MobilityCoins – Tradable credits and heterogeneous user groups: effects of allocation and charging schemes in large-scale networks

P. Servatius[a,*], B. Wang[b], K. Bogenberger[a] and M. Keyvan-Ekbatani[b]

[a] Technical University of Munich (TUM), School of Engineering and Design, Chair of Traffic Engineering and Control, Munich, Germany
philipp.servatius@tum.de, klaus.bogenberger@tum.de

[b] Complex Transport Systems Laboratory (CTSLAB), Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand
bo.wang@pg.canterbury.ac.nz, mehdi.ekbatani@canterbury.ac.nz

* Corresponding author

Extended abstract submitted for presentation at the Conference in Emerging Technologies in Transportation Systems (TRC-30)
September 02-03, 2024, Crete, Greece

April 29, 2024

Keywords: tradable mobility credits, heterogeneous users, multinomial logit, traffic assignment

1 INTRODUCTION

Congestion and increased emissions are prominent in global metropolitan areas, largely due to the lack of restraints on car usage. The spatial constraints owing to the high density of infrastructures and population are distinctive city by city. While the industry is innovating in shifting to less carbon-intensive engines, the congestion problem has not been well solved.

We propose a novel policy instrument called MobilityCoin System (Blum *et al.*, 2022). Based on tradable mobility credits, every user receives a credit budget at the start of each term that can be used to pay for trips. The trip costs are dependent on the externalities caused by the travelling activities and can be either positive or negative values, where a negative price refers to an incentive for active mobility. The limited supply of mobility credits creates a market price that acts as an economic incentive to promote the use of sustainable transportation modes. The managing agency can adjust the volume of credits allocated to the system and the credit prices per trip over time to achieve a long-term objective, e.g., to reduce carbon emissions.

The aim of using the MobilityCoin System to reduce greenhouse gas emissions is only attainable with a viable market. As such, the market functionality will be crucial: if the transaction value of a MobilityCoin falls to zero, its regulatory effectiveness will be suspended. As the need for mobility grows, demand for mobility credits is expected to rise. The supply of these credits, however, is guided by considerations of equity, employing methods like uniform distribution, individual allocation, or grandfathering approaches. This strategic allocation decision is pivotal in maintaining a stable market price. However, the effects of the various allocation strategies have not been applied to large-scale networks.

In this paper, we investigated the impacts of this innovative approach. In particular, different credit allocations across various user groups and the impacts on mode-shift, MobilityCoin market equilibrium, and emissions in the transportation network of Munich. It represents a follow-up of the conceptional work of (Servatius *et al.*, 2023). As a methodological novelty, we demonstrated the market clearing condition via an optimization approach using the Brent algorithm, which in this framework is more efficient than variational inequality (VI) or mixed complementarity (MCP) formulations.

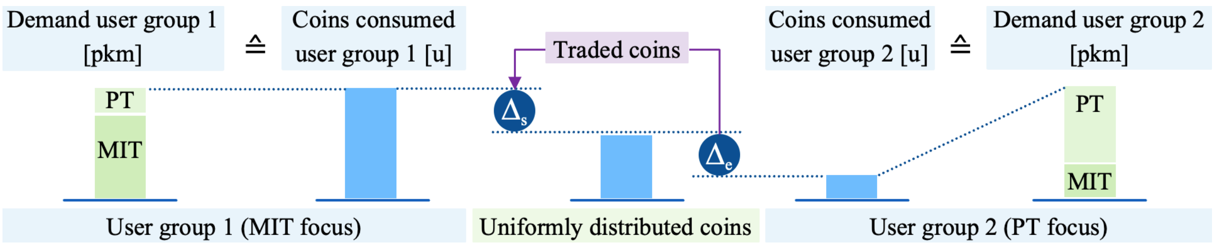

Figure 1 – *Motivation: Influence of Heterogeneous User Groups*

2 METHODOLOGY

Commonly, user groups show diverse patterns in travel demand, which leads to different needs in MobilityCoins. With shortage or excess, an urge to trade the mobility credits will be formed, which is shown in figure 1, resulting in various levels of pressure on the market. We illustrate our innovative methodological contributions step by step in analogy with the model architecture shown in fig. 2. We consider a **network** $G = (N, L)$ with a set N of 3349 nodes and a set L of 7143 directed links. The travel demand is obtained from the Munich Transportation Model and fixed. Preliminary computations were undertaken to determine the traffic flows and travel times without the activation of the MobilityCoin System.

