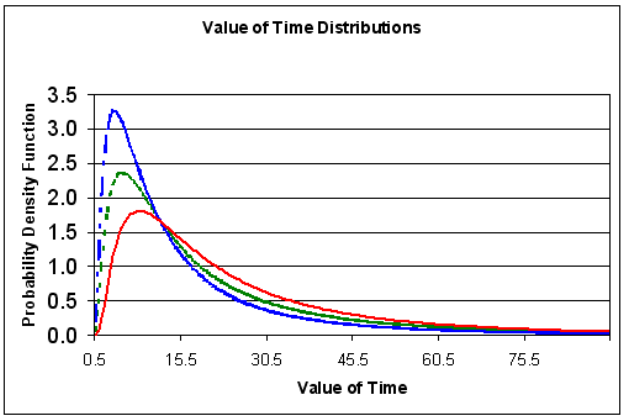

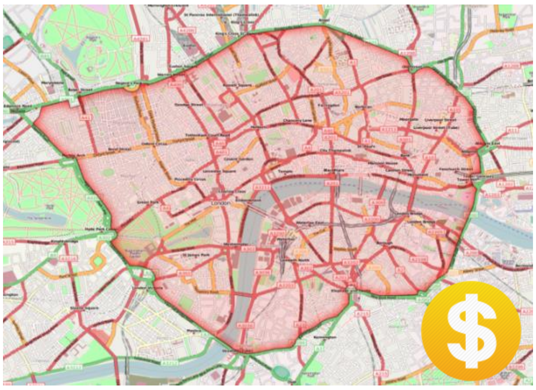

Area-based Pricing Strategies for Multimodal Urban Networks with Users of Heterogeneous Value-of-time

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Abstract

In this paper, we investigate congestion pricing schemes for networks of heterogeneous population with respect to income level and value-of-time (VOT). Six income-based groups are introduced to categorize the entire population, where each group is assumed to have a unique VOT from a Gini-indexed VOT distribution. We utilize a mathematical model to reproduce the aggregated traffic dynamics in a bi-modal (cars and buses) urban environment and the travel behaviour (e.g. mode choice), under different congestion pricing schemes. This system model is built on the Macroscopic Fundamental Diagram (MFD) model and the multi-modal MFD model, and able to represent congestion dynamics for given demand and urban networks. While the concept of the MFD has been widely applied on the development of traffic management strategies at network scale such as perimeter flow control, we discuss how efficient and equitable pricing scheme can be developed with this concept. Three pricing schemes are under investigation and discussion: a flat toll, a dynamic (time-dependent) toll and a VOT-based toll. A case study is carried out in a hypothetical two-region (center-periphery structure) urban city, and a morning-peak traffic demand profile is simulated. The performances of three scenarios are tested and compared with a base scenario where no pricing is applied. We firstly show that a flat toll scheme whose objective is to minimize the total travel cost (include the total travel time and the toll paid) can effectively eliminate congestion as expressed by the MFD. Then we focus on the different impacts of pricing schemes on the entire system performance and the individual groups. Our results illustrate that (i) travel behaviour exhibits significant differences among the user groups, such as mode shift under high prices, (ii) when applying the flat-rate pricing, users of high VOT though benefit less in time-unit savings, however they always gain more in savings of monetized cost, and (iii) all user groups may obtain equal benefit in travel cost savings, when prices are charged on a VOT base. On-going works investigate pricing schemes for distributing the collected toll to improve equity, e.g. to subsidize the users of public transport or to subsidize the low-income groups. Future effort will be given on incorporating trip choice, departure time choice, and schedule delay in the modelling and optimization frameworks.

Keywords

Multimodal, MFD, Area-based Pricing, Heterogeneity, Value-of-time, Equity

1. INTRODUCTION

Pricing has served as a traffic management policy for alleviating traffic congestion and pollution in urban regions. By charging the external costs created by the road users, pricing aims to change users' behavior choice, e.g. mode choice, to prevent the occurrence of congestion at demand level. A comprehensive literature summary on the classical first- and second-best pricing models can be found in reference [1]. On the treatment of heterogeneity of users, particularly with respect to value-of-time (VOT), it was pointed out in early research that ignoring heterogeneity in VOT may bias the calculated welfare effects of pricing [2]. Empirical studies confirmed the distribution of VOTs among population [3][4], depending on the characteristics such as income level. Many theoretical works since then have been dedicated to explorer the impact of pricing for different user groups. A brief review towards this direction is given in reference [5]. As a general remark, these studies utilized the well-known Vickrey's equilibrium model and extended the model to reveal behavioral change under pricing policies and social welfare for various types of users. However, the inadequacies of these approaches are that (i) few work incorporated flexibility of mode choice, (ii) the underlying traffic models of most works assume a BPR-type of capacity-supply function which is not consistent with the physics of congestion, (iii) the link-based pricing is difficult to implement in practice, and computationally complex for large-scale application, and (iv) insufficient effort has been made to develop pricing schemes that take into account the difference in VOT among population and result equitable savings and benefit[2]. While pricing schemes of aggregated links and networks (see for example references [6][7]) have similar ambiguity, e.g. traffic conditions are considered stationary whereas travel cost is known as state-dependent [8].

