MobilityCoin system design– modelling challenges and opportunities

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Abstract

The design of MobilityCoin schemes, an innovative generalization of tradable mobility credit schemes (TMC), is challenging as little is known about which designs are feasible, yet efficiently leading to desired environmental and socio-economic outcomes. We present a macroscopic policy model based on Wardrop's equilibrium principle for the investigation of the design of MobilityCoin schemes. It provides origin-destination and link-specific charges and incentives for all transport modes, depending on the system's objective. We formulate the policy model as a mixed complementarity problem (MCP) and use an illustrative using a simple network how the model can be used to explore policy designs.

Keywords

Policy design; tradable credits; network optimization

Introduction

Tradable mobility credits (TMC) are currently discussed as a promising alternative to existing road user charging schemes, e.g., fuel excise taxes or congestion charges. TMC schemes do not follow the idea of Pigouvian pricing, i.e., marginal social cost pricing; contrary, TMC schemes are cap-and-trade schemes that define an upper limit to a to-be-regulated quantity, e.g., external costs, which is then linked to the credit volume. Credits are distributed among participants and schemes then usually requires credit redemption upon using or creating of the to-be-regulated quantity. Participants can trade credits based on supply and demand, while the resulting market price factors into the economic decisions of individuals and companies. In transport, the use of such credits has been proposed almost thirty years ago by Verhoef, Nijkamp, and Rietveld (1997), with increasing interest ever since especially on understanding the public's response to such policy proposal (Kockelman and Kalmanje, 2005; Krabbenborg, van Langevelde-van Bergen, and Molin, 2021). While textbook TMC schemes focuses on private transport and imposes charges, the idea can be generalized to imposing charges and providing incentives (negative charges) to all modes of transport. This idea has been proposed under the MobilityCoin framework by Blum et al. (2022). This framework is used in the following. In addition to studying the public's response, research on TMCs also focused on understanding experimentally how users interact on the market, e.g., Tian, Chui and Sun (2019) and Brands et al. (2020), as well as developing first integrated models to understand system design, responses and outcomes, e.g., Balzer and Leclercq (2022) and Tian and Chiu (Tian and Chiu, 2015). However, no policy model exists that studies the policy design of MobilityCoins schemes as a generalization of TMCs.

The introduction of policy instruments affecting entire nations means that a deep understanding is required of how a policy design affects individuals, the economy, and the environment. Especially for such radical innovations like TMC schemes the design problem is very complex as plenty of aspects must be considered and design decisions must be made (Provoost, Cats, and Hoogendoorn, 2023). Here, it can be considered that the core policy challenge is the definition of the overall system's objective, e.g., reduction of congestion and emissions or maximization of accessibility, and the derivation of suitable market volume, initial allocation to all travellers and the charging scheme. With the plethora of dimensions to be analysed, tools are required that can identify feasible, reasonable, and efficient parameter contributions. While agent-based approaches generally allow to investigate many of the mentioned aspects at an individual level, their large computation time especially for larger metropolitan areas or even nations, basically precludes any larger global parameter optimization. In. this paper we present our research on developing a macroscopic integrated transport model to investigate the policy design problem of MobilityCoin and TMC schemes.

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Policy design problem

To investigate the outcomes of a particular MobilityCoin or TMC design, let us consider a transportation system with a network of nodes $\mathcal{N}$ and arcs $\mathcal{A}$. Nodes are referenced by $i, j, k \in \mathcal{N}$ and arcs are referenced by their start-end pair $(i, j) \in \mathcal{A}$. The system has modes of transport $\mathcal{M}$that are referenced by $m \in \mathcal{M}$. The transportation system has origin-destination pairs $\mathcal{O}$, which are referenced by $(o, d) \in \mathcal{O}$. The set of origins and destinations $\mathcal{O}$ is a subset of the set of nodes $\mathcal{N}$. We consider three modes of transport: car, public transport, and bicycle, where only the first mode sees congestion effects, while the other two have fixed origin-destination travel times. We let X_{odm} being the share of travellers on origin-destination pair (o, d) using mode m, where W_{odm} describes the minimal travel costs on origin-destination pair (o, d) using mode m. Further, let T_{ij} be the travel time, Q_{ij} the flow of vehicles, and C_{ij} the total cost including charges and incentives on link (i, j). M_{ij} is the minimum travel cost from node i to j using the car. Further, consider that Y_{ijk} describes the flow of vehicles on link (i, j) towards node k and P the MobilityCoin/TMC market price. The policy design parameters are the individual initial allocation of credits, γ, origin-destination charges and incentives for each mode, λ_{odm}, and link-specific charges and incentives for each mode, κ_{ijm}.

