Design and Comparative Analysis on Real-Time Trade of Road Priority in Connected Traffic

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ABSTRACT New technologies present opportunities to re-think the real-time traffic operation. Trade of road priority using schemes such as auctions, credits, and direct-transactions, provides a novel way to better serve heterogeneous traffic demands in the future connected environment. Implementations of these schemes come with a common phenomenon called the network effect, meaning that the value of the scheme depends heavily on the percentage of travelers that subscribe to this scheme. To encourage travelers to be subscribers, the traffic operator needs to reasonably consider the treatments for both subscribers and outsiders, and have the knowledge of each scheme’s impact on individuals and society. Only in this way can the government choose an appropriate scheme that will be accepted by the public. However, most existing studies simply assumed a 100% of subscribers and ignored the travelers’ autonomy and smartness in choice behavior. Such neglect may easily render the economic schemes failed in practice due to public resistance or loss in subscribers. To fill up this research gap, this paper designs treatments to both subscribers and outsiders for different schemes in intersection operations. We investigate travelers’ choice behaviors under different scenarios, and make comparative analysis about individual benefits, social benefit, and social equity between different schemes. The findings of this paper can support the government’s decision on the system design of road priority trading.

INDEX TERMS Auction, benefit, comparative analysis, credit scheme, direct-transaction, economic schemes, equity, network effect, subscribing choice, trade of road priority.

I. INTRODUCTION

Recent years, rapid development in connected/automated vehicle technology and mobile payment has given rise to opportunities for reshaping the traffic system in the near future. Trade of road priority (TORP), which comes from the combination of connected/automated vehicle technology and mobile payment, has attracted the researchers’ attention and been regarded as an effective way to improve the social welfare [1]. Specifically, it allows travelers to trade their road priority with a slight payment in real-time. In this way, travelers with high value of time (VOT) have the chance to pay the government or other travelers so as to save time on the road. Under the connected traffic environment, TORP can better serve heterogeneous traffic demand when road resources are limited.

In general, current studies mainly use three different schemes for TORP, and we name them auction schemes [2]–[7], credit schemes [8]–[19], and direct-transaction schemes [20]–[27] in this paper. These schemes have been designed for various traffic management fields, including intersection control [2], [19], [20], [22], [24], lane change control [21], [23], [27], network mobility management [8]–[18], [26]. By considering travelers’ VOT, researchers have shown that TORP can not only achieve almost minimum delay, but also significantly improve the valuated efficiency of the system. For example, with the direct-transaction schemes, the valuated efficiency can be improved by about 50% to 100% compared with the first-come-first-serve control, and 10% to 20% compared with the delay-minimizing control [24].

Among the three types of schemes for TORP, auction schemes can be thought of as advanced tolling schemes, whereby vehicles auction their time in ways that capture heterogeneity in VOT. It requires vehicles to bid for road priority,
TABLE 1. Summary of different schemes in TORP.

| Scheme         | Mechanism                                                                 | Main application scenes | Revenue-neutral | External cost |
|----------------|---------------------------------------------------------------------------|-------------------------|-----------------|---------------|
| Auction        | Travelers bid for road priority, and pay operator for using it.           | Intersection control    | No              | Low           |
|                | Travelers receive credits from operator, then pay operator credits for using road priority. | Network management, intersection control | Yes             | High          |
| Credit         | Credits can be traded among travelers.                                    |                         |                 |               |
| Direct-transaction | Travelers make transactions on road priority, and pay other travelers for using it. | Lane-change, intersection control | Yes             | Low           |

In credit schemes, credits are like a traffic currency which is pre-distributed by the government freely and periodically (e.g. weekly, monthly). Travelers are then required to pay credits for using the right-of-way. Credits can be traded among users so that people with extra credits can sell their credits to people with insufficient credits. Credit price is determined through free trading, and transaction cost can be incurred during trading [13], [17], [18]. The idea of credit schemes can be traced back to Dales’s work for water quality management [29]. The concepts were then extended for vehicle emission control [30] and traffic management [31]. A milestone was established when [8] made rigorous quantitative modeling and analysis of the credit scheme for network mobility management. It was then developed to cover more complicated traffic conditions [9]–[12] and impact evaluations on travelers [13]–[18]. Some papers also apply credit schemes in intersection control. Unlike the network traffic management where the charged credits for using each link are determined by the government, in intersection control, the charged credits for passing the intersection are dynamically auctioned1 by vehicles in real time [19].

Compared with auction and credit schemes, the concept of using direct-transaction in traffic management is relatively new, which was introduced recently in [20]–[27]. In direct-transaction schemes, vehicles pay each other for using the right-of-way as opposed to paying the operator. Hence unlike auction-based approaches, priority losers in direct-transaction schemes are directly compensated by priority winners for giving out priority. The offered prices of vehicles for the priority (similar to the bids) are the key parameters for determining the winners and payments.

We refer to the above three schemes collectively as economic schemes as they all involve monetary transactions. The main features of different schemes are summarized in Table 1. As we can see, 1) all economic schemes can be implemented in intersection control; 2) credit schemes have higher external costs for travelers than auction and direct-transaction schemes due to the time and money spent on credit tradeings [1], [13]; and 3) both credit and direct-transaction schemes are revenue-neutral as their monetary transfers only happen among travelers, while auction schemes are not revenue-neutral since they require the priority winners to pay the government. Note that schemes that are not revenue-neutral can be easily mistaken by the travelers as taxation tools and thus incur public resistance.

Implementations of the above economic schemes come with a common phenomenon called the network effect. That is, the value of the scheme depends on the size of the subscribers (a subscriber in this paper means a traveler that subscribes to the economic scheme). For a scheme with positive network effect, if all travelers are subscribers, the value of the scheme reaches the maximum; if there is only one subscriber, the scheme becomes useless. One way to guarantee enough subscribers is to create policies to force travelers to subscribe to the economic scheme, but such hard-line policies could easily cause social objection. When travelers are allowed to choose freely, their subscribing choices will significantly depend on whether they can increase their individual benefits by joining the scheme. In addition, the network effect will also influence some social attributes. On the one hand, the social benefit, which is the sum of individual benefit and operator benefit, changes with the subscriber size. On the other hand, the social equity in the distribution of income changes gradually as travelers with various income levels obtain different individual benefits. We show their relationships in Fig. 1. All these elements could jointly influence the government’s decisions on whether to implement a scheme and which scheme to choose.

Unfortunately, the network effect phenomenon along with its related benefit and equity issues received scant attention in the literature, as shown in Table 2. Most of the existing

1Although auction mechanism is used here, we call them credit schemes since it is the credit that is used to pay for the auctioned priority.
research assumed that all travelers are subscribers, while a few studies considered a fixed proportion of travelers to be outsiders permanently (static assumption). The evolution of the economic scheme system with dynamic outsiders is still unknown. Although a few studies quantitatively calculated the benefit or evaluated the equity, they have not figured out how the three schemes influence the benefit/equity differently. Lack of such knowledge could make it difficult for the government to select a proper scheme in practice. Therefore, to close the research gap, this paper calculates the individual benefit under different schemes, and investigates its impact on travelers’ choice behaviors. We assume that travelers are rational and smart, hence they will dynamically adjust their subscribing choice to maximize their own expected individual benefit. The social benefit is computed to see if each scheme will increase or decrease the social welfare, and the equity is quantitatively evaluated to see whether each scheme will widen or close the gap between rich and poor.