To overcome the lack of treatment on congestion dynamics, reference [8] proposed to apply a macroscopic traffic model, namely the Macroscopic Fundamental Diagram (MFD), to identify optimal pricing schemes at city-level. Let us first have a short summary of the MFD. The idea of macroscopic traffic model for car-only urban networks has been initially proposed in reference [9] and was re-initiated later in references [10] and [11]. The demonstration of the existence with dynamic features and field data was in reference [12]. This work showed that: urban single-mode regions exhibit an MFD relating network flow capacity and state dynamically, and the MFD is a property of the network itself. Later, a bi-modal MFD [13] and a three-dimensional MFD (3D-MFD) [14] was studied for mixed bi-modal urban networks where cars and buses share the network. In addition to the reveal of the aggregated urban traffic dynamics, the MFD and 3D-MFD facilitate the development of effective traffic management strategies. This is because the states of a network can be monitored and optimal states can be identified clearly from the MFDs. Control actions can be designed and activated to maintain the network operate around the desired states [15] [16]. For the application of the MFD in pricing, recent studies have shown promising results. Reference [17] develops an

MFD-based cordon-pricing scheme and evaluates the efficiency of pricing via an agent-based simulation. This work also makes effort towards the equity issue of pricing, by comparing the behavior changes of trips with different purposes. Reference [13] integrates area-based pricing scheme within a bi-modal MFD framework, to improve the utilization of allocated road space to dedicated lanes for public transport. Both works conclude that MFD-based pricing schemes not only effectively relieve congestion in the city center (where pricing is enforced), but also generate positive social gain, e.g. total travel time savings outweighs the total toll paid without transferring the burden of congestion to the periphery regions of the center.

Building on the knowledge of the MFD-based modeling and management, we seek to investigate in this paper the impact of dynamic and VOT-based pricing schemes on traffic performance in multimodal urban networks with heterogeneous user groups. The rest of the paper is organized as follows. Section 2 describes the methodology of the paper, including the categorization of user groups, the system model that reproduces traffic dynamics given the demand and infrastructure of a network, and the three pricing schemes under investigation. Section 3 discusses the resultant system performances under area-based pricing schemes: flat toll, time-dependent toll, and a VOT-dependent toll.

2. METHODOLOGY

This section firstly explains the treatment of user heterogeneity among travelers, where the whole population categorized and each group represents people of a unique income level. Then the dynamic system model which is based on the bi-modal MFD model [13] (referred as the base model in the remaining of this paper) is briefly presented. Finally, the pricing schemes under investigation are introduced: a flat toll, a dynamic toll and a group-dependent toll.

An income-based VOT categorization

In the base model, demand generation (per time period) was a single group of identical travelers. Here the travelers are differentiated according to their income levels. Assume a traveler's value-of-time is directly correlated with her income level. The value of time for this person p therefore can be written as:

$$VOT_p = \alpha \cdot I_p \qquad (1)$$

where I_p being the income for this person p, and α is a scale parameter. The income is assumed to distribute following the Lorenz curve [18]. Income distribution among the entire population can be modified on the basis of the Gini coefficient [19]. In this paper, Gini coefficient is set to 0.6, which indicates a clear disparity in behavior between groups with low and high incomes respectively. Assume that a large proportion of the population has an income smaller than a certain threshold, while beyond the threshold the higher the income value the less it occurs among the sample population. A lognormal distribution would be a reasonable choice to generate sample groups which represent population of different income levels. Note that the lognormal distribution is chosen for the entire population neglecting the power law distribution for the very high incomes.

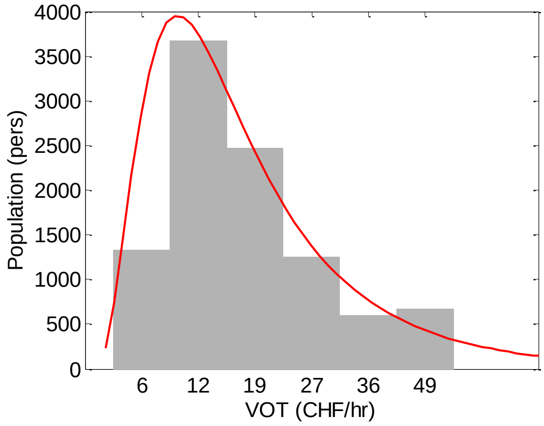

Fig. 1 The VOT distribution of six user groups

To interpret this distribution in a discrete form, the population is split into six groups. People of each group then have similar VOT. All with the same breadth of VOT except of the sixth group which includes all individuals with a VOT greater than its threshold. The median VOT of the entire population is set to 16 CHF/hour, hence the person with the median income has a value of time of 16 CHF/hour independently of the Gini coefficient of the population (in accordance with reference [4]). Individuals in the same group are assumed to have the same VOT, which is the median of the group within the interval of VOT assigned to each group. The two lower groups encompass the one half of the population that has VOTs below the overall median and the other four include the people above the median. Fig. 1 displays the resultant distribution of VOTs and the six chosen values: 6, 12, 19, 27, 36 and 49.

Treatment of system dynamics

Consider a bi-modal city is divided into regions. Criteria for the division (clustering) of the city are: homogeneous distribution of congestion within each region to obtain a low scatter MFD [20], similar topological characteristics and similar type of mode usage. Any region i can be partitioned into sub-regions if needed. A sub-region contains a specific type of mode usage for each mode m, e.g. bus-only lanes or mixed traffic lanes. In this paper, the partition and road space allocation for each usage are given, which is the optimal condition obtained by the base model.

