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Tradable Credit Scheme for Multimodal Urban Networks

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SHORT SUMMARY

A Tradable Credit Scheme (TCS) is a demand management policy promoting more sustainable travel behaviors. The regulator defines the credit distribution among the population. It also determines the required credit charges for each travel alternative at different times of the day. The credit price is determined by the trade of credits between travelers. Defining the credit scheme at the urban level and estimating its impacts on user travel decisions and the network congestion dynamics is challenging. We propose a framework wherein travelers change their departure times and choose between solo car driving, Public Transportation (PT), and carpooling to complete their trips under a dynamic TCS, meaning the credit charge is time-dependent. A multimodal macroscopic traffic simulator based on a generalized bathtub model captures the congestion dynamics for the different transport modes. Additionally, we consider different values of time, trip lengths, and desired arrival times.

The proposed TCS minimizes the congestion cost and the carbon emissions. The stochastic user equilibrium is computed through an iterative method. The methodology is implemented and applied to a realistic test case in Lyon (France). The dynamic TCS profiles result in up to 20% congestion reduction for 57% fewer carbon emissions.

Keywords: departure time; generalized bathtub; mode choice; multimodal traffic management; tradable credit scheme

1 Introduction

Automotive congestion has been an issue for many cities worldwide for decades. A Tradable Credit Scheme (TCS) is a quantity-based framework introducing a commodity (credits) to foster sustainable transportation behaviors. The regulator issues and distributes credits to the travelers. Depending on the departure time and transportation mode, a traveler must spend credits to access the transportation network. The credits can be traded between travelers through a dedicated marketplace. The TCS permits to reduce the congestion along with other objectives, such as the environmental footprint of the transportation network. However, reducing congestion or pollution might lead to different TCS, and trade-offs must be found.

A substantial part of the literature on TCS aims to optimize the travelers' route choices by charging the links of the networks (Yang & Wang 2011). Implementation of those contributions in an urban area is practically complex. The present work focuses on mode and departure time choices at the network level. Most TCS studies in the literature (Tian et al. 2013, Nie 2015, Miralinaghi et al. 2019) used Vickrey's bottleneck (Vickrey 1969): a point queue with a fixed capacity. In the mentioned studies, the credit charge is dynamic, meaning the number of credits required to pass the bottleneck is time-dependent (i.e., based on the departure time choice). The purpose is to encourage travelers to switch from on-peak to off-peak hours.

In our previous study, we proposed a TCS based on the trip-based Macroscopic Fundamental Diagram (MFD) in order to capture trip heterogeneity (trip length) and congestion dynamics at a large scale (Balzer & Leclercq 2022). We considered Public Transportation (PT) with fixed cost based on a given departure time and origin-destination locations. The credit charge was static, i.e., the required number of credits does not depend on the departure time, as the focus is the shift from personal cars to PT. In this work, the TCS is dynamic and depends on the users' departure time and mode (private car, PT, and carpooling) choices. In addition, we consider a multimodal extension of the generalized bathtub model (Jin 2020) to address the network equilibrium with

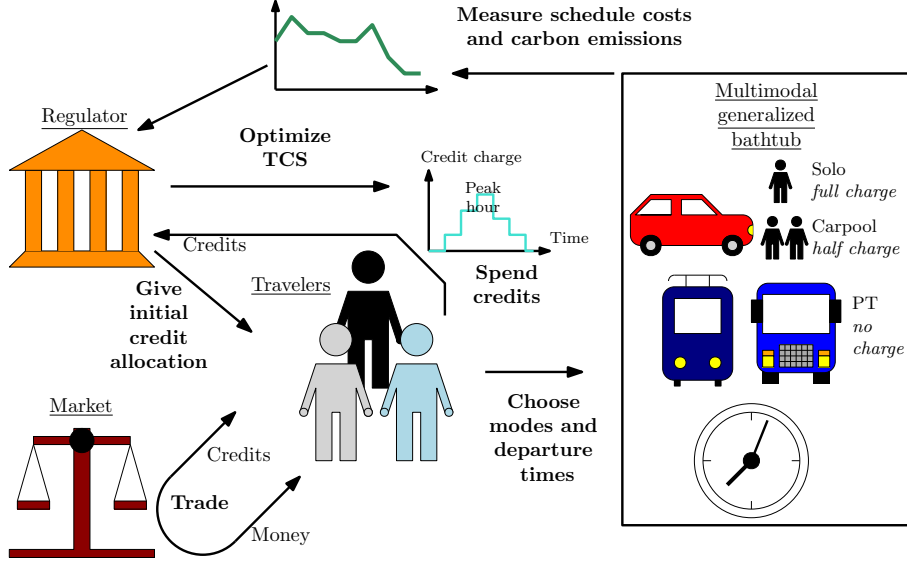


Figure 1: Framework of the multimodal bathtub under TCS.

a heterogeneous demand profile and to investigate the effect of a TCS on mode and departure time choices. Moreover, we account for carbon emissions. In the literature, few studies consider environmental goals with TCS at the link level (Gao & Sun 2014).

