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Mode shift with tradable credit scheme: a simulation study in Lyon

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Abstract

Several tradable credit schemes have been proposed over the last decade to restrict the use of personal cars and reduce negative traffic externalities such as congestion and pollution. Two of the main arguments of this approach compared to congestion pricing are that it is revenue-neutral and that the market could self-regulate the credit price. The trip-based MFD (Macroscopic Fundamental Diagram) framework is an efficient tool to simulate traffic dynamics at a large-urban scale considering multimodal options. It is very convenient to test demand management strategies targeting all travelers. In this paper, we propose to use such a simulation framework to investigate a tradable credit scheme, which aims to foster mode shift by regulating access to the road network. Credits are allocated to the users and are required for using their car. They can save their credits for another day or trade them using a marketplace. The credit scheme impacts are illustrated through a numerical implementation with a demand typical of a peak hour (7:00 to 8:00) in Lyon with 115 628 trips. The main result of the simulation is the potential for such a tradable credit scheme to increase public transportation share and thus reduce total travel costs.

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Keywords: tradable credits; trip-based MFD; reservoir; agent-based simulation

1. Introduction

Congestion is a major concern in most big cities. The related delay has a negative impact on the economy, and the associated pollution participates in global warming and is a severe public health concern. A considerable literature body proposes solutions to tackle the congestion at a large scale, for example, by introducing perimeter control or by implementing congestion pricing. Congestion pricing has been deployed as urban tolls in different cities such as Singapore, London, and Stockholm, to name the most famous ones (See [Gu et al. \(2018\)](#) for more details). Tradable Credit Schemes (TCS) are also investigated in the literature mainly to deal with bottleneck issues. However, to the authors' best knowledge, they have never been implemented in the field for transportation applications.

TCS is seen as an alternative to congestion pricing. The regulator emits credits and allocates them to the travelers. The urban toll consists of a given amount of credits, which means the car users have to pay the toll using those credits

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instead of real money. The users can sell their unused credits and buy some if they need more, either with the regulator or with other users. The users taking the least tolled paths (in time, space or mode) are then rewarded with the money they earn selling credits. TCS was initially proposed by Verhoef et al. (1997). With Yang and Wang (2011) a TCS was formulated with a credit link tolling. Several papers extended this formulation with different variants, such as Ye and Yang (2013) for a continuous formulation. Lessan and Fu (2019) provides an overview of TCS and tradable permit schemes. However, only a few works assumed the credits received on a given day could be spent on another day. The works of Ye and Yang (2013), Tian and Chiu (2015) and Guo et al. (2019) present three different frameworks where the credits are valid for a given period of several days. In Miralinaghi and Peeta (2016), the users can report credits from one period to another. Thus they have more flexibility in organizing themselves on how to spend their credits. Furthermore, most of those papers include simple static link travel time functions, like BPR (Bureau of Public Roads) ones, which do not capture congestion effects well, including congestion spreading at a large scale.

Daganzo (2007) proposed a new representation of urban networks with the Macroscopic Fundamental Diagram (MFD). In the MFD formulation, the speed or the outflow of the network is a function of the accumulation of vehicles at a given time. The trip-based MFD (sometimes called bathtub model or speed-MFD) permits to consider the distribution of the different trip-lengths (Mariotte et al. (2017), Lamotte and Geroliminis (2018), Jin (2020)). In a submitted paper, Liu et al. (2020) propose a TCS using the trip-based formulation. The users choose their departure times to minimize their costs, and the regulator optimizes the tolling profile to minimize the total travel time.

In this paper, a TCS is proposed with a trip-based MFD formulation to take into account the dynamic of a large-scale urban network and the heterogeneity of the trip lengths. The users can choose between taking their car and paying the credit toll or switching to Public Transportation (PT). We aim to assess how such a scheme can foster modal shift and if the price evolution remains acceptable. The originality of this work lies mainly in the simultaneous use of a free market driven by offer and demand to trade the credits, the possibility for the users to manage their credits over a receding horizon, the modal choice (elastic demand), and a trip-based MFD as a dynamic model for the road network.