Each sub-region has its MFD or bi-modal MFD, where the MFD relates traffic throughput of a region to its traffic state. The MFDs can be analytically estimated based on the topology and signal settings of the region/network, see [8]. Knowing the MFD, an aggregated system model describes the flow movement inter- and intra-regionally, and estimates the trip completion rate (let us call this outflow). Denote the outflow from current region i to the next destination region j, $O_i^{jm}(t)$ of vehicles and $OP_i^{jm}(t)$ of passengers of the region, the accumulation of vehicles $N_{ij}^{m}(t)$ and passengers $NP_i^{jm}(t)$, and the passenger occupancy $occ_m(t)$ at time t. The MFD gives $O_i^{jm}(t) = G(N_i^{jm}(t)\ )$ where G is the function form of the MFD, given the total accumulation $N_i^m(t) = \sum_j N_i^{jm}(t)$. Our system model treats passenger flow dynamics as well. Denote $NP_i^m(t)$ the total passenger accumulation, $O_i^m(t)$ the total outflow, and $OP_i^m(t)$ the total passenger outflow.

Thanks to the aggregated MFD model, we do not require detailed modeling of flow movement at micro level (road level) to capture the dynamics at network level.

Fig. 2(a) graphically illustrates the traffic flow movements in a multi-region city, where index i, j, l denote regions. The displayed vehicular and passenger flow dynamics respect the mass conservation law of flow at region level [13]: the change of accumulation N_i^{jm} is the difference of the regional input and output, where the input is the generated demand $Q_i^{jm}$and the total incoming outflow $O_{l\to i}^{jm}(t)$ from the adjacent regions to i while the output is the outflow $O_i^{jm}(t)$. For the passenger flow dynamics, the same relation applies.

Given the accumulations and outflows over time, the travel time of traveling with each mode m can be estimated. This travel time is an important part of the utility cost function $C_i^{jm}(t)$ that influences the mode choices of the travellers when they start their trips (detailed information on mode choice can also be found in [13]).

The aforementioned system is illustrated in

Fig. 2(b). With this framework, the strategy of congestion pricing will be investigated. The goal for the city is to determine tolls such that the total travel cost of all travelers over time for all modes of transport is minimized. We aim to operate different types of congestion pricing schemes. The toll prices are part of $C(t)$, which will affect the mode choice of demand $Q_i(t)$, $Q_i(t) = \sum_g Q_{i,g}(t) = \sum_g \sum_m O_{i,g}^m(t)$, g is group index. Since we consider users value their travel cost specifically based on their VOT, mode split among different mode m is treated separately for each group g.

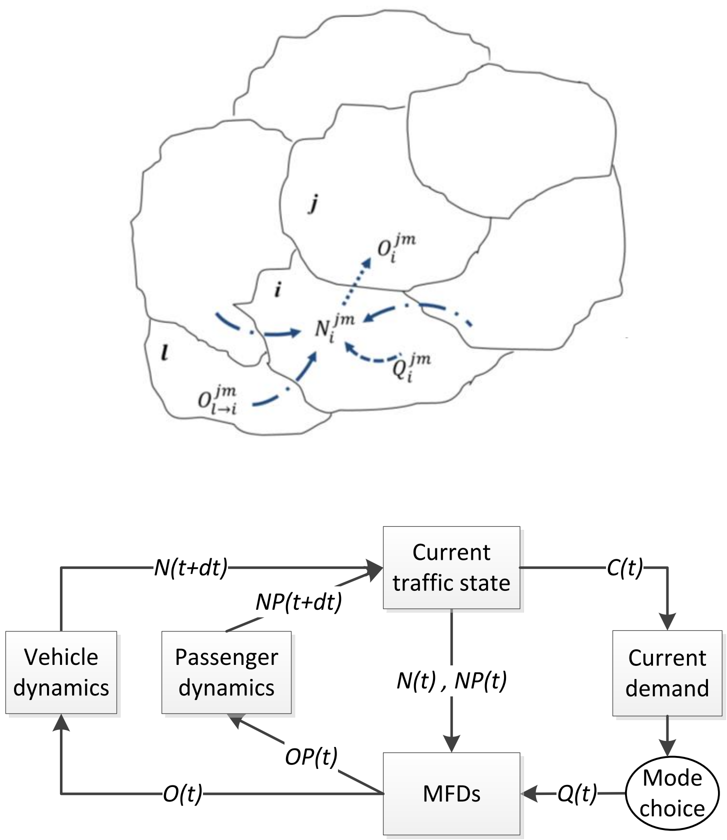

Fig. 2 Illustration of the (a- top) vehicle traffic flow dynamics of a multi-region city (time indices are neglected in the figure); and (b - bottom) Illustration of the dynamics of a multimodal transport system from time t to time $t + \Delta t$ (region and mode indices are neglected)

Pricing schemes

We develop area-based pricing schemes. Car-users pay for a toll once they travel inside a protected area, regardless of their trip length and duration. Three schemes will be investigated in the next sections: a flat toll, a time-dependent dynamic toll and a group-dependent VOT-based toll. In this paper, we focus mainly on the difference in behavior (such as mode choice) and welfare (such as saving in travel cost) among user groups. Developing optimal prices for each scheme will be reported briefly later and more detailed in a later version of the paper.

The flat toll applies a charge independent of time. An optimum flat toll can be obtained where the total cost of all users is minimized. For a large city with multiple regions, such as the one illustrated in

Fig. 2(a), different toll rates may be implemented in different regions as uneven distribution of congestion can happen over time. A dynamic toll improves the efficiency of the pricing, as price is charged based on the temporal pattern of congestion (thus considering demand fluctuation). Dynamic tolls can also be obtained through optimization procedure, see for example in [13], or self-regulated through a time-to-time learning process, see for example in [22].