In this paper, we shall first design the treatments for both subscribers and outsiders in all three schemes, and treat travelers as smart individuals to choose between being subscribers or outsiders. We then design four kinds of possible scenarios for implementing the TORP in the future. For each scenario, the expected individual benefits (with different VOTs) the social benefit in each scheme are obtained through simulating the travelers’ choice behavior in a dynamic system. The impact of different schemes on the social equity are analyzed using the Gini index. The comparative analysis among different schemes could serve as a reference for the government to select economic schemes when real-time TORP is possible in real world in the near future.

We organize this paper as following: the next section designs the mechanism of different economic schemes in the presence of both subscribers and outsiders. The third section designs four specific scenarios implementing the TORP, and compares the individual benefits, social benefit, and social equity between different economic schemes. The last section concludes the paper.

### II. MECHANISM DESIGN

#### A. VEHICLE GROUPS

TORP using economic schemes have been used in many traffic scenes, e.g., the intersection passing scene [20], [24], the lane-change scene [21], [27], and the network management scene [8], [26]. Without loss of generality, we choose the intersection framework in [24] to introduce and design each scheme in details in this section.

Imagine the intersection controller has an existing control strategy and then finds a candidate control strategy at its decision time. If there exists conflicting movements, different vehicles may prefer different strategies considering their passing time. In effect, these vehicles are competing for their passing priority. Here, we define a vehicle’s potential time saving (PTS) as the time saving under its preferred strategy, compared with its disliked one. Obviously, PTS is non-negative. Excluding the vehicles with PTS = 0, if there are still two nonempty vehicle groups (PTS > 0) preferring different strategies, we can denote them by $A$ and $B$ (randomly), and let $-A = B$, $-B = A$.

Suppose any group $G \in \{A, B\}$ consists of $|G|$ number of vehicles: $G = \{v_1^G, v_2^G, \ldots, v_{|G|}^G\}$. We have $A \cap B = \emptyset$ and denote a union set $U = A \cup B = \{v_1^A, \ldots, v_{|A|}^A, v_1^B, \ldots, v_{|B|}^B\}$. Each vehicle $v \in U$ has an attribute tuple $a_v = (\beta_v, \tilde{\beta}_v, t_v)$, where $\beta_v \in \mathbb{R}_+$ is the Real VOT (R-VOT), $\tilde{\beta}_v \in \mathbb{R}_+ \cup \{0\}$ is the Declared VOT (D-VOT) and $t_v \in \mathbb{R}_+$ is the PTS. We set $\tilde{\beta}_v = 0$ when $v$ is a subscriber, and $\tilde{\beta}_v = 0$ when $v$ is an outsider. The number of subscribers in $U$, denoted by $N_{U}^s$, is hence

$$N_{U}^s = \sum_{v \in U} \mathbb{1}(\tilde{\beta}_v > 0),$$

where $\mathbb{1}(\cdot)$ is the indicator function which equals to 1 if $(\cdot)$ is true or 0 otherwise. The number of outsiders in $U$, denoted by $N_{U}^o$, is then

$$N_{U}^o = |U| - N_{U}^s,$$

where $|U|$ is the size of $U$.

#### B. VALUATED TIME SAVING

The valuated time saving (VTS) refers to the product of VOT and the time saving. We define the Real VTS (R-VTS) of $v$ as the product of $\beta_v$ and $t_v$:

$$w_v = \beta_v t_v.$$  

(3)

In practice, a vehicle’s R-VTS is usually unavailable to others as it is private. Vehicles may lie about their VOT ($\beta \neq \tilde{\beta} > 0$), or may choose to be the outsiders (VOT is hidden with $\tilde{\beta} = 0$). We define the Declared VTS (D-VTS) of $v$ as the product of $\tilde{\beta}_v$ and $t_v$:

$$\tilde{w}_v = \tilde{\beta}_v t_v.$$  

(4)

If the controller directly uses D-VTS $\tilde{w}$ as the weight to allocate priority, outsiders will unavoidably be treated...
Fairly since their $\tilde{w}$ are 0. This is how outsiders were treated in the literature [19], [24]. To improve fairness, we design a non-zero weight, the Estimated VTS (E-VTS, denoted by $\hat{w}$), for all outsiders. Specifically, if there is any subscriber in a game ($N_{sU} \geq 1$), the outsider’s weight (E-VTS) is equal to the mean of all subscribers’ D-VTS. We have

$$\hat{w}_U = \sum_{v \in U} \tilde{w}_v \max(1, N_{sU}/N_{s}) + 1(N_{sU} = 0),$$

where $\max(\cdot, \cdot)$ is the max function. Note that if there is no subscriber ($N_{sU} = 0$), then $\sum_{v \in U} \tilde{w}_v = 0$, and all outsiders’ weight would be 1. If there is exactly one subscriber ($N_{sU} = 1$), then all outsiders’ weight would be the same with the subscriber’s weight, which equals to the D-VTS of the subscriber. For clarity, all notations in this paper are summarized in Table 3.

We show the relationships between $w$, $\tilde{w}$, and $\hat{w}$ in Fig. 2. In summary, R-VTS is the private information that is only known by vehicles. D-VTS is vehicles’ broadcast information when they approach the intersection, which comes from the asymmetric information. E-VTS is the adjusted weight for outsiders by the controller, which aims to improve fairness in the priority allocation.

C. INTERSECTION OPERATION WITH ECONOMIC SCHEMES

Based on D-VTS and E-VTS, the sum-weight of group $G$, denoted by $\tilde{\Sigma}_G$, is calculated by

$$\tilde{\Sigma}_G = \sum_{v \in G} (1(\tilde{\beta}_v > 0)\tilde{w}_v + 1(\tilde{\beta}_v = 0)\hat{w}_U).$$

We have $\tilde{\Sigma}_G > 0$. Furthermore, we define a bijective function\(^2\) $S$ for a given economic scheme of the controller to allocate priority, $S: \{A, B\} \rightarrow \{0, 1\}$, where 1 means winning the priority, and 0 means losing the priority. For a scheme that maximizes the sum-weight, we have

$$S(A) = 1 - S(B) = \begin{cases} 
1 & \text{if } \tilde{\Sigma}_A \geq \tilde{\Sigma}_B \\
0 & \text{otherwise}
\end{cases}.\quad(7)$$

Note that each group could be regarded as group $A$ with an equal probability of 50%. Also, if we suppose the controller is “smart” enough, the sum-weight of the candidate strategy should not be lower than the existing one.