A stated **mode-choice** experiment with over 1,200 participants was conducted in Munich, Germany, to examine the trade-offs between the travel time, internal and external travel costs within a TCS (Schatzmann *et al.*, 2023). Utilizing the travel information of the Stated Preference (SP) survey, the mode-choice coefficients for modal attributes were estimated with user groups segmented into low-income, medium-income, and high-income categories. This estimation was accomplished through regression analysis using the Biogeme multinomial logit model (Bierlaire, 2023). The mode-specific and user-specific utilities were computed for car and bus trips (mobility credit consumption), as well as for bicycle trips (mobility credit earnings), following eqn. 1 and 2. A list of parameters and variables, along with their descriptions, can be found in tab. 1.

$$\mathrm{u}_{m,u,i,j} = \alpha_{m,u,i,j} + \beta^{t}_{m}\,\mathrm{t}_{m,u,i,j} + \beta^{c}_{m}\,\mathrm{c}_{m,u,i,j}\,\mathrm{d}_{m,u,i,j} + \beta^{d}_{m}\,\mathrm{d}_{m,u,i,j} - \beta^{\mathrm{loss}}_{m}\,\kappa_{m,u,i,j} \tag{1}$$

$$\mathrm{u}_{\mathrm{b},u,i,j} = \alpha_{\mathrm{b},u,i,j} + \beta^{t}_{m}\,\mathrm{t}_{\mathrm{b},u,i,j} + \beta^{d}_{m}\,\mathrm{d}_{\mathrm{b},u,i,j} - \beta^{\mathrm{gain}}_{m}\,\kappa_{m,u,i,j} \tag{2}$$

We assume a multi-class network **traffic assignment** problem, determining the user equilibrium following Wardrop's First Principle through the Frank-Wolfe algorithm. The price paid as MobilityCoins contributes to the overall generalized costs, capturing congestion dynamics following eqn. 3. Whereas the bus and bike modes, which are not subject to congestion, are constrained by a fixed cap to reflect their limited capacity.

$$C_{m,u,i,j} = T_{m,i,j}(Q_{m,i,j}) \;+\; \kappa_{m,u,i,j}\,P \tag{3}$$

In addressing the **market clearing** condition within the transportation network, the method employed includes the utilization of an optimization model, specifically the Brent Algorithm. This step is fundamental in establishing the equilibrium market price and calculating the resultant consumption of MobilityCoins. This process iteratively employs a mode-choice model and a multi-modal traffic assignment model to determine the total MobilityCoins required to enable the traffic demands in the system. The optimization model is designed with the objective of minimizing the difference between the MobilityCoins allocated and consumed, ensuring the MobilityCoin market price is maintained at a positive value, shown in fig. 2. Crucially, this market price acts as a unified exchange rate between the MobilityCoins and the travel time across the transportation system based on various travel modes, achieving a consensus among all users of the system regarding its value in analogy with Yang & Wang (2011).

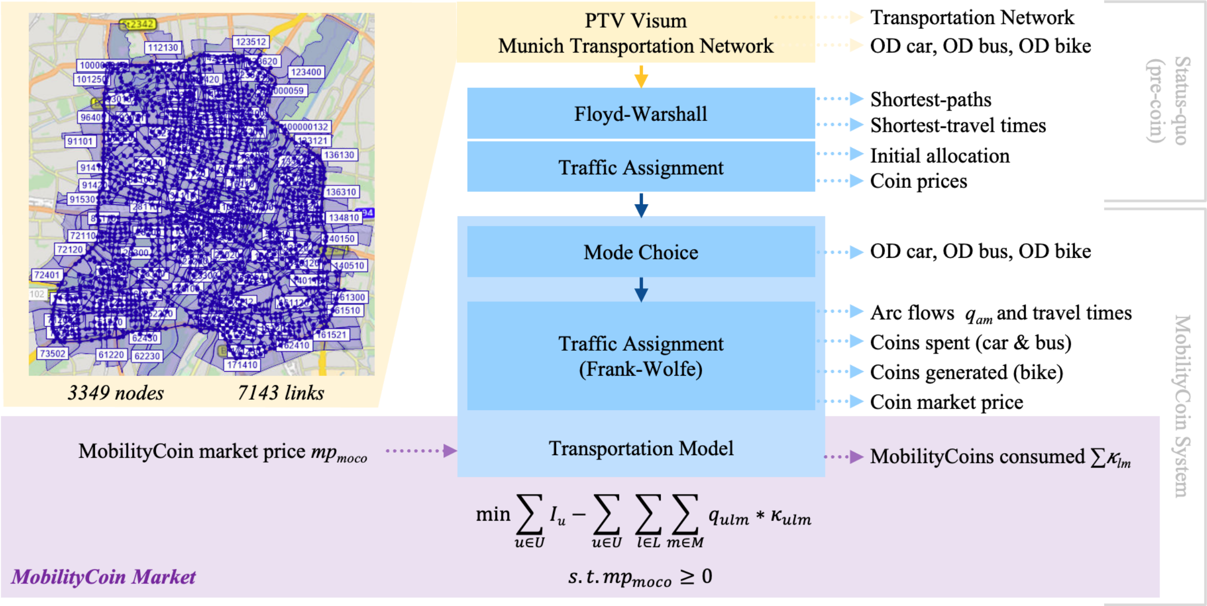

Figure 2 – *Model: Building Blocks and MobilityCoin Market*

The base parameter are calibrated to match mode demands given by the Munich Transportation Model. Upon convergence of the user equilibrium and market equilibrium, a new market price is formed, which is set as the baseline to compare further equilibrium states. When the delta between the supply and demand of MobilityCoins in the market approaches a value less than one, the fluctuations of the market price become comparably small, observably only at the fourth decimal place. This suggests a reasonable approximation under the set conditions.