This paper is organized as follows: in section 2 the TCS, the demand and the network models are presented. The results are discussed in section 3. Section 4 concludes this paper.

2. Model

2.1. Proposed tradable credit scheme

Each day, each user receives a given amount of credit κ from the regulator of the transportation network. To use their car in the regulated area on a given day, the users need to spend a fixed amount of credit: the credit toll τ . The total amount of credits is fixed, and one cannot buy extra credits from the regulator. The ratio between the allocation and the toll permits the regulator to control the number of cars using the network and thus influence the mode ratio. If they are not using the credits (they take PT), they can keep them for later use because their utility for using the car might be higher on another day. Otherwise, they can sell them to other car drivers in a marketplace. Most of the previous works do not allow the possibility to report the use of the credits, as some assumptions and measures need to be taken to avoid unwanted speculative behavior. In this case, the credits bought on the market have to be used on the same day. A similar measure was proposed by Miralinaghi and Peeta (2020).

2.2. Users

The travel cost $\tilde{C}_i(d, m)$ of the user i for the day d using the mode m has three parts:

$$\tilde{C}_i(d, m) = \alpha \tilde{T}_{i,m}(d) + p\tau_m + \mu_{i,m}(d), \quad (1)$$

where $\tilde{T}_{i,m}$ is the estimated travel time per mode, α the Value of Time (VoT), τ_m the credit toll (τ if using the car, 0 otherwise), p the market price of one credit, and $\mu_{i,m}(d)$ is the extra penalty for not using the car on day d . It means taking the PT instead of the car will induce an extra cost: $\mu_{i,car} = 0$ and $\mu_{i,PT}(d) > 0$ for some days d . It represents the need for users to use their car on specific days, to buy groceries or pick-up someone for example.

At the end of each day d , the users are updating their estimation of the travel time by car:

$$\tilde{T}_{i,car}(d+1) = \tilde{T}_{i,car}(d) + \Delta_T(T_{i,car}(d) - \tilde{T}_{i,car}(d)), \quad (2)$$

where Δ_T is the learning rate and $T_{i,car}(d)$ is the experienced (for car users) or virtual (for PT riders) travel time. It is calculated from the trip-based MFD simulation.

The users are assumed to have the same VoT. They have different Origin-Destination (OD) pairs. It means the trip lengths and PT alternatives are heterogeneous. Their departure times are also heterogeneous. Two users on the same OD will not necessarily experience the same travel time with an MFD approach, but they would with a static model such as the BPR one.

The user chooses its transportation mode each day d by minimizing its estimated costs over a decision horizon h :

$$C_i(\mathbf{m} = (m_1, \dots, m_h)) = \sum_{j=1}^h \tilde{C}_i(d_j, m_j), \quad (3)$$

where $\mathbf{m} \in \{0, 1\}^h$ is the vector of mode choice from the current day d_1 to the end of the decision horizon d_h . 0 stands for riding PT and 1 for using the car. The mode choice follows a receding horizon: the user i chooses \mathbf{m}^* minimizing $\mathbf{m} \mapsto C_i(\mathbf{m})$. It takes the car if $m_1^* = 1$ and if it manages to secure enough credits for the toll. If needed, it tries to buy credits on the market. Otherwise it will ride PT. If $m_1^* = 0$, meaning it *chooses* to ride PT and if it owns enough credits to cover its planned consumption over the horizon $\tau \sum_{j=1}^h m_j^*$, then it will try to sell the remaining credits.

2.3. Double auction market

The users can trade credits using a double auction market. Each day, they can generate a bid, or an ask consisting of the desired quantity to buy/sell and the corresponding price. The market is cleared once every user made its bid/ask. The market follows a uniform institutional price setting. It means the price is set by the regulator and is the same for all the transactions. The price is set to match the intersection of the decreasing offer prices and the increasing demand prices to maximize the total traded quantity. See [Parsons et al. \(2006\)](#) for more information about double auction markets.