\(^2\)Bijective function connects elements of two sets such that, it is both one-to-one and onto function, https://www.cuemath.com/algebra/bijective-function/

### Table 3. Notations in this paper.

| Parameter | Description |
|-----------|-------------|
| $A, B, G, U$ | nonempty vehicle group, $G \in \{A, B\}, U \equiv A \cup B$ |
| $a$ | attribute tuple |
| $\alpha_1, \alpha_2$ | positive constants |
| auc | an auction scheme: auc $\in \{“1auc”; “2auc”\}$ |
| $B$ | individual benefit |
| $C$ | D-VOT in credit |
| cre | a credit scheme: cre $\in \{“cre.a”; “cre.s”\}$ |
| $D$ | distributed amount per game from the government |
| $e$ | an economic scheme |
| $F_{inc}$ | CDF or PDF of travelers’ annual income |
| $F_{vot}$ | Lorenz curve function |
| $F_{vot}$ | income-VOT function |
| $f, \tilde{f}, f_t$ | PDF of R-VOT, PDF of D-VOT, PDF of PTS |
| $f_{inc}, f_{vot}$ | PDF of old income, PDF of new income |
| $G$ | function maps a vehicle to its corresponding group |
| $g, \tilde{g}, \tilde{g}, \Delta g$ | Gini index, Gini index under the non-economic scheme, Gini index under an economic scheme, and influence of an economic scheme in equity |
| $H, \tilde{H}$ | income-change function, and its inverse function |
| $I_g$ | social benefit improvement index |
| $I_\text{total}$ | total income of cumulative share of people from lowest income to an income $i$ |
| $i$ | iteration step |
| $\max$ | max function |
| $N_{gam}$ | average number of games per vehicle per year |
| $N_{pop}$ | number of population |
| $N_{trav}$ | average number of travelers per vehicle |
| $N_{sU}$ | number of subscribers or outsiders in group $U$ |
| $N_{s}$ | number of all vehicles in the system |
| $N_{o}$ | number of subscribers in the system |
| $O$ | function maps a group to its state of passing in a non-economic scheme: with ($\geq 1$) or without ($\leq 0$) priority |
| $\tilde{p}(\tilde{\beta})$ | probability that D-VOT belongs to $[\tilde{\beta} - \Delta \tilde{\beta}, \tilde{\beta} + \Delta \tilde{\beta}]$ |
| $p_c$ | real-time price of one credit |
| $p_r(t)$ | probability that PTS belongs to $[t - \Delta t, t + \Delta t]$ |
| $\delta$ | government’s mean received revenue from per game per vehicle |
| $r$ | government’s mean received revenue from per game per vehicle |
| $S$ | function maps a group to its state of passing in an economic scheme: with ($\geq 1$) or without ($\leq 0$) priority |
| $s$ | any scenario: $s \in \{1, II, III, IV\}$ |
| $t, \Delta t$ | PTS, differential of PTS |
| $\gamma$ | a direct-transaction scheme: $\gamma \in \{“hra”; “jra”; “ira”\}$ |
| $V_-$ or $U_-$ | group with all vehicles in $U$ excluding vehicle $v$ or vehicle $u$ |
| $V_+, V_-$ | R-VTS, D-VTS, and E-VTS |
| $\tilde{\Sigma}_G$ | sum-weight VTS of group $G$ in controller’s calculation |
| $\alpha$ | R-VOT, D-VOT, and differential of VOT |
| $\delta$ | discount factor for outsiders |
| $\beta$, $\tilde{\beta}$ | discount factor for credit scheme |
| $\Delta \beta$ | a traveler’s annual income, annual income under the non-economic scheme, annual income under an economic scheme, and additional annual income |
| $\Pi(\cdot)$ | indicator function equals to 1 if $(\cdot)$ is true or 0 otherwise |
| $\beta$ | set of all vehicles in the system |
| $\Delta E B, \Delta E B$ | expected benefit, expected additional benefit |
| $\beta R$ | mean received amount per game per vehicle |
| $\beta S$ | set of all positive real number |
| $\gamma S$ | set of all subscribers in the system |
We define a function $G$ that maps all vehicles $v \in \mathcal{U}$ to the corresponding group, $G: \mathcal{U} \rightarrow \{A, B\}$. Hence,

$$G(v) = G, \quad \text{if } v \in G. \quad (8)$$

The composite map $(S \circ G): \mathcal{U} \rightarrow \{0, 1\}$ is then defined by

$$(S \circ G)(v) = S(G(v)). \quad (9)$$

In an economic scheme, the priority winners usually need to make payments (either to the third party, or to the priority losers) in exchange for obtaining the priority if they are subscribers. We denote the received amount (in currency) of vehicle $v$ in a specific economic scheme $e$ during a priority competition by $R^e_v$. Hence if $v$ belongs to the winner group, $R^e_v < 0$; otherwise $R^e_v > 0$.

Finally, considering effect of the outsiders, we define a discount parameter $\delta \in [0, 1]$ in $R^e_v$’s calculation:

$$\delta = \min\left\{ \frac{\sum_{v \in A} \tilde{W}_v}{\sum_{A}}, \frac{\sum_{v \in B} \tilde{W}_v}{\sum_{B}} \right\}, \quad (10)$$

where $\min(\cdot, \cdot)$ is the min function. We can find that, if $N^e_{ul} = |\mathcal{U}|$, $\delta = 1$; if $N^e_{ul} \leq 1$, $\delta = 0$. In general, with more outsiders, $\delta$ becomes smaller.

To calculate $R^e_v$, one needs to first determine the group’s total received amount $\sum_{v \in G} R^e_v$, and then split the total amount within the group. Each group member’s received amount is weighted by their D-VTS (if there are more than one member). We next introduce how to calculate $R^e_v$ in different economic schemes.

### D. AUCTION SCHEMES

As mentioned before, in auction schemes, vehicles bid for priority and the group with a higher bid wins the priority and pays the third party (e.g., operator) in exchange for the priority. In this paper, we study two kinds of most commonly used auction schemes in traffic management: the first-price auction and the second-price auction. We refer them to “1auc” and “2auc”, respectively, and have auc $\in \{\text{“1auc”, “2auc”}\}$.

In “1auc”, the winner vehicles need to pay the third party the amount themselves bid, and the loser vehicles receive nothing. Therefore

$$R^1_{auc} = \begin{cases} -\delta \tilde{W}_v & \text{if } (S \circ G)(v) = 1; \\ 0 & \text{otherwise} \end{cases}, \quad (11)$$

Note that since $\tilde{W}_v$ is 0 if $v$ is an outsider, the received amount of the outsider is hence always 0, regardless of it is a winner or loser.

In “2auc”, the winner group only needs to pay the third party the loser group’s (smaller) bid, and still, the loser group receives nothing. Then the total received amount is split in proportion to their D-VTS. Hence

$$R^2_{auc} = \begin{cases} -\delta \frac{\sum_{G(v)} \tilde{W}_v}{\sum_{G(v)}} \tilde{W}_v & \text{if } (S \circ G)(v) = 1; \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

### E. CREDIT SCHEMES

In credit schemes, the operator periodically distributes credits to travelers, and travelers use credits to pay for the passing priority. Credits can be traded among travelers so that people with extra credits can sell their credits to people with insufficient credits. The credit prices are determined through free trading.