2 Methodology

This section describes the proposed methodological framework to address the TCS problem, including the Stochastic User Equilibrium (SUE) calculation based on the multimodal generalized bathtub under TCS. Fig. 1 depicts an overview of the different components and interactions. The travelers get a fixed amount of credits κ daily from the regulator for free. They choose their transportation mode m and departure time t_d according to the credit charging profiles $\tau(t_d, m)$ and scheduling preferences. The regulator determines the credit charging profile to achieve its economic and environmental goals. The credit charge is significant for highly congestive modes like private cars during peak hours and low for more sustainable choices like PT or carpooling outside peak hours. In the following, the regulator only chooses the charging profile for car drivers $\tau(t_d, \text{car})$. It is free for PT riders: $\tau(t_d, \text{PT}) = 0$ and only the half for carpoolers as we assume two travelers per car, who share the credit charge: $\tau(t_d, \text{pool}) = \frac{1}{2}\tau(t_d, \text{car})$. Travelers can trade the credits on a specific market. The credit price p results from the offer and demand in this market, so it depends on the travelers' choices. We do not consider the details of the trade mechanism. We adopt the widely used Market Clearing Condition (MCC), as in (Yang & Wang 2011), to represent the market mechanism: the price is zero or all issued credits are spent. Thus, there are complex interdependencies between travelers' choices, the market, and the traffic congestion level. While describing credit price evolution during the transitional phase is very challenging, it is possible to calculate the credit price at equilibrium when all interactions stabilize.

Regarding the practical implementation, it is relatively straightforward considering connected vehicles: the travelers interact with the TCS through a mobile application or a website to consult and trade credits. When a connected vehicle communicates with the infrastructure (e.g., road-side antenna), it gives the user identification number of the travelers along with the departure time. The associated credit charge is then deducted from their credit accounts.

Each traveler has a characteristic trip length l , desired arrival time t_a , and belongs to a socioeconomic class c . The travel times are computed with the multimodal generalized bathtub framework. For each mode m , we define a virtual traveler $t \mapsto z_m(t)$ which keeps track of the cumulative traveled distance since the origin of times, as introduced by (Lamotte & Geroliminis 2018). The speed of mode m v_m depends on the accumulations of all modes. The accumulation $H_m(t)$ at time t for mode m consists of the trips that started before t and are long enough to be ongoing by t . Therefore, we introduce the density, with respect to departure time t_d , of the number of vehicles with trip length longer than l : $F_m(l, t_d) dt_d$. The traffic dynamics are based

on the formulation of (Ameli et al. 2022) and extended here to account for different modes. The bathtub dynamics of mode m is given by Eq. 1.

$$\begin{cases} z_m(t) &= \int_0^t v_m(\{H_{m'}(s)\}_{\forall m'}) ds \\ H_m(t) &= \int_0^t F_m(z_m(t) - z_m(t_d), t_d) dt_d \\ F_m(l, t_d) &= \int_{l' > l} \int_{t_a} \sum_c f(c, l', t_a, t_d, m) dl' dt_a \end{cases} \quad (1)$$

The travel cost (TC) accounts for the early or late arrival, the travel time, and the TCS-related cost, i.e., the monetary value of the required credits:

$$TC = \alpha_c \left((\hat{t}_a - t_d) + \tilde{\beta}_c \max(0, t_a - \hat{t}_a) + \tilde{\gamma}_c \max(0, \hat{t}_a - t_a) \right) + p\tau(t_d, m). \quad (2)$$

α_c , $\tilde{\beta}_c$, and $\tilde{\gamma}_c$ are respectively the VoT and the normalized marginal cost for early and late arrival. The discrete logit-based decision depends on the TC of all alternatives regarding departure time and mode choice, and on the logit parameter θ_c :

$$\psi(c, l, t_a, t_d, m) = \frac{e^{-\theta_c TC(c, l, t_a, t_d, m)}}{\int_{t'_d, m'} e^{-\theta_c TC(c, l, t_a, t'_d, m')}}. \quad (3)$$

$\psi(c, l, t_a, t_d, m)$ is the ratio of travelers with characteristics c, l, t_a wanting to travel at t_d with mode m . It may be different from the *actual* travel assignment $f(c, l, t_a, t_d, m)/d(c, l, t_a)$.