The users choose their auction price as the price equalizing their travel costs by car and by PT as defined in Eq. (1). They thus want to sell/buy credits at their true value. It also means they do not try to generate profit by reducing their prices when buying or increasing their prices when selling.

2.4. Traffic simulation and case study

Trip-based MFD permits the assessment of the travel times of different agents by taking into account the dynamic aspect of congestion. Its resolution is based on an event-based framework, and the properties of the results are difficult to predict before the resolution occurs. For this reason, this paper illustrates the proposed TCS on a simulation study with Lyon as a unique reservoir (Fig. 1, left). It means car traffic will share the same mean speed over the network at a given time ([Mariotte et al. \(2020\)](#)).

The simulation takes the typical demand for the 7:00-8:00 peak hour. The demand is split into several OD pairs using the 10 reservoirs of [Mariotte et al. \(2020\)](#). The boundaries are split into five additional regions to account for trips starting or ending outside the reservoir. It results in 225 OD pairs (224 are used because one OD pair has no demand for the considered time period). The demand is scaled by 100 to reduce the number of agents and thus the computing time. The scaled demand is rounded up to the closest integer while ensuring a minimum of one agent for OD with non-zero demand. Thus the 115 628 trips are represented by 1177 agents. The trip length distribution of the scaled demand is represented in the right part of Fig. 1.

The users are assumed to have fixed departure times, uniformly distributed across the peak hour. We assume that PT travel times only depend on the departure time and are not influenced by the traffic level in the network. We use historical travel time estimates gathered through the HERE API ([HERE Developer](#)) to determine PT travel times for any OD pair inside the city. Note that historical PT travel times account for the average effect of existing traffic conditions and change with the departure time.

The workflow of the overall framework for one iteration of one day is the following:

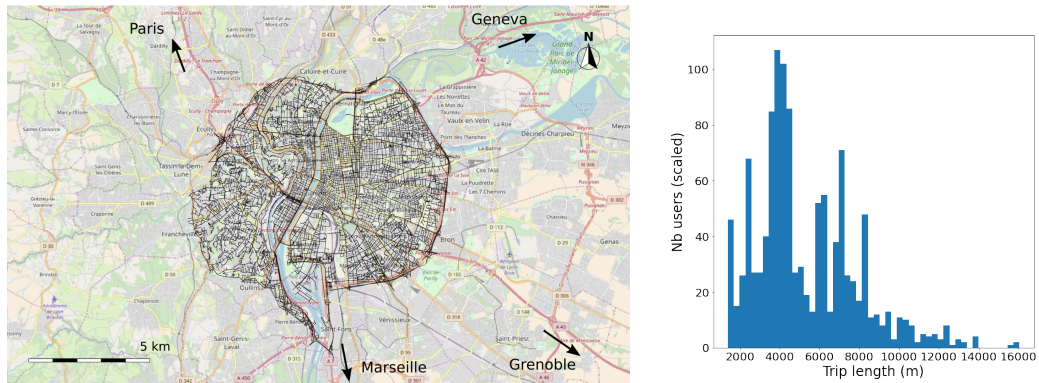


Fig. 1. (left) The urban area under consideration (Mariotte et al. (2020), ©OpenStreetMap); (right) the different car trip lengths for the demand scenario.

- Each user receives its allocation of credits;
- Some users can change their choices regarding their mode of transportation;
- The trade of credits takes place;
- Users wanting to use the car but not owning enough credits (even after the trade) are forced to switch to PT;
- The trip-based MFD traffic simulation takes place;
- Users update their estimation of car travel time by using the results of the simulation.

The iterative process is repeated until either a user equilibrium or the maximum number of iterations is reached. In the presented results, the algorithm stops because the user equilibrium is reached.

The parameters used for the TCS and the simulation are listed in Table 1. The VoT used is based on the findings of Fosgerau et al. (2007). The day for which the car is preferred (it means when μ_{PT} is not zero) is the same weekday every week. It is assigned following a uniform distribution for each user.