As for the group-dependent thus income-based toll, the principle is that the more income a user earns the more the user pays for a toll. Previous studies argued that people's VOT increases with their income levels, e.g. in [4]. It can be interpreted as that people of high-income perceive savings in travel time higher than those who earn less. Consequently people of high-income would gain more from pricing, if the travel time saving can be found. Assume travel time saving is the main measure of the welfare gain from pricing, then to promote an equitable pricing scheme and motivate people of different income levels to accept congestion pricing schemes, proposing an income-based thus VOT-based toll is reasonable and meaningful. Mathematically an income-based toll can be expressed in the equation below:

$$Toll_g = c \cdot f\left(VOT_g\right) \qquad (2)$$

where $Toll_g$ is the toll by income group g and varies in function of VOT_g, c is a scale parameter, f is a toll distribution function that determines the magnitude that the incomes are linked to the toll to pay. Time index can be added in Equation (2) if dynamic pricing is considered. Function f can be a linear function, or functions whose first-order derivatives have non-negative values. After careful trial investigations, we decide to consider a square-root function and a logarithmic function for f. We will show shortly in the case study that both give reasonable toll profiles. As for the latter case, the logarithmic function can generate a scenario where the lowest income group would pay a negative toll, due to the characteristic of the function. This enables us to examine pricing schemes where some user groups receive travel subsidy.

3. CASE STUDY ANALYSIS

In this section, we present case study result on the system performance under the different pricing schemes. We carry out our analysis for a hypothetical two-region bi-modal city with a congested center region, where dedicated bus lanes are allocated and congestion pricing is implemented, and a peripheral region which generates high demand towards the center region and has sufficient space to accommodate its own traffic. We focus on a typical morning commute of 4-hour duration (from 8h to 12h), with a symmetric trapezoid-shape demand profile. Peak-hour starts after 1.5 hour and lasts for 1 hour (from 9h30 to 10h30). In the center region, buses operate on the well-designed dedicated-bus-lanes and receive no influence from the congestion of the car network. We set a base scenario where no toll is applied. Congestion occurs in the car network of the center region. Network flow decreases as more users enter the network traveling with cars. This is clearly indicated by its MFD, as displayed in Fig. 3(a). The maximum flow capacity of the network is 1600vehs/3min, at an accumulation of 5200 vehicles. For scenarios with congestion toll implemented, the toll period overlaps with the peak-hour (1hour from 9h30 to 10h30).

Flat toll

The resultant MFD at a toll of 5 CHF is displayed in Fig. 3(b). Comparing to the MFD of the no-toll case in Fig. 3(a), the center region network operates much more efficiently as the congested branch of the MFD is eliminated. The optimal price to achieve this result is 5CHF/trip, where the optimization aims to minimize the total travel cost (travel time plus toll cost). The reduction of congestion of the car network is attributed to the mode shift to bus which we will elaborate in the next paragraph. Fig. 3(c) and (d) displays the resultant mode share of bus under no-toll case and the 5CHF-toll case. In the figures, income groups are represented from lowest to highest by the colors blue, green, red, cyan, pink and beige, respectively (color representations of the groups remain the same through the rest part of the paper). It can be observed that in both cases, bus share increases significantly after the peak hour (9h30) starts. In the no-toll case shown in Fig. 3(c), bus share increases monotonically as congestion gradually spreads in the car network. Consequently the utility of traveling with cars becomes smaller. While for the 5CHF-toll case, the maximum bus share can be found in the beginning. Then it decreases slightly and keeps steady until the end of the peak hour. The explanation is that now that the cost of traveling with cars now includes the toll cost, the bus share starts to decrease slowly as people learn and adapt the travel condition, until the travel cost is equivalent using either of the modes. There exists a slight fluctuation right after the end of the peak-hour in Fig. 3(d), as people who enter the network at this time point adapt to the fact that toll period ends. Note that the minimum bus share for groups G1, G2, G3 and G4 is 0.1, representing the captive bus users from the low- and middle-class income groups.

Now let us compare the behavioral differences among the different groups. It appears that a group of higher VOT tends to be more willing to choose bus, when there is no toll implemented. In the case of 5CHF-toll, all groups show nearly identical preference of traveling with bus during the peak-hour (regardless of their VOT), albeit a group of lower VOT is relatively more in favor of bus.

A general remark on the mode choice heterogeneity is that: As long as travel time between the two modes differs, a higher-income group will always favor the mode that enables less travel time. This may not be consistent with what we observe in reality, e.g. rich people (of higher VOT) rarely take public transport such as buses or trams (unless it is long-distance travel by train or others). The reason is that in reality people's mode choice involve other utility terms, such as personal comfort, car dependency, symbol of social status, that make the choice process complicated. While capturing the impact of all these factors is beyond the scope of this study, we argue that (as aforementioned) travel time saving is the most important welfare measure.