Table 1 – *Transportation Model Parameters and Variables*

Indices	**Definition**
m	Travel mode (car, bus or bike).
u	User group (low-income, medium-income or high-income).
Parameter	**Definition**
α_m	Mode-specific intercept.
β_m	Mode-choice coefficients of modal attributes.
$d_{i,j}$	Link length from node i to j.
I_u	User group specific initial MobilityCoin endowment.
Variable	**Definition**
$C_{m,u,i,j}$	Travel costs by mode m and user group u from i to j.
$\kappa_{m,i,j}$	Basic coin charge by mode m from node i to j.
P	MobilityCoin market price.
$Q_{m,i,j}$	Link flow by mode m from i to j.
$T_{m,i,j}$	Travel time by mode m from i to j.
$u_{m,u,i,j}$	Utility by mode m and user group u from i to j.

3 RESULTS

In the pursuit of equitable distribution mechanisms, different allocation schemes were calculated for the low-income, medium-income, and high-income groups to assess their impacts comprehensively. The baseline for these investigations was established as the uniform allocation method, which is predominantly discussed in the literature. This method stipulates that users from each user group receive an identical amount of mobility credits, aligned with the respective demand percentages.

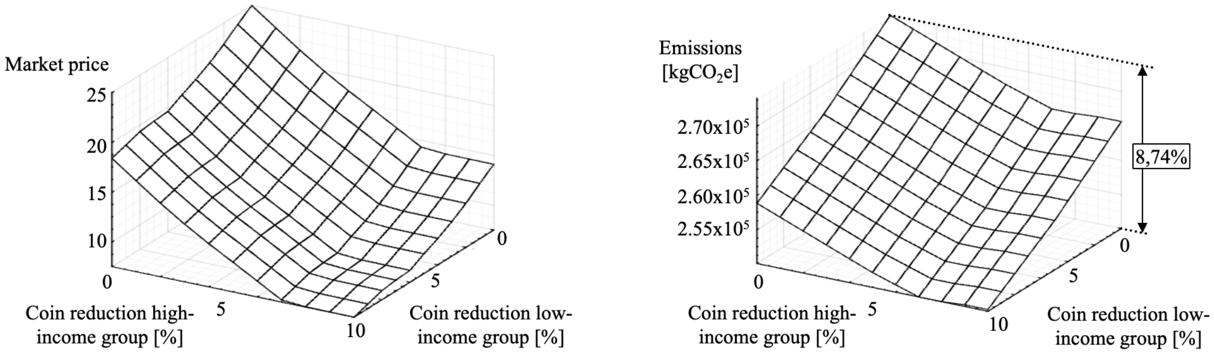

Figure 3 – *Market Price and Emission Trends by Allocation Reduction Across Income Groups*

Following the initial baseline scenario, a study was conducted to explore the user-group-related variations, illustrated in fig. 3. This approach is aimed at evaluating the potential benefits of the re-distributive policies and their effects on the overall economic equity among different income levels. The plot distinctly exhibits asymmetric slope characteristics, demonstrating disparate outcomes when a uniform percentage reduction of the mobility credits is applied to the low-income and high-income user groups. In the circumscribed examination area we achieved an emission reduction of 8.74% while reducing the number of mobility credits by 10% due to shifting 9.4% of the car demand to more sustainable modes. The break points in the wire-grid indicate the limits of the system's capabilities. These results offer insights to derive promising policy strategies regarding the greenhouse gas reduction for the transportation system of Munich.

4 DISCUSSION

In the full paper, we will present an in-depth analysis of the core design parameters and variables interactions, e.g., user-specific initial allocation I_u, and emission costs κ. In particular an analysis of the distributional effects across the population, as well as the temporal evolution of dynamic pricing in a multi-period environment, resulting in different strategies on how the proposed scheme can be used to meet set emission targets.

References

Bierlaire, Michel. 2023. A short introduction to Biogeme. *Transport and Mobility Laboratory, ENAC, EPFL.*

Blum, Philipp, Loder, Allister, Hamm, Lisa, & Bogenberger, Klaus. 2022. Conceptualizing an individual full-trip tradable credit scheme for multi-modal demand and supply management: the MobilityCoin System. *Frontiers in Future Transportation.*

Schatzmann, Thomas, Álvarez-Ossorio Martínez, Santiago, Loder, Allister, Axhausen, Kay W, & Bogenberger, Klaus. 2023. Investigating mode choice preferences in a tradable mobility credit scheme. *Arbeitsberichte Verkehrs-und Raumplanung*, **1837**.

Servatius, Philipp, Loder, Allister, Provoost, Jesper, Balzer, Louis, Cats, Oded, Leclercq, Ludovic, Hoogendoorn, Serge, & Bogenberger, Klaus. 2023. Trading activity and market liquidity in tradable mobility credit schemes. *Transportation Research Interdisciplinary Perspectives*, **22**, 100970.

Yang, Hai, & Wang, Xiaolei. 2011. Managing network mobility with tradable credits. *Transportation Research Part B: Methodological*, **45**, 580–594.