The share of travellers X_{odm} is obtained using a logit-based assignment as a function of W_{odm}.

$$X_{odm} = \frac{\exp(-\mu W_{odm})}{\sum_{m' \in \mathcal{M}} \exp(-\mu W_{odm'})}$$

Where μ is a logit scale parameter. We obtain W_{odm} for cars and the other modes separately as defined below, where τ_{odm} is the exogenous and constant travel time.

$$W_{odm} = \begin{cases} M_{od}, & m = \{"car"\} \\ \tau_{odm} + P \cdot \lambda_{odm}, & else \end{cases}$$

The minimal travel costs M_{od} results from the link travel cost C_{ij}

$$C_{ij} = T_{ij} + P \cdot \kappa_{ij,\text{car}}$$

where T_{ij} is modelled by using the Bureau of Public Roads (BPR) function, computing link travel times T_{ij} as a function of flow Q_{ij}, and the arbitrage condition that describes Wardrop's user equilibrium. It states that an equilibrium is reached when no road user can reduce her or his travel costs anymore by unilateral action, where ⊥ indicates complementarity (Ferris, Meeraus, and Rutherford, 1999)

$$C_{ij} + M_{jk} \geq M_{ik} \quad \perp \quad Y_{ijk} \geq 0$$

The flow on link (i, j) towards node k is positive only if the travel costs from i to k via j are equal to the minimum travel costs between i and k. Then, the total link flow Q_{ij} is obtained as follows.

$$Q_{ij} = \sum_k Y_{ijk}$$

Importantly, we must ensure that the in- and outflows at each node are balanced. This is ensured by the following constraint, where n_{od} is the total travel demand between origin-destination pair (o, d).

$$X_{od,\text{car}} \cdot n_{od} = \sum_{(o,j) \in \mathcal{A}} Y_{ojd} - \sum_{(j,o) \in \mathcal{A}} Y_{jod}$$

Last, the market clearing of the MobilityCoin/TMC scheme must be formulated. Here, only if the demand exceeds or is equal to the supply of MobilityCoins or credits, the market price P becomes non-zero and then results in an economic signal to individuals and companies (Yang and Wang, 2011).

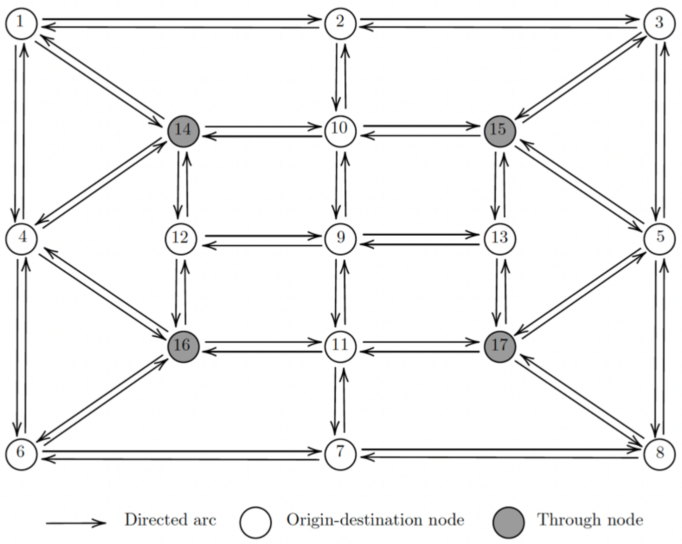
$$\gamma \sum_{(o,d) \in \mathcal{O}} n_{od} \geq \sum_{m \in \mathcal{M}} \sum_{(i,j) \in \mathcal{A}} Q_{ij} \kappa_{ijm} + \sum_{m \in \mathcal{M}} \sum_{(o,d) \in \mathcal{O}} n_{od} X_{odm} \lambda_{odm} \quad \perp \quad P \geq 0$$

All listed constraints are then formulated as a single mixed-complementarity problem (MCP) (Ferris, Meeraus, and Rutherford, 1999). The key policy parameters γ, λ_{odm}, and κ_{ijm} can then be varied and the MCP be solved subsequently to assess the macroscopic outcomes of interest, e.g., mode choice, travel time and traffic externalities, and in particular the gap towards the set objective. Here, as emphasized by Balzer and Leclercq (2022), a starting point for defining a scheme's objective function for the identification of policy parameters are total travel times and carbon emission.