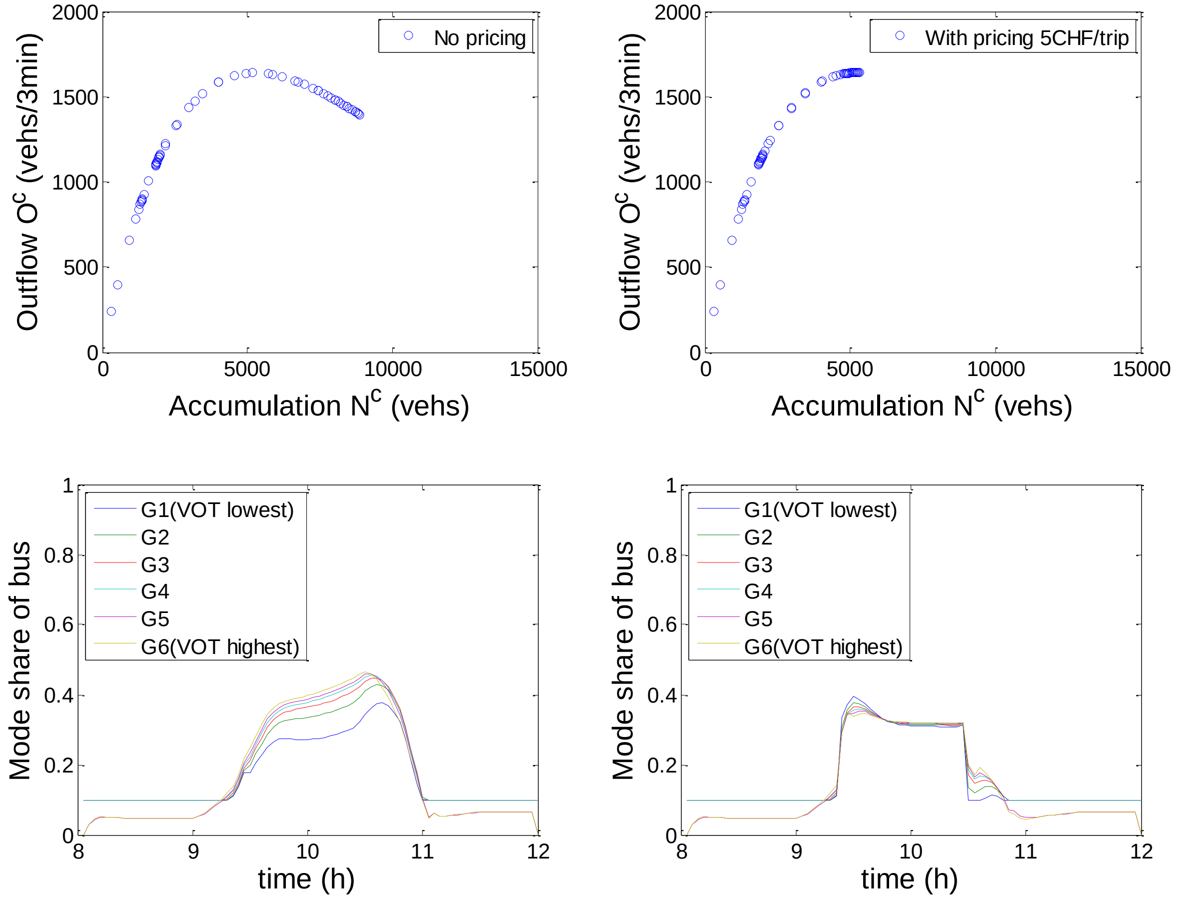

Fig. 3 The MFD of the network (a- top left) without toll, (b- top right) with flat toll of 5 CHF, and mode share of buses for the six groups (c- bottom left) without toll and (d- bottom right) under the toll of 5 CHF.

Nevertheless our model can reproduce the heterogeneous behavioral among different groups and will help identify the efficiency and equity of different pricing strategies, which we will show later. Comparing numerically the total share of bus, it is found surprisingly that bus share decreases slightly in the 5CHF-toll case. One may expect the opposite as the travel cost of cars becomes larger. However this is a reasonable result. As a large amount of demand chooses to buses since the beginning of the peak hour, the car network is able to maintain an uncongested state. Later when buses are full, the speed of buses decreases due to the increase of service dwelling time and the discomfort increases as the buses are crowded. Traveling with car thus has a better utility and becomes again attractive. In the 5CHF-toll case, the incentive of choosing bus is not time savings, which is the case of no-toll case, but instead the toll to be paid.

Now let us have a look at the performances under different rates of a flat toll: 3CHF, 6CHF, 9CHF and 12CHF. A comparison of the resultant total travel time (TTT) over time is displayed in Fig. 4. It can be seen that TTT decreases considerably as the toll amount increases, though the improvement in TTT becomes marginal at higher toll rates. The time series in red represents the condition at 6CHF which is close to the optimum toll of 5 CHF. If we estimate the travel time savings (TTTS), which is the difference between the TTT of the no-toll case and the other toll cases, we would draw the same conclusion on the marginal gain. Comparing the TTTS between 9CHF and 12CHF cases, the improvement is minor, indicating that the efficiency (e.g. cost/benefit) of the tolls is not optimal at high tolls. To increase the efficiency, it is dispensable that the alternative mode, buses, serves as a faster mode because people are forced to use it due to the tolls. If revenue from toll collections can be redistributed to public transport sector and improve the service of those modes, both TTTS and toll efficiency can be further enlarged, examples can be found in [22].