We investigate two credit distribution policies in this paper: (i) credits distributed to all travelers, named “cre.a”, and (ii) credits only distributed to subscribers, named “cre.s”.

We denote any credit scheme as cre in the rest of this paper, where $cre \in \{\text{“cre.a”, “cre.s”}\}$. A cre needs to combine with a toll or auction scheme so that the operator can retrieve the credits in operation, and we adopt the “2auc” rule in cre in this paper. In cre, travelers report their VOTs in credit, denoted by $\tilde{v}_v$ (unit: credit/h), and their received credit is

$$c^\text{cre}_v = \begin{cases} -\delta \frac{\sum_{G(v)} \tilde{v}_u \tilde{W}_v}{\sum_{G(v)} \tilde{W}_v}, & \text{if } (S \circ G)(v) = 1; \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

Let $p_c$ denote the real-time price of one credit (unit: currency/credit), then we have $\tilde{c} = \tilde{v}_v \cdot p_c$. Substituting $\tilde{c} = \tilde{v}_v \cdot p_c$ into Eq. 13 yields

$$R^\text{cre}_v = \begin{cases} -\delta \frac{\sum_{G(v)} \tilde{v}_u \tilde{W}_v}{\sum_{G(v)} \tilde{W}_v}, & \text{if } (S \circ G)(v) = 1; \\ 0 & \text{otherwise} \end{cases} \quad (14)$$

Note that Eq. 14 is the same with Eq. 12, this is because paying credits or paying currency does not make a difference to the value of a vehicle’s received amount.

### F. DIRECT-TRANSACTION SCHEMES

In direct-transaction schemes, the winner group makes a payment to the loser group, but not the third party. This paper analyzes three commonly used direct-transaction schemes in the literature, and names them the half transaction [21], the joint transaction [24] and the incentive-compatible transaction [32]. We refer them to “htra”, “jtra” and “itra”, respectively, and have tra $\in \{\text{“htra”, “jtra”, “itra”}\}$.

In “htra”, the winner group pays half of its own sum-weight to the loser group, discounted by $\delta$:

$$R^\text{htra}_v = \begin{cases} -0.5 \delta \tilde{W}_v & \text{if } (S \circ G)(v) = 1; \\ 0.5 \delta \frac{\sum_{G(v)} \tilde{W}_v}{\sum_{G(v)}} & \text{otherwise} \end{cases} \quad (15)$$

In “jtra”, the payment is jointed determined by the sum-weights of both groups, which is given as

$$R^\text{jtra}_v = \begin{cases} -0.25 \delta \frac{\sum_{G(v)} + \sum_{G(v)} \tilde{W}_v}{\sum_{G(v)} \tilde{W}_v}, & \text{if } (S \circ G)(v) = 1; \\ 0.25 \delta \frac{\sum_{G(v)} + \sum_{G(v)} \tilde{W}_v}{\sum_{G(v)} \tilde{W}_v} & \text{otherwise} \end{cases} \quad (16)$$

In “itra”, to achieve the incentive compatibility (i.e., every vehicle can achieve the best outcome by reporting their true VOTs), one needs to assume that all participants of direct-transaction schemes have the same belief of VOT distribution. We denote $\mathcal{U}_- = \mathcal{U} - \{v\}$ (similarly, $\mathcal{U}_- = \mathcal{U} - \{u\}$).
and “itra” gives a Bayesian solution as

$$K_v^{itra} = \delta \left( \int_{\mathbb{R}_+^{|D|-1}} \sum_{u \in V} (S \circ G)(u) \tilde{w}_u f_Y \tilde{\beta}_{Y^{-}} \tilde{\beta}_{Y^{-}} \right) - \frac{1}{|U| - 1} \sum_{u \in V} \int_{\mathbb{R}_+^{|D|-1}} \sum_{i \in U} (S \circ G)(i) \tilde{w}_u f_L \tilde{\beta}_{L^{-}} \tilde{\beta}_{L^{-}} ), \quad (17)$$

where $f_Y(\tilde{\beta}_{Y^{-}})$ is the joint probability density function (PDF) of vehicles $V$'s D-VOTs, and $\tilde{\beta}_{Y^{-}}$ is the differential of vehicles $V$'s D-VOTs. In short, the first part of Eq. 17 is $v$’s expectation on the others ($V^{-}$), and the second part is $v$'s guess about others’ ($V^{-}$) expectation on their corresponding others ($U_{-}$).

III. COMPARATIVE ANALYSIS

Based on the designed mechanism for each scheme, we shall conduct comparative analysis regarding individual benefits and social equity between different schemes in this section.

A. BASIC SETTINGS

We adopt the simple setting of an intersection with two single-lane one-way streets, as shown in Fig. 3. That is, we consider two conflicting through movements. We set that each movement has at most one vehicle participating in the trading simultaneously. That is, $|A| = |B| = 1$ if there are conflicting vehicles at intersection. The main inputs for the simulation include the PDF of R-VOT and PTS, as shown in Fig. 4. Among them, the PDF of R-VOT in Fig. 4(a) is adopted from the investigation results of VOT by Brownstone, et al. in San Diego [33]. The median is 30 $/hour, with an upper quartile of 43 $/hour and a lower quartile of 23 $/hour. The background shows the cumulative values of its PDF. The PDF of PTS in Fig. 4(b) is constructed by ourselves, which is a log-normal distribution with a mean of 2 s. Note that we choose the log-normal distribution because it could guarantee the PTS to be positive. We use 2 s because we estimate the headway of vehicles for passing the intersection in Fig. 3 is around 2 s.

For credit schemes, we set an extra input $\theta$, which is the discount coefficient due to the high external cost in credit trading, to be 0.9.

We consider four possible scenarios for implementing real-time TORP (sorted by their complexity):

- **Scenario I:** honest VOT reporting without outsiders.
- **Scenario II:** honest VOT reporting with outsiders.
- **Scenario III:** dishonest VOT reporting without outsiders.
- **Scenario IV:** dishonest VOT reporting with outsiders.

“Honest VOT reporting” means we assume that all vehicles will report their true VOT to the system, while “dishonest VOT reporting” relieves this assumption. “Without outsiders” means the system forces all vehicles to be subscribers, while “with outsiders” means the system allows vehicles to choose freely whether to subscribe to the economic scheme or not. Note that the most practical way to implement the TORP in connected traffic in the near future is Scenarios III and IV. This is because it is very hard to force travelers to be honest since the R-VOT is private information and can hardly be known exactly by the government. In the far future, with the development of artificial intelligence, it may be easier to investigate whether users are honest. Scenarios I and II will be more meaningful by then.

For all scenarios, we assume that vehicles are rational to maximize their expected benefit when choosing their D-VOT. Note that a D-VOT of 0 means that the vehicle chooses to be an outsider. We use numerical simulation to investigate the evolution of the dynamic system. The simulation iterations stop until the D-VOT choices of all travelers are stable.