Table 1. TCS and simulation parameters.

Parameter	Notation	Value
VoT	α	10.8 EUR/h
Endowment	κ	100 credits
Toll	τ_{car}	{150, 200, 250, 300} credits
Decision horizon	h	3 days
Initial credit price	$p(0)$	{0, 0.01, 0.1} EUR/credit
Extra PT penalty	μ_{PT}	5 EUR
Learning rate	$\Delta_{\mathcal{T}}$	0.1

3. Results

The price of one credit may greatly impact the users' choices, as the cost of using the car increases linearly with the credit price. As its initial value is arbitrarily fixed, we need to assess its effect on the TCS. The evolution of the credit price and the modal ratio for different initial prices are presented in Fig. 2. The toll level is set to 200 credits, i.e., a user needs 200 credits to travel by car. Users receive 100 credits per day from the regulator as allocation. It will be seen later that this ratio of toll and allocation improves social welfare.

The position of the modal ratio relative to the toll-allocation ratio (calculated by $1 - \tau/\kappa$) is a valuable proxy to assess the stability of the TCS. A sustainable PT share has to be above this ratio because under it, the users are depleting their stocks and will eventually run out of credits. This event happens for the 0 EUR/credit case around day 60 and the 0.1 EUR/credit case around day 110. The credit price eventually stabilizes around 0.011 EUR/credit for

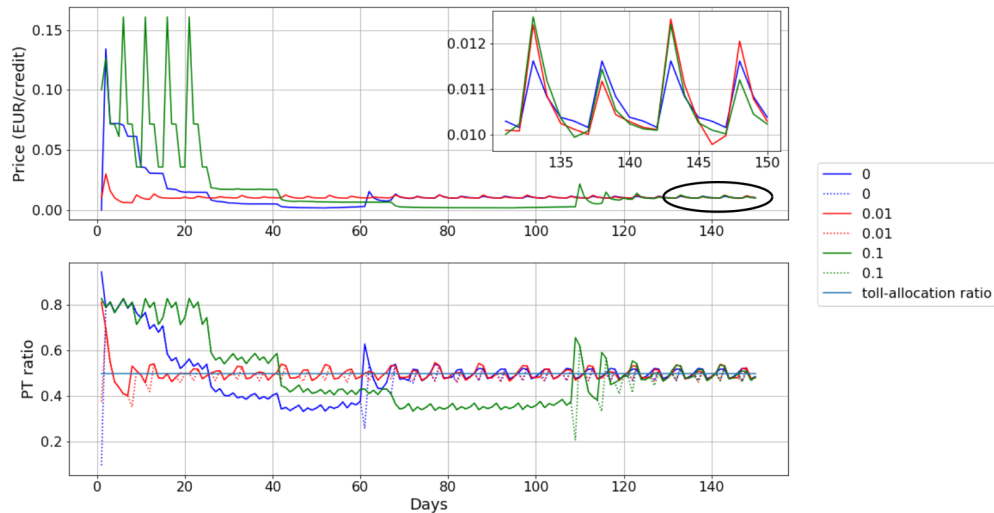


Fig. 2. Evolution of the credit price (upper) and the modal share (lower) for different initial prices for a toll level of 200 credits. The dotted lines are the ratio of using wanting to take the PT. The differences lie in the users unable to secure enough credits to take their car.

the three different initial prices, and the PT ratio converges to the toll-allocation ratio. Thus the out-of-pocket toll cost is about 1.1 EUR since 100 credits are allocated, and 100 others need to be bought. It is acceptable in comparison to the VoT since it represents only 6 minutes.

The tuning parameter of the regulating authority is the ratio between the credit toll to be levied for each car circulating in the controlled area and the allocation each user gets. In the case of a fixed allocation, a high toll forces many users to take the PT. The TCS efficiency is measured using the total social cost: the sum of the travel times of all the agents weighted by their VoT. The tolls are not taken into account as the TCS is revenue-neutral, and the transactions only take place between the network users. The influence of different toll levels on the system is found in Fig. 3. The initial credit price is 0.01 EUR/credit, as the previous results show a relatively fast convergence. The allocation is fixed to 100 credits per user and per day as only the ratio matter.