Case study

We illustrate the proposed policy design problem for MobilityCoin schemes using the simple network shown in Figure 1. For simplicity, we assume that cars have only link-specific charges and public transport, and bicycles have only origin-destination-specific charges. The network has 17 nodes of which 13 are origins and destinations of the travel demand. The origin-destination travel times τ_{odm} of public transport and bicycles are set to a multiple of the free-flow travel times of cars, i.e., 1.35 and 1.4 respectively. All parameters of the network are available in the full paper.

Figure 1. The case-study network (own illustration)

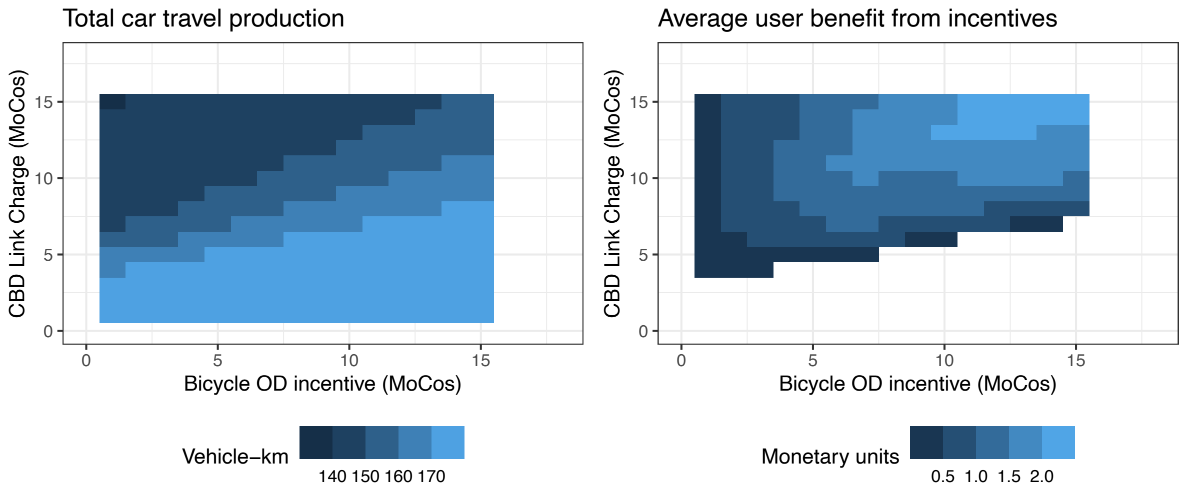


For the initial analysis, we set $\gamma = 1$ MoCo and $\kappa_{ij,\text{car}} = 0.5$ MoCo, and all other policy parameters to zero. We then incrementally impose a "central-business district" (CBD) charge for cars on all links from and to node "9" ranging from 1 to 16 MoCos as well as incrementally provide flat incentives for cyclists on all origin-destination pairs of 1 to 16 MoCos. We then solve the MCP and compute the total car travel production as a measure of externalities and the benefit each cyclist receives that computed as $|P \cdot \lambda_{odm}|$. Figure 2 shows the results. With higher CBD charges, car travel is reduced as less MoCos are available and the costs of alternative modes are cheaper. However, providing more MoCos as an incentive, i.e., increasing the market volume, slightly weakens the impact of increasing CBD taxes. Considering the benefits cyclists receive we find that at low CBD charge levels the market is oversupplied as the market price is zero, leading to zero benefit. Generally, we see that the benefit is increasing with the incentive provided, but it is larger when CBD charges are high.

Discussion

Already the simple example provided highlights complexity of MobilityCoin/TMC schemes and emphasizes that a throughout analysis of the interactions of system design parameters is required. A starting point would be the integration of the proposed macroscopic policy model into a mathematical problem with equilibrium constraints (MPEC) that has been previously been applied to transport-policy problems (Loder, Bliemer, and Axhausen, 2022). However, it is unlikely that this algorithm identifies a global optimum, but when using the status quo of a transportation system as the starting point, it can be expected that the solver identifies an optimal solution in the area around this starting point. Consequently, it can be argued that although a global optimum is not guaranteed, an optimum is found that is most policy relevant. In closing, the proposed model is clearly just a starting point. The next steps are the application to a real-world network and adding more details, e.g., socio-economic status of travellers. Further, adding better parameters on the behavioural responses to TMC/MobilityCoins supports the discovery of feasible, reasonable, and efficient policy parameters.

Figure 2. Simulation results (own illustration)



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