B. INDIVIDUAL BENEFIT

1) ADDITIONAL BENEFIT FOR ECONOMIC SCHEMES

Let $B_v^e$ denote the individual benefit of vehicle $v$ in a priority competition game when the system implements economic scheme $e$. It is defined as

$$B_v^e = (S \circ G)(v)w_v + K_v^e + D_v^e, \quad (18)$$

where $D_v^e$ is the distributed amount per game from the government (discounted by $\theta$ due to the external cost), and $e \in \{"1auc", "2auc", "cre.a", "cre.s", "htra", "itra", "itra"\}.
Note that $D^e_t$ is positive only in credit schemes. We assume that credits are evenly distributed and then retrieved by the operator through games, and every vehicle plays similar number of games. Then $D^e_t$ can be estimated by

$$D^e_t \approx \begin{cases} -\theta \sum_{u \in A} R^e_{u_t} & e = \text{cre.a} \\ -\mathbb{E}(\tilde{f}_v) > 0)\theta - \max_{\beta \in \mathbb{N}_k} \mathbb{E}\sum_{u \in A} R^e_{u_t} & e = \text{cre.s} , \\ 0 & \text{otherwise} \end{cases}$$

(19)

where $A$ is the set of all vehicles in the system, $S$ is the set of all subscribers in the system, $\mathbb{E} R^e_{t}$ is the mean received amount per game per vehicle, $N_k$ is the number of all vehicles, and $N_S$ is the number of subscribers.

For the intersection setting in Fig. 3, when a vehicle $v$ competes the priority with a vehicle $u$ at intersection, according to Eq. 18, its benefit would be jointly decided by its own R-VOT $\beta_v$, D-VOT $\tilde{\beta}_v$, its own PTS $t_v$, $u$'s D-VOT $\tilde{\beta}_u$, and $u$'s PTS $t_u$. Hence we can calculate v's expected benefit $\mathbb{E}(\tilde{B}_v^e|\beta_v, \tilde{\beta}_v)$ with the knowledge of the distribution of $t_v$, $\tilde{\beta}_v$, and $t_u$. Algorithm 1 shows how we numerically calculate $\mathbb{E}(\tilde{B}_v^e|\beta_v, \tilde{\beta}_v)$ in the simulation, where we assume $t_v$ and $t_u$ are independently and identically distributed.

**Algorithm 1 Calculation of $\mathbb{E}(\tilde{B}_v^e|\beta_v, \tilde{\beta}_v)$**

1. **Input:**
2. PDF of D-VOT: $\tilde{f}$, v's R-VOT: $\beta_v$, v's D-VOT: $\tilde{\beta}_v$, differential of VOT: $\Delta \beta$, probability that D-VOT is $\tilde{\beta}_v$: $\tilde{\beta}_v$ ← $\tilde{f}(\tilde{\beta})\Delta \beta$, PDF of PTS: $f$, differential of PTS: $\Delta t$, probability that PTS is $t$: $p(t) ← f(t)\Delta t$, economic scheme: $e$.
3. **Iterate:**
4. $E \leftarrow 0$.
5. **For** $u$'s D-VOT $\tilde{\beta}_u = \{0, \Delta \beta : \beta : \beta_{\max}\}$ do:
6. $u$ is an arbitrary opponent vehicle
7. **For** $v$'s PTS $t_v = \{\Delta \beta : \Delta t : \Delta t_{\max}\}$ do:
8. $E \leftarrow E + \tilde{B}_v^e(\tilde{\beta}_v) p(t_v)p(t_u)$
9. $E \leftarrow E + \tilde{B}_v^e(\tilde{\beta}_u)p(t_v)p(t_u)$
10. **Result:**
11. $\mathbb{E}(\tilde{B}_v^e|\beta_v, \tilde{\beta}_v) \leftarrow E$.

It is worth mentioning that there are two methods to obtain the expected benefit. One is using agent-based simulation to simulate the traffic operations (e.g., vehicle arrival, priority trading, vehicle leaving) at intersection, and output the average benefit. This method requires a huge number of simulations with various levels of traffic demands to eliminate the randomness in both vehicle arrivals and VOTs, which could be tedious and time-consuming. Another is using the PDF of PTS and VOT to directly calculate the expected benefit through numerical simulation, as we did in Algorithm 1. This method does not need various traffic demands as inputs since the randomness is considered mathematically. We adopt the second method in this paper since it is time-saving and accurate.

**Algorithm 2 Simulation for Different Scenarios**

**Input:**
2. PDF of R-VOT: $f$, initial PDF of D-VOT: $\tilde{f}^0 = f$, differential of VOT: $\Delta \beta$, economic scheme: $e$, scenario: $s \in \{I, II, III, IV\}$, iteration step: $i = 0$, probability that D-VOT is $\tilde{\beta}_v$: $\tilde{p}_u(\tilde{\beta}) \leftarrow f(\tilde{\beta})\Delta \beta$.
3. **Iterate:**
4. **For** each iteration step $i$ do:
5. Build 0-vector with same size of $\tilde{p}_u^0(\cdot)$ ← 0.
6. **For** each possible R-VOT $\beta$ do:
7. If $s = I$ then:
8. Best D-VOT choice: $\tilde{\beta}_v^I(\beta) \leftarrow \beta$.
9. Elseif $s = II$ then:
10. Best D-VOT choice: $\tilde{\beta}_v^I(\beta) \leftarrow \arg \max \tilde{E}^B(\tilde{\beta} \in [0, \beta])|\tilde{\beta}, \tilde{p}^I\Delta \beta$.
11. Else $s = III$ then:
12. Best D-VOT choice: $\tilde{\beta}_v^I(\beta) \leftarrow \arg \max \tilde{E}^B(\tilde{\beta} \in [0, \Delta \beta] \Delta \beta : \beta_{\max} | \tilde{\beta}, \tilde{p}^I\Delta \beta)$.
13. Else:
14. Best D-VOT choice: $\tilde{\beta}_v^I(\beta) \leftarrow \arg \max \tilde{E}^B(\tilde{\beta} \in [0, \Delta \beta] \Delta \beta : \beta_{\max} | \tilde{\beta}, \tilde{p}^I\Delta \beta)$.
15. Update $\tilde{p}_u^I \leftarrow \tilde{p}_u^{I+1} = \tilde{p}_u^I + \tilde{p}_u^0(\beta)$.
16. If $s = I$ then:
17. Break;
18. Elseif $\tilde{p}_u^{I+1} = \tilde{p}_u^I$ then: $\% \tilde{p}$ is stable
19. Break;
20. Next iteration: $i \leftarrow i + 1$.
21. **Result:**
22. Output D-VOT function $\tilde{B}_v^{e,s}(\beta)$.
23. For each possible R-VOT $\beta$ do:
24. Calculate expected benefit for scheme $e$: $\tilde{E}^B|\beta_v = \beta \leftarrow \max \tilde{E}^B(\tilde{\beta} = \tilde{B}_v^{e,s}(\beta) | \beta_v = \beta)$.

