments can be made for vehicle B, other types of games, and when $v_{A,t}A < v_{B,t}B$. The (mean) net personal benefits of the game are summarized in Tables III and IV.

**E. Dishonest VOT reporting without abandonment**

Suppose that the government can only know citizens’ declared VOT. All travelers are still rational. To increase net personal benefits, vehicles/drivers may place bids based on false VOTs. We denote by $\tilde{v}_A$ the reported VOT and allow dishonest VOTs to be drawn from different distributions $f_{\tilde{v}_A}$ for vehicle A and $f_{\tilde{v}_B}$ for vehicle B. We also use the notation $\tilde{a}_{auc}$ and $\tilde{a}_{tra}$ to indicate that these fractions are calculated based on reported VOTs. The net personal benefits realized are still based on true VOT. For example, if vehicle A bids $\tilde{v}_{A,t}A$ in a first-price auction and wins, their net personal benefit is $(v_A - \tilde{v}_A)l_A$. If system abandonment is not allowed, net personal benefits in a system with dishonest VOT reporting are summarized in Table V when vehicle A wins and in Table VI when vehicle B wins. The declared VOT distribution will keep dynamically changing. If the operator also uses a dynamic economic instrument (for example, $\chi$ is not fixed for the direct transaction), the benefit will also be unstable.
After about 20 iterations, all expected extra benefits become stable or repeatable. We show their values/mean values in Fig.

### TABLE V: Net personal benefits when $\tilde{v}_A t_A \geq \tilde{v}_B t_B$

| Game | Net Benefit | A (winner) | B (loser) | Operator |
|------|-------------|-----------|-----------|----------|
| First-price | | $0$ | $0$ | $\tilde{v}_A t_A$ |
| Sec.-price | | $0$ | $0$ | $\beta_2 t_A \tilde{v}_A t_A$ |
| Dir. trans | | $0$ | $0$ | $\beta_4 t_A t_B$ |

### TABLE VI: Net personal benefits when $\tilde{v}_A t_A < \tilde{v}_B t_B$

| Game | Net Benefit | A (loser) | B (winner) | Operator |
|------|-------------|-----------|-----------|----------|
| First-price | | $0$ | $0$ | $\tilde{v}_B t_B$ |
| Sec.-price | | $0$ | $0$ | $\beta_2 t_A \tilde{v}_A t_B$ |
| Dir. trans | | $0$ | $0$ | $\beta_4 t_A \tilde{v}_B t_B$ |

It is clear that both credit and transaction games perform well, but pure auction strategies can not make all travelers happy.

![Fig. 8: Benefit in lying scenario.](image)

### IV. CONCLUSION

With the popularity of connected vehicle technology and mobile payment, economic instruments can better serve heterogeneous vehicles with different values of time (VOT) in intersection operations. Most papers consider the influence of economic instruments from the perspective of system optimization, but few papers analyze what the users’ concerns are. When a new management method appears, users want it to be easy to learn and operate, that it can save time or money, and that it can reduce the rich-poor gap. We haven’t analyzed the rich-poor gap in this paper but propose to do so in future research. We found that auction mechanisms will enlarge the rich-poor difference, and the other mechanisms cannot guarantee a reduction of the gap.

Based on a comparative analysis, we found that the credit scheme and free-market scheme can both benefit users. The second price auction can only benefit high VOT vehicles. However, considering the operational difficulties, a credit scheme is not easy to learn and operate for travelers.

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