There seems to be an optimal toll level: when it is too low, like 150 credits, too few agents are forced to shift from car to PT. When it is too high, like 300 credits, too many agents are forced to ride PT, and the gain on the traffic conditions does not outweigh the burden of the agents shifting from car to PT. It should be noted that the modal share is not constant across the days, as on each day, different users will have a preference to take the car, and the credits can be stocked. The credit toll of 200 credits is the best between those four levels. It permits the reduction of the total social cost by about 15 % in steady state. The mean speed increases by about 2.5 m/s, and the PT ratio increased by 0.18 points, which represents an increase of about 55 %. It should be noted that there are only a few differences between plain and dotted lines for the PT ratio. It means only a few agents choose to take the car but do not manage to secure enough credits and thus are constrained to take the PT.

4. Conclusion

These simulation results highlight the potential for TCS to minimize car use while improving the total travel time. Users taking the PT are rewarded by the money earned selling their credits, and the car users enjoy better traffic conditions and thus reduced travel times. In addition to taking into account the heterogeneity of the agents, the heterogeneity of the days is induced by introducing an extra car utility on some days. Nevertheless, after a transient period, the TCS measures are relatively smooth and stable. Allowing the credits to be stocked allows users to plan their mode choices over a receding horizon and potentially never spend money to use their car. This last point is a crucial argument to improve the acceptability of a demand management scheme.

This paper assumes that the users do not try to make a profit out of the TCS since they auction in the market with their true price. Future work should investigate the impacts of learning behaviors related to the interaction between

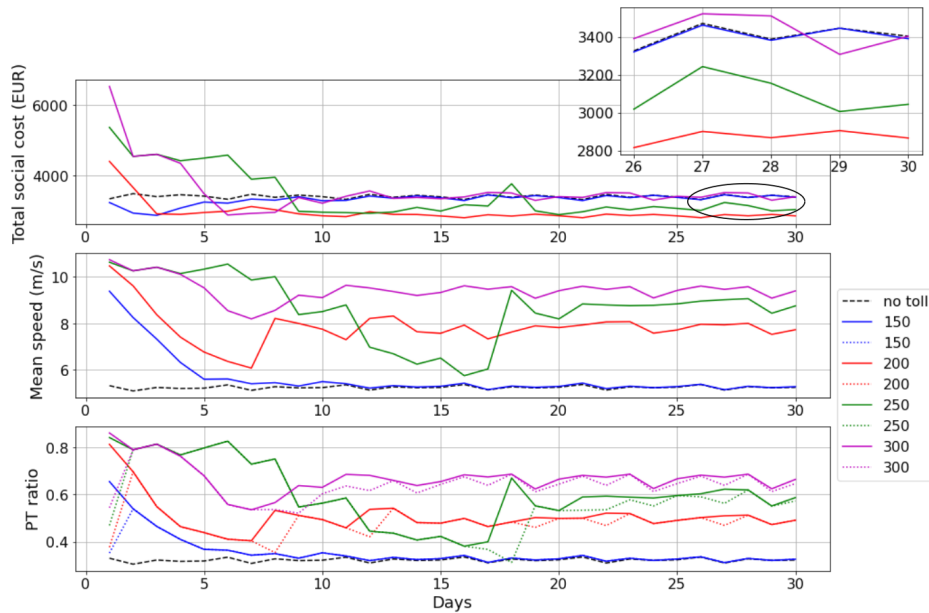


Fig. 3. Evolution of the scaled total social cost (upper), the mean speed in the network (middle), and the modal share (lower) for different credit tolls. The dotted lines are the ratio of using wanting to take the PT.

the agent and the market. Especially if the agent begins to demonstrate intelligence and learning behavior to generate profit, the loss of efficiency of the TCS should be quantified to assess its robustness. The impact of the decision horizon should be investigated as well.

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