Once $\mathbb{E}(\tilde{B}_v^e|\beta_v, \tilde{\beta}_v)$ is known, v could pick a $\tilde{\beta}_v$ such that its expected benefit is maximized. Algorithm 2 shows how we simulate the travelers’ dynamic choice behaviors in different scenarios. In practice, each iteration step can be regarded as one day. By the end of each iteration (day), the government can release the PDF of D-VOT and PTS online, which will be used by travelers to adjust their subscribing decisions of the next day. The simulation stops (system converges) when all travelers’ choices remain unchanged.

Similar to function $S$, we define a bijective function $O$ to allocate priority when no economic schemes are implemented. $O: \{A, B\} → \{0, 1\}$, where 1 means winning the priority, and 0 means losing the priority. We adopt the rule that priority is given to the group with more vehicles, hence

$$O(A) = 1 - O(B) = \begin{cases} 1 & \text{if } |A| \geq |B| \\ 0 & \text{otherwise} \end{cases}$$

(20)

Note that $O$ is similar to the max-throughput control. Also, for a system implementing an economic scheme, if all vehicles
are outsiders, function $S$ degenerates to function $O$. Similar to Eq. 9, the composite map $(O \circ G): U \to \{0, 1\}$ is then defined by

$$ (O \circ G)(v) = O(G(v)). $$  \hspace{1cm} (21)

Let $B^\text{non}_v$ denote the individual benefit of vehicle $v$ in a non-economic system, we have

$$ B^\text{non}_v = (O \circ G)(v)w_v. $$ \hspace{1cm} (22)

For the intersection setting in Fig. 3, since $|A| = |B| = 1$, we have $\mathbb{E}[(O \circ G)(v)] = 0.5$. From Sec.III-A, we have $\mathbb{E}t_v = 2$. Because they are independent, we have

$$ \mathbb{E}B^\text{non}_v = 0.5\mathbb{E}w_v = 0.5\mathbb{E}t_v = \beta_v. $$ \hspace{1cm} (23)

Compared with a non-economic system, the expected additional benefit (denoted by $\Delta \mathbb{E}B$) for $v$ by subscribing to an economic scheme $e$ is

$$ \Delta \mathbb{E}B^e_v = \mathbb{E}B^e_v - \mathbb{E}B^\text{non}_v. $$ \hspace{1cm} (24)

2) SIMULATION RESULTS

$\Delta \mathbb{E}B$ of travelers with different R-VOTs in all schemes for Scenarios I-IV from the simulation when the system status is converged are shown in Fig. 5(a)-(d), respectively. For Scenarios II and IV, when the line overlaps with the x-axis, it means that all travelers are outsiders. Otherwise, it means that all travelers are subscribers.

For Scenario I, travelers are honest and forced to be subscribers. In “1auc”, $\Delta \mathbb{E}B^\text{1auc}$ is always negative and decreases with larger R-VOT. In “2auc”, there is still 7% of high R-VOT vehicles with positive $\Delta \mathbb{E}B^\text{2auc}$. That is because, although both auction schemes have no compensation for vehicles, high R-VOT vehicles’ payments in “2auc” are much smaller than their payments in “1auc”. Hence, as they win priority with a higher probability, they earn some additional benefits in “2auc”. All three direct-transaction schemes can guarantee $\Delta \mathbb{E}B^\text{tra} > 0$ for all vehicles. Specifically, “itra” benefits low R-VOT vehicles more, “jtra” and “itra” benefit high R-VOT vehicles more. The differences between direct-transaction schemes and auction schemes are that (1) the payment of priority winners are usually smaller, and (2) the priority losers are compensated. These two features enable vehicles in direct-transaction schemes to achieve positive $\Delta \mathbb{E}B^\text{tra}$. $\Delta \mathbb{E}B^\text{cre}$ of any credit scheme is also positive for all vehicles despite that it uses the “2auc” rule to compete for priority. This is because the paid credits are distributed by the operator, but not directly out of the pockets of travelers.

For Scenario II, vehicles are honest and free to be subscribers or not. We see that all vehicles in auctions choose to be outsiders, hence the economic system degenerates into a non-economic system with $\Delta \mathbb{E}B^\text{auc} = 0$. This is because (1) in “1auc”, $\Delta \mathbb{E}B^\text{1auc}$ of being subscribers is always negative (shown in Scenario I); and (2) in “2auc”, although there are 7% of subscribers with $\Delta \mathbb{E}B^\text{2auc} > 0$ at the first iteration.
(shown in Scenario I), their $\Delta E^2_{auc}$ at the second iteration will also be negative after the rest 93% of vehicles choose to be outsiders. As for direct-transaction schemes, allowing vehicles to be outsiders does not make any difference compared with the results in Scenario I. They still choose to be subscribers in Scenario II. In “cre. s” that only distributes credits to the subscribers, all vehicles will choose to be subscribers, which is the same with Scenario I. However, in “cre.a” that distributes credits to all vehicles, we see a totally different story: in the beginning, all vehicles choose to be subscribers; then some vehicles find that being outsiders can earn money through selling the credits while do not need to make payments for passing the intersection, they hence choose to be outsiders; and gradually, all vehicles choose to be outsiders. This is a stable Nash Equilibrium which makes the economic system degenerate into a non-economic system.

For Scenario III, travelers are free to declare their VOTs but forced to be subscribers. We find that “1auc” and “2auc” performs similarly: around 93% low VOT vehicles have negative $\Delta E^2_{auc}$, and the rest 7% high VOT vehicles have positive $\Delta E^2_{auc}$. The difference of “1auc” between Scenario I and III is caused by vehicles’ lying behavior to maximize their own benefit. About the direct-transaction schemes (compared with Scenarios I and II), we can see that there is (1) a decrease in $\Delta E^2_{itra}$ of low VOT vehicles, but a dramatic increase in $\Delta E^2_{itra}$ of high VOT vehicles, (2) a slight increase in $\Delta E^2_{ita}$ of high VOT vehicles, and (3) no change in $\Delta E^2_{ita}$. In general, “itra” performs best among three direct-transaction schemes, and their results become quite similar in Scenario III. As for the credit schemes, allowing for lying behavior does not make any difference compared with Scenarios I and II: $\Delta E^E_{cre} > 0$ for all vehicles, and $\Delta E^E_{cre} < \Delta E^E_{ita}$ for most of the vehicles.

For Scenario IV, travelers are free to declare their VOTs and free to be subscribers or outsiders. All vehicles in “cre.a” and auction schemes finally choose to be outsiders, which is similar to Scenario II and leads to a non-economic system. However, in “cre.s” and direct-transaction schemes, all vehicles are subscribers, and they perform the same with Scenario III. Furthermore, we do a sensitive analysis on the outsiders. We suppose 20% of travelers can only choose to be outsiders (e.g., they do not have an e-wallet), and the rest 80% travelers follow the setting of Scenario IV. The simulation results are shown in Fig. 6. We find that although the existence of 20% permanent outsiders reduces the additional benefit of the rest 80% travelers, it does not change their subscribing decisions: still, all rest travelers choose to be outsiders in “cre.a” and auction schemes, while all rest travelers choose to be subscribers in “cre.s” and direct-transaction schemes. This is because the permanent outsiders only reduces the rest traveler’ trading probability. Such reduction in probability will result in a discount in the additional benefit, but will not turn a positive additional benefit into a negative one. Hence the travelers’ choices remain unchanged.