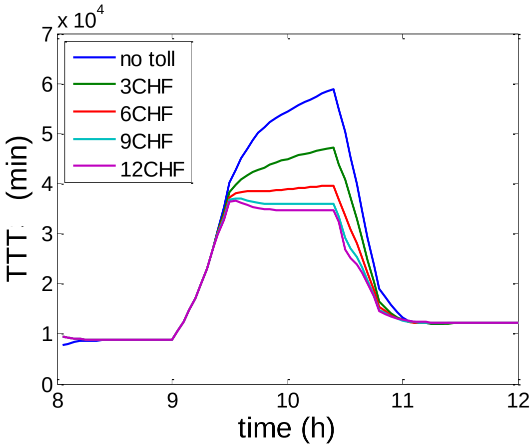

Fig. 4 TTT under different flat tolls

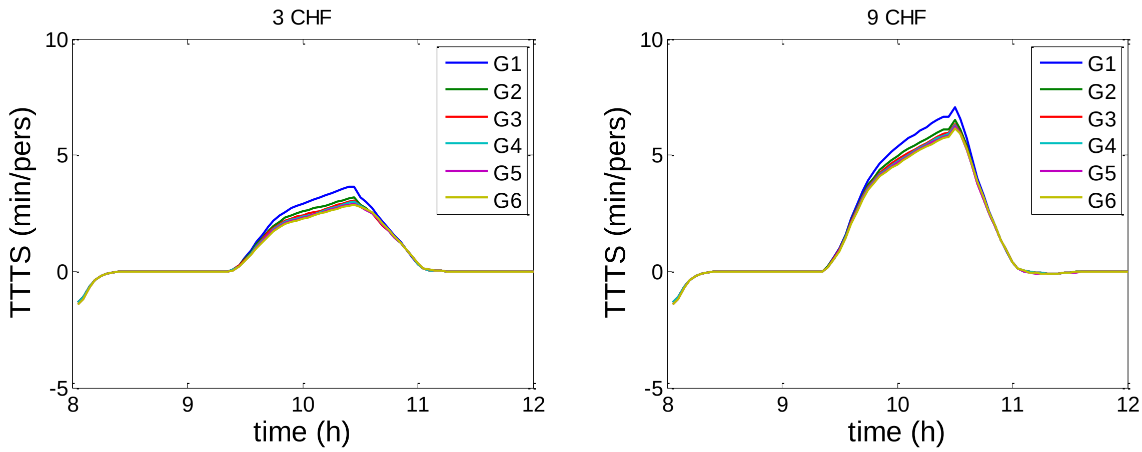

Fig. 5 TTTS per person by income groups and tolls of (a) 3 CHF, (b) 9 CHF

To investigate the gain at disaggregated level, Fig. 5displays the TTTS per person by group in comparison to the no-toll case. It can be seen that the individual TTTS does not differ significantly from one group to another, though it increases with the value of toll (if comparing Fig. 5(a) with (b)). One interesting observation is that users of the lowest VOT (G1) better off the most, and TTTS clearly monotonically decreases as VOT increases.

However, this changes completely when TTTS are monetized. In Fig. 6, we display in (a) the resultant TTTS under a toll of 6CHF, and in (b) the total travel cost savings (TTCS). TTCS is the multiplication of TTTS and VOT. It is evident that G6 which is the group of the highest VOT gains the most when TTCS is taken into account. Furthermore, what is interesting in Fig. 6(b) is that the monetized saving goes to negative in the beginning of the toll. This happens mainly due to the existence of toll cost. Nevertheless, it shows that from a monetized perspective, the gain is in direct proportion to VOT which indicates un-equity. This stems from the fact that the toll is the same for all users irrespective of their income levels. For the low-income users, the toll is weighed much higher than the time savings. While for the high-income groups, the time savings are more important. Therefore, the high-income users benefit from the improved traffic condition while the low-income users on the other hand pay for it.

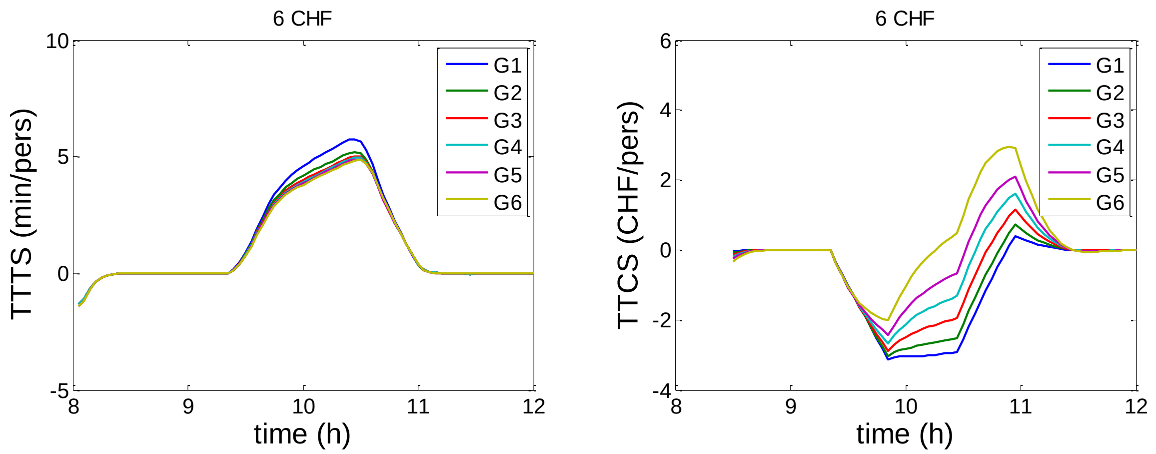

Fig. 6 (a) TTTS and (b) TTCS per person for all income groups under a toll of 6 CHF

Dynamic pricing strategies

Having provided an extensive explanations and understanding of the system dynamics in the previous section, we will in this section discuss the performance of dynamic toll schemes. In particular, we evaluate the VOT-based (thus an income-based) toll schemes which aim to achieve an equitable monetized savings among the six groups.

- **Time-dependent toll**

A constant (time-independent) toll may cause an over-charging on users during off-peak, or an under-charging during the peak hour. A time-dependent toll therefore gives a pricing scheme the flexibility of pricing based on demand fluctuation, and improves the efficiency. Normally this type of pricing charges users based on congestion condition. However, a dynamic pricing should not vary the toll rates too frequently as people need time to adapt. We assume a pricing profile have a symmetric trapezoid shape (it slowly raises and sets at the on-set and off-set of peak hour, while remains at a maximum value during) overlapping the peak-hour demand turning time points.