The SUE is reached when the flow distribution matches the logit distribution:

$$d(\omega)\psi(\omega) = f(\omega) \quad \forall \omega \in \Omega, \quad (4)$$

with Ω the space of all travelers' characteristics and degrees of freedom. The flow conservation requires the travel demand with specific characteristics to match the sum of the flows with the same characteristics:

$$\int_{t_a, m} f(c, l, t_a, t_d, m) = d(c, l, t_a) \quad \forall c, l, t_a. \quad (5)$$

The TCS-specific constraints are respectively the credit cap (CC): the consumed credits cannot exceed the allocated amount, the MCC, and the positivity of the price:

$$\begin{cases} \int_{\omega \in \Omega} f(\omega)\tau(\omega) \leq D\kappa; \\ (\int_{\omega \in \Omega} f(\omega)\tau(\omega) - D\kappa) p = 0; \\ p \geq 0. \end{cases} \quad (6)$$

The SUE is calculated by discretizing the problem and using an iterative process: compute the travel costs, the logit-decision, update the assignment and the credit price and start again until the SUE is reached.

3 Results and Discussion

The travel demand considered for the case study represents the typical morning commute of 384,200 travelers in Lyon (France) between 7:00 and 10:00. There are ten regions and five boundaries, creating 224 different OD-pairs with non-zero demand. The travel demand consists of trips in Lyon and through Lyon, i.e., we also account for travelers starting or/and ending their trip outside the city. Fig. 2(a) represents the studied network. The synthetic desired arrival times are shown in Fig. 2(b). The distribution has a bell shape: the demand is low at 7:00 and 10:00 and high between 8:00 and 9:00.

The Pareto front is shown in Fig. 3, with the no TCS case for comparison. The proposed TCS enables congestion reduction from 15% to 20% and pollution reduction from 57% to 90%. To achieve a low carbon footprint, the TCS significantly penalizes the car, and many travelers switch to PT and carpooling. When the mode shift is significant, the traffic improvement does not offset the use of slower modes, and the total congestion cost increases due to increased travel times.

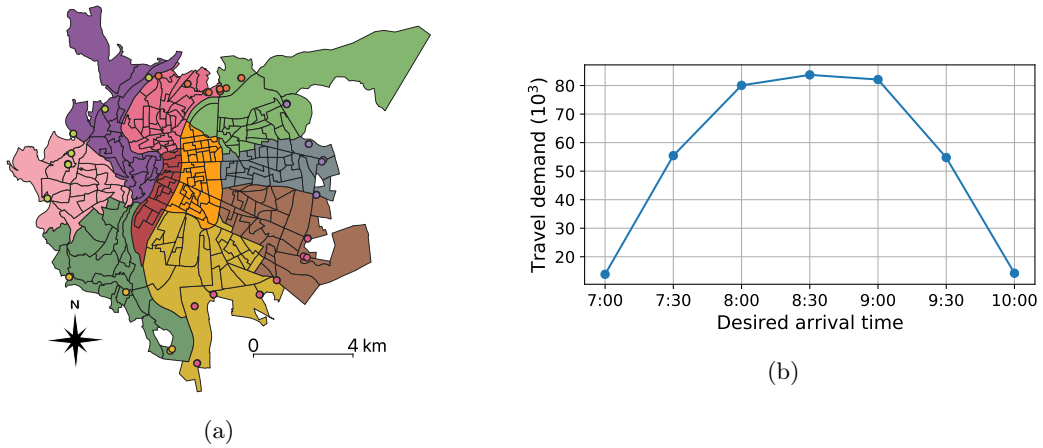


Figure 2: Supply and demand for the scenario: (a) the ten regions formed by the IRIS areas and the access points merged in five boundaries (circles) (b) and the distribution of the desired arrival times.

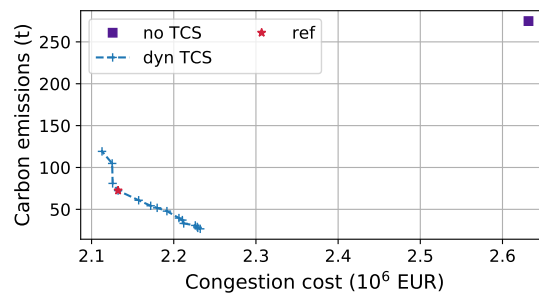


Figure 3: Congestion cost vs. carbon emissions for different dynamic TCS against the statu quo (no TCS). The red star 'ref' is the TCS used for further discussion.

4 Conclusions

During the last two decades, the literature improved the bottleneck’s model to quantify better the economic losses caused by congestion. It also allowed us to understand better the potential benefits of demand management policies such as congestion pricing and Tradable Credit Scheme (TCS). The main mean of action was the spread of the departure times. We formulate a multimodal generalized bathtub to account for different types of vehicles and transportation modes. Each travel choice consists of mode and departure time. We add a TCS to foster mode shift during the peak hour. Public Transportation (PT) users ride for free, solo car drivers pay the total charge, and carpoolers only half. We compute the Stochastic User Equilibrium (SUE) to account for the uncertainty of users’ choices. A realistic scenario based on the morning commute in Lyon illustrates the proposed methodology. The dynamic TCS permits a better reduction of congestion costs and carbon emissions.

Further steps in the evaluation of dynamic TCS include the validation of the traffic simulation through micro-simulation and the estimation of travelers’ behavior and acceptance through surveys.

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