To summarize, all scenarios finally converge to a status with all subscribers or all outsiders, even in Scenario II and IV where travelers are free to choose to be subscribers or outsiders. From the perspective of individual benefits, we can find that direct-transactions are generally the most attractive schemes. Among all schemes, direct-transaction schemes and “cre.s” are most likely to get implemented successfully in practice as they bring additional benefits to all travelers.

C. SOCIAL BENEFIT

Compared with the messy individual benefit curves, the social benefit could offer a more comprehensive and straight-forward view to understand the benefit of a scheme. We define the social benefit to be a sum of individual benefit and the government’s revenue. Denote the government’s mean received revenue from per game per vehicle in scheme $e$ and scenario $s$ by $r^{e,s}$, we have

$$r^{e,s} = \begin{cases} -\frac{\mathbb{E}_{v} R_{v}^{s}}{v} & e = auc \\ 0 & \text{otherwise} \end{cases},$$

where $R^{e,s}_{v}$ is the received amount per game per vehicle when scenario $s$ is stable. Note that since credit and direct-transaction schemes are revenue-neutral, their $r^{e,s}$ are always 0.

We then define a social benefit improvement index (SBI), denoted by $I_{S}$, to evaluate a scheme’s performance in social benefit. $I_{S}$ is designed such that the SBI of a non-economic scheme is 0%, and the SBI of a scheme with maximum social benefit is 100%. It is calculated as

$$I^{s} = \frac{\sqrt{\mathbb{E}_{v} \left\{ \Delta E^{s}_{v} \right\} + r^{e,s}}}{\sqrt{\mathbb{E}_{v} \left\{ \Delta E^{ita}_{v} \right\}} \times 100\%},$$

where $\Delta E^{s}_{v}$ is the expected additional individual benefit of scheme $e$ when scenario $s$ is stable. Note that we pick “itra” scheme in Scenario I as the denominator because it has the maximum social benefit: travelers with higher R-VTS always win the priority since all travelers are honest subscribers. All other scheme-scenario pairs that maximize the social benefit can also serve as the denominator.

Fig. 7 shows the SBI for different schemes in the four situations. The main findings include:
1) **Effect of system’s degeneration.** In scenarios II and IV, if the system degenerates into a non-economic scheme, the SBII is 0%.

2) **Effect of strategyproofness and external costs.** For strategyproof schemes including “2auc” and “itra”, as long as they have 100% subscribers, their SBII achieves 100%. This is because when all travelers honestly declare their VOTs, the travelers with higher R-VTS will always win. Hence the social benefit is maximized. However, the SBII of credit schemes are only 57% despite that they are strategyproof. This is because credit schemes suffer from high external costs, which result in a loss in social benefit.

3) **Effect of Lying behavior.** For scenarios with dishonest VOT (III and IV), the non-strategyproof schemes including “1auc”, “ftra”, and “btra”, would face a small decrease in SBII (varying from 96% to 98%), indicating that lying behaviors have limited impact on the social benefit.

In general, from the social benefit perspective, the direct-transaction schemes perform the best as they can achieve near-maximum social benefit in all scenarios.

### D. SOCIAL EQUITY

In the long term, the different individual benefits of travelers through participating the economic schemes in daily trips will gradually influence citizens’ income distribution. We use the Gini index ($g$) to estimate the equity in distribution of income, and focus on the population who choose the car as traveling mode. As shown in Fig. 8, $g$ is equal to the double area between the 45 degree curve and the **Lorenz curve** ($F_{\text{lor}}$).

$$g = 1 - 2 \int_0^1 F_{\text{lor}}(\rho_i) \, d\rho_i,$$

(27)

where $F_{\text{lor}}(\rho_i)$ plots the proportion of the travelers’ total income, given the cumulative share of people $\rho_i$ from the lowest income to a given income $\iota$. $\rho_i$ is given as

$$\rho_i = F_{\text{inc}}(\iota) = \int_{\iota_{\min}}^{\iota} f_{\text{inc}}(x) \, dx, \ i \in [\iota_{\min}, \iota_{\max}],$$

(28)

where $f_{\text{inc}}$ and $F_{\text{inc}}$ are the PDF and Cumulative Distribution Function (CDF) of travelers’ income, respectively. $\iota_{\min}$ and $\iota_{\max}$ are the lowest and highest income, respectively, of the population. As can be seen from Fig. 8, if the Lorenz curve overlaps with the line of equality, then $g = 0$, meaning that the social wealth is evenly distributed to all citizens. On the contrary, $g = 1$ is another extreme case where all social wealth is in the hands of the richest people. Hence a decrease in $g$ implies an increase in equity, and vice versa. We denote $\hat{g}$ as the Gini index under the non-economic scheme of Eq. 20, and $\hat{g}$ as the Gini index under an economic scheme. Taking $g$ as the baseline, we calculate the influence of an economic scheme in equity by $\Delta g = \hat{g} - \tilde{g}$.
We denote the income of a traveler under the non-economic scheme as \( \dot{i} \). To calculate \( g \), one needs to know the PDF of \( \dot{i} \).

The data in [34] shows that \( \dot{i} \) and \( \log(\beta) \) are highly correlated with each other given a study year. Hence it is reasonable to assume that

\[
\beta = F_{\text{VOT}}(\dot{i}) \approx a_1 \cdot e^{a_2},
\]

where \( a_1 \) and \( a_2 \) are two positive constants, and the income-VOT function \( F_{\text{VOT}} \) reflects how VOT develops over time as income grows. We calibrate \( a_1 \) and \( a_2 \) using the income and VOT data in [33] through minimizing the sum of absolute values of income differences between simulated data and real data. The results are shown in Fig. 9.