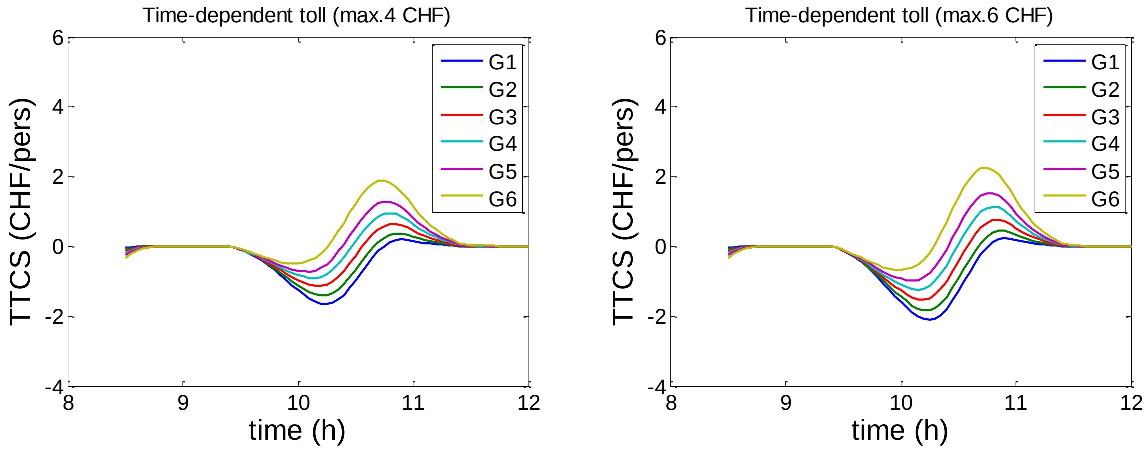

Fig. 7 TTCS per person by groups with a triangular-shape time-dependent toll, under maximum tolls of (a) 4 CHF and (b) 6 CHF.

Fig. 7 illustrates TTCS per person by groups under two dynamic toll schemes. The two schemes charge a toll up to 4 and 6 CHF during peak-hour respectively. The resultant TTCS/per in both cases exhibit similar shape as observed in Fig. 6(b), though the transitions of the TTCS is relatively smoother. These results indicate that a time-dependent tolling scheme cannot lead to a more favorable welfare condition for the low-VOT groups. Nevertheless, a dynamic toll scheme improves the TTCS of all groups, especially during the on-set and off-set of the peak-hour. Note that the slope of the toll rates during the on-set of the peak hour has minor influence on the results.

- **Income-based toll**

Motivated by the discussion above, we now propose and investigate an income-based toll scheme, where the six groups will pay different toll based on their VOT level. Equation (2) is applied, and the two f functions are examined: a logarithmic form and a square root form. We show results with c is equal to 6 (having different values for parameter c will not significantly change the pattern of the system performance.). Fig. 8 displays the resultant toll profiles for the six groups respectively. In Fig. 8(b) it can be observed that a negative toll scheme is established for group G1, while a nearly zero toll for group G2. Users from these two groups have the lowest VOT. As we mentioned before, this negative toll rates can be interpreted as a subsidy to the low-class population.

In Fig. 9, we estimate and plot the resultant TTCS over time under the two VOT-based pricing schemes. Comparing Fig. 9(a) with Fig. 7 and Fig. 6(b), we can see that the situation changes entirely. A group of a higher VOT now has to pay a higher toll. This toll is more than they gain from their perceived monetized travel time savings. Furthermore, a group with lower VOT always gains more. This however happens only during the tolling period. In the case with the logarithmic toll in Fig. 9(b), the two groups G1 and G2 obtain non-negative gains. Though most groups have negative gains during the tolling period, it is promising to see this type of toll scheme in favor of the population with low incomes. On the other hand, however, the toll scheme seems extremely unfair towards the high-income groups. They pay considerably higher tolls, while do not benefit from it. Once again, this is due to the fact that car is always a faster mode than bus. The high-income groups would rather choose to pay for the high toll to use cars and gain savings in travel time, causing them receive no improvement in the perceived cost.

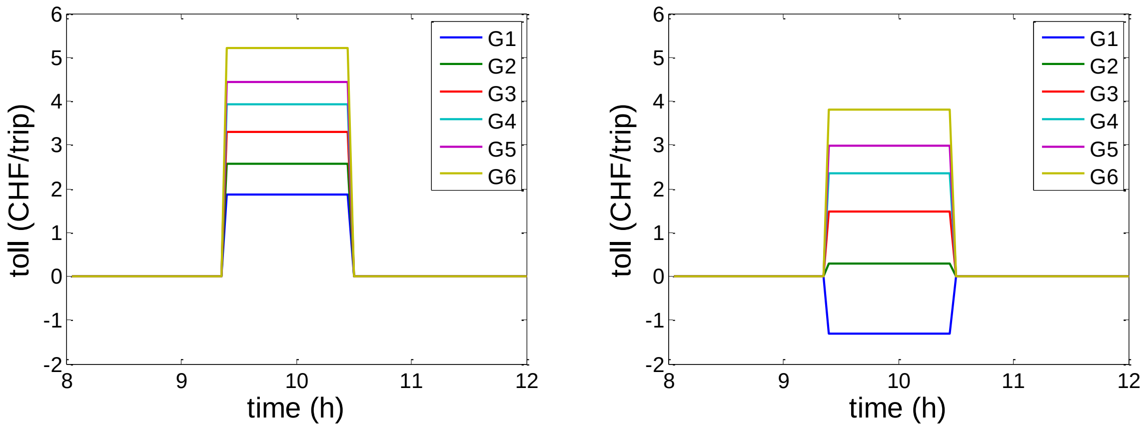

Fig. 8 The resultant toll profiles by VOT group for (a) $f_g = \sqrt[2]{VOT_g}$ and (b) $f_g = log(VOT_g)$.

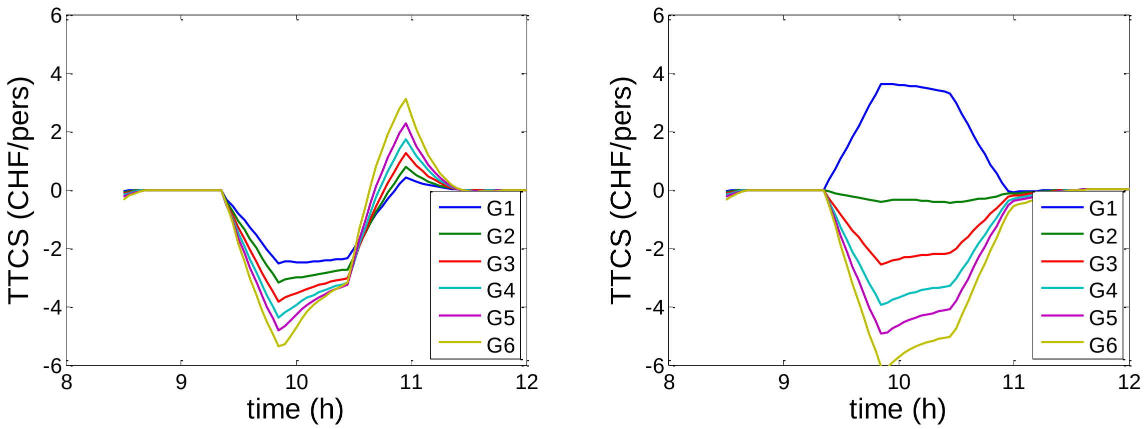

Fig. 9 TTCS per person by VOT group for (a) $f_g = \sqrt[2]{VOT_g}$ and (b) $f_g = \log(VOT_g)$.

- **Optimal VOT-based toll**

We show in the previous section that VOT-based toll can lead to situations that favors the low-income groups while worse off the high-income groups. To promote a fairer pricing scheme, a modification of model (2) is conceptually proposed in the following:

$$Toll_g = c_g \cdot f\left(VOT_g\right) \qquad (3)$$

where c_g is scale parameter on the toll rate for group g and to be determined through a bi-objective optimization, where the first objective is to maximize the TTCS of all users while the second objective to minimize the differences in TTCS among the six groups. Mathematically it can be formulated as the follows:

$$\begin{cases} \max_{c_g} \sum_g \text{TTCS}\left(C_g\right) \\ \min\limits_{c_g} Var(\{\mathbf{TTCS}_{\boldsymbol{g}}\left(\boldsymbol{C}_{\boldsymbol{g}}\right)\}) \end{cases} \qquad (4)$$

s.t.

$$C_g^{min} \leq C_g \leq C_g^{max}$$

$$Toll_{G1} \leq Toll_{G2} \leq Toll_{G3} \leq Toll_{G4} \leq Toll_{G5} \leq Toll_{G6}$$

The first constraint controls the magnitude of the scale parameter, e.g. the value of toll should be large enough to affect mode choice and yet affordable. The second constraint assures the toll scheme is income-based. Optimization of (4) is highly non-linear. The determination of C_g^{min} and C_g^{max} may not be trial and requires empirical calibrations. Results and insightful discussion of the optimization-based toll scheme will be reported in a later version of the paper.

4. DISCUSSIONS

In this paper, we investigated congestion pricing schemes for networks of heterogeneous population with respect to income level and value-of-time (VOT). We utilized a bi-modal macroscopic system model to reproduce the aggregated traffic dynamics and travel behavior under congestion pricing. Six income-based user groups are introduced, where each group was assumed to have a unique VOT and the distribution of VOT came from a gene index of 0.6. We presented and discussed the impacts of pricing on the whole population and the individual groups. W shown that: (i) an area-based pricing based on aggregated traffic model can reduce congestion effectively: system optimum can be obtained where the total travel time savings outweigh the total toll paid, (ii) pricing schemes would in general benefit better a group of users with a higher VOT, regardless it is a flat-toll or a dynamic toll and (iii) a VOT(income)-based pricing scheme can provide a more equitable condition and more in favor of the groups of low VOTs. The findings of this paper can provide some important insight on congestion pricing policies. Equity issue is often considered as a major barrier when implementing congestion pricing. By using an income-based pricing scheme, costs and benefits of different groups among population can be evaluated and equitable pricing schemes can be developed. On-going work investigates (i) optimal VOT-based tolls, where the objectives are to reduce congestion effectively and provide savings more equally, and (ii) how promotion of public transport (bus) can further improves the efficiency and equity of such pricing schemes. Another future direction is to give flexibility in trip choice and departure time choice. A larger positive gain may be obtained, if peak-hour demand was flattened and users can travel during off-peak period when it is faster and cheaper. For such cases, a penalty on earliness and lateness of performing a scheduled activity (include traveling) should be introduced.

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