The calibrated PDF of income in Fig. 9(b) is taken as the baseline under the non-economic scheme, denoted by \( f_{\text{inc}} \). We then deduct the income PDF under the economic scheme \( e \). We denote a traveler’s additional income under \( e \) as \( \Delta \dot{i} \), and we assume that the expected additional benefits under \( e \) has potential to be transferred to \( \Delta \dot{i} \) in the following way:

\[
\Delta \dot{i} \approx \frac{N_{\text{gam}}}{N_{\text{trav}}} \Delta E\dot{B}_V^e(\beta),
\]

where \( \Delta \dot{i} \) is the additional annual income, \( \Delta E\dot{B}_V^e \) is the expected additional benefit of scheme \( e \) in Fig. 5, \( N_{\text{gam}} \) is the average number of games per vehicle per year, and \( N_{\text{trav}} \) is the average number of travelers per vehicle. As \( \Delta \dot{i} \) can also be regarded as a function of \( \dot{i} \), we then have the new income \( \dot{i} \) of a traveler under an economic scheme as

\[
\dot{i} = H_e(\dot{i}) = \dot{i} + \Delta \dot{i}(\dot{i}) = \dot{i} + \frac{N_{\text{gam}}}{N_{\text{trav}}} \Delta E\dot{B}_V^e(a_1 \cdot \dot{i} \cdot a_2)
\]

where \( H_e \) is an income-change function reflecting how the income in an economic scheme \( e \) changes with the basic income under the non-economic scheme. We can find from data that \( |d\Delta \dot{i}/d \dot{i}| \ll 1 \), hence \( dH_e(\dot{i})/d \dot{i} \) is always positive, and \( H_e \) has the inverse function \( H_e^{-1} \) with \( \dot{i} = H_e^{-1}(\dot{i}) \). Given \( f_{\text{inc}} \), we have the PDF of new income, \( \hat{f}_{\text{inc}} \), under \( e \) as

\[
\hat{f}_{\text{inc}}(\dot{i}) = \frac{dH_e^{-1}(\dot{i})}{d\dot{i}} f_{\text{inc}}(H_e^{-1}(\dot{i})).
\]

For any PDF of income \( f_{\text{inc}} = \hat{f}_{\text{inc}} \) or \( f_{\text{inc}} = \hat{f}_{\text{inc}}^e \), we have the total income \( I \) of cumulative share of people from lowest income to an income \( \dot{i} \) as

\[
I_i = N_{\text{pop}} \int_{\text{min}}^{\dot{i}} x f_{\text{inc}}(x) \, dx,
\]

where \( N_{\text{pop}} \) is the number of population. Combined with Eq. 28, we can obtain the Lorenz curve as

\[
F_{\text{lof}}(\rho) = \frac{I_i}{I_{\text{max}}} = \frac{\int_{\text{min}}^{\rho} x f_{\text{inc}}(x) \, dx}{\int_{\text{min}}^{\text{max}} x f_{\text{inc}}(x) \, dx},
\]

where \( F_{\text{inc}}^{-1} \) is the inverse function of \( F_{\text{inc}} \). Combining Eq. 27, 28 and 34, we can calculate \( g \) using \( f_{\text{inc}} \), and calculate \( \hat{g} \) using \( \hat{f}_{\text{inc}}^e \). \( \Delta g \) can then be obtained.

Taking \( N_{\text{gam}} = 200 \times 365 \), and \( N_{\text{trav}} = 1 \), we have \( \Delta g \) of different economic schemes in the four scenarios in Table 4. Note that the changes of \( N_{\text{gam}} \) and \( N_{\text{trav}} \) will not influence the final tendencies (increasing or decreasing the equity).

As can be seen from Table 4, auction schemes will decrease the social equity in Scenarios I and III, and they have no impact on equity in Scenarios II and IV (all travelers choose to be outsiders, hence the system becomes non-economic). “cre.s” can slightly improve social equity in all scenarios,
while “cre.a” can only improve equity in Scenarios I and III, and has no impact on equity in Scenarios II and IV. Direct-transaction schemes can further improve the social equity in all scenarios. The reasons are as follows: 1) In auction schemes, the poor tend to lose the priority without any compensation, while the rich are likely to win the priority with an accepted payment. This inevitably worsens the social equity. 2) In credit schemes, initial credits are equally distributed to all travelers (“cre.a”) or subscribers (“cre.s”) for free. This could be regarded as an equal compensation to travelers with different income levels. And the resulted income improvement ratio is higher for the poor since their original incomes are lower. Hence equity in credit schemes is slightly improved. 3) In direct-transaction schemes, the priority losers (usually the poor) are directly compensated for giving the priority, and the compensation is related to the winners’ offered price. Hence the richer the winner is, the more compensation the loser is likely to receive. This helps the direct-transaction schemes further improve the social equity.

Generally, from the social equity perspective, direct-transaction schemes are most likely to get accepted by the public in the long term, compared with credit and auction schemes.

IV. CONCLUSION

With the popularity of connected vehicle technology and mobile payment, real-time trade of road priority (TORP) using economic schemes becomes possible. It could better serve heterogeneous traveling demands with various value of time. The implementations of economic schemes (auctions, credits and direct-transactions) come with the network effect phenomenon, which means the value of an economic scheme depends on the size of its subscribers. Most existing studies simply assume a 100% of subscribers, and ignore the autonomy of travelers in choosing whether to be subscribers or not. Such economic schemes will have to be enforced to guarantee full subscribers, otherwise they can easily fail in practice due to lack of reasonable consideration for outsiders. However, the enforcement can easily face strong public resistance, which will render the schemes infeasible in practice.

This paper designs the mechanisms for three kinds of economic schemes with consideration of both subscribers and outsiders. Based on four possible implementation scenarios of TORP, we conduct comparative analysis on individual benefit, social benefit, and social equity between different schemes. The comparison results are summarized in Table 5. We list the main findings as below. 1) Considering the individual benefit and social equity, direct-transaction schemes perform the best in attracting the economic scheme subscribers, then are the credit schemes. 2) Travelers tend to be outsiders in auctions schemes and credit scheme (that always distributes the credit to all vehicles). Hence, if the government tries to implement an auction scheme, it is better to limit travelers’ opportunity of free choice; if the government tries to implement a credit scheme, it is better to timely observe whether the vehicles are subscribers and only distribute the credit to the subscribers. 3) The network effect will significantly influence the system’ performance considering the perspective of individual benefit, social benefit and social equity. 4) Direct-transaction schemes and credit schemes have a positive network effect. Auction schemes have a positive network effect considering the social benefit and may have a negative network effect considering the individual benefit and social equity. 5) Lying behaviors only slightly reduce the social benefit, while the transaction and external cost in credit schemes will reduce the social benefit a lot. Hence, if the government plans to implement a credit scheme, they should pay attention to reducing the subscribers’ transaction and external costs.

The future research can relax some assumptions and study their influence on the system. First of all, researchers could relax the rational human assumption as humans are not always rational. Some travelers may have “path dependency” when making decisions, and their experience can not cover “all knowledge”. Hence, their behaviors may deviate from the rational assumption. It is interesting to investigate how such irrational behaviors will influence the system performance. Secondly, we assume an ideal traffic environment and a simple road structure. The real-world traffic includes vehicles of different types and sizes, non-motorized vehicles and pedestrians. And urban networks include diversified intersections and links. It is meaningful to test the models in such complicated and more practical networks. Thirdly, we assume that the intersection controller is able to quickly collect, calculate, and release information, e.g., it can timely offer the accurate potential time saving information to the subscribers. Note that among all economic schemes, the incentive-compatible direct-transaction scheme is the most complex. It is of high time complexity and hence not appropriate for regular intersection controllers. Finally, we assume that the probability distributions of declared value of time and potential time saving are open information so that travelers learn their best strategies directly, and their choices in simulation can converge fast. If the information is not available, travelers’ learning process will be random, and their choices will therefore converge very slowly. How to deal with this issue is worth studying in the future research.

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