MobilityCoins - an integrated multimodal Wardropian model for policy analysis

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Short summary

MobilityCoins are a tradable mobility credit (TMC) scheme, where all modes can have link-specific and origin-and-destination-specific charges and incentives. These schemes are alternatives to congestion pricing and fuel excise taxes. Their design as a cap-and-trade scheme means that a fixed market volume is defined based on a to-be-regulated quantity. MobilityCoins are distributed to all travelers, who use them to pay for mobility or sell them on a market. However, the question of how to select policy parameters of such schemes in real-world contexts remains unanswered. In this paper, we develop a multimodal Wardropian transport model with integrated MobilityCoins scheme for transport policy analysis. Travelers have the choice between cars, public transport, and bicycles, where only cars experiences congestion effects. Using a simple model, we illustrate how a MobilityCoins scheme impacts transport outcomes under different system designs, e.g., declining overall market volume of MobilityCoins.

Keywords: Transport policy; transportation network modeling; tradable mobility credits; road user charges

1 Introduction

It has been argued that "economists have had limited success in promoting economically efficient transportation and environmental externality policies" (Lindsey & Santos, 2020). The state-of-the-art policies, if one may called it, are fuel excise taxes. However, when considering the advent of electric vehicles that are not paying any fuel excise taxes at all, one realizes that not only the tax revenue will decline with the obvious consequences for the transportation system funding, but also does the ability to use this policy to manage demand and congestion vanishes. Thus, new policies and mixes of them are required for "for deep CO2 mitigation in road transport" (Axsen et al., 2020).

In economics, a long discussion on "price vs. quantities" exists for the regulation of an economic system, i.e., setting standards or limits or charging taxes (Weitzman, 1974). Here, Dales was one of the first proposing such a a quantitative instrument to manage external costs using a cap-and-trade scheme (Dales, 1968). In transport, such policy instrument based on tradable mobility credits (TMC) has been put forward by Verhoef et al. to regulate externalities (Verhoef et al., 1997), but so far did not see any real-world implementation. Nevertheless, such a policy instrument did see already see implementation in energy in order to, e.g., manage carbon emissions (Perroni & Rutherford, 1993) and to promote green energy deployment (Frei et al., 2018). The general idea of taxation is to impose a tax on the market price which in case of elastic demand reduces demand. Contrary, in the cap-and-trade scheme, a regulator defines an upper limit to the to-be-regulated quantity, e.g., emissions or congestion delays, and issues credits or permits to use parts of this overall quantity. As market participants can negotiate and allocate the credits among themselves, greater market efficiency is aimed for.

TMC research already developed among others the fundamental mathematical mechanism (Yang & Wang, 2011) also in a multimodal context (Balzer & Leclercq, 2022), compared its effectiveness to common road pricing (de Palma et al., 2018), and studied user perceptions, the system's acceptance and its feasibility (Krabbenborg et al., 2020, 2021; Kockelman & Kalmanje, 2005). Recently, it has been proposed to use TMCs not only as a charge, but to use them as an incentives too and integrate TMCs into the entire transportation system, hence using the term "MobilityCoins" to describe this integrated nature (Bogenberger et al., 2021; Blum et al., 2022). In the following, we build on this particular implementation of a TMC scheme.

Variables	Explanation
P	Tradable mobility credit market price
X_{odm}	Share of travelers using the car on origin-destination pair (o, d)
T_{ij}	Travel time on link (i, j)
C_{ij}	Travel cost on link (i, j)
Q_{ij}	Flow on link (i, j)
Y_{ijk}	Partial flow on link (i, j) towards k
W_{odm}	Minimum travel costs from origin-destination (o, d) using mode m
M_{ij}	Minimum travel costs between i and j
μ	Mode choice scale parameter
γ	Initially issued credits per traveler
λ_{odm}	Origin-destination-specific MobilityCoins charges
κ_{ij}	Link-specific MobilityCoins charges
τ_{odm}	Free-flow travel time between origin o and destination d using mode m
t^0_{ij}	Free-flow travel time on link i-j
c_{ij}	Capacity on link i-j
β	BPR function parameter
n	BPR function parameter

Table 1: Variables and parameters in the model

In this paper, we present an integrated multimodal Wardropian model for the MobilityCoin system. The model solves for the user equilibrium of car, public transport and bicycle travelers. Travel times for public transport and bicycles are fixed, while car travel times incorporate congestion effects. The overall travel demand is distributed to modes usinga a logit-based mode choice based on the origin-destination travel times. The MobilityCoin system has two kinds of charges: origin-destination-based charges for all modes and link-specific charges for cars to influence route choice and manage congestion. We illustrate the model using a simple network configuration and explore how the different design parameters impact transport outcomes.

2 MODEL

Consider a transport network with $\mathcal{N}$ nodes, $\mathcal{A}$ arcs, and $\mathcal{M}$ modes of transport. Nodes are referenced by $i \in \mathcal{N}$ (and j or k), arcs are a distinct pair of nodes and are referenced by the link star-end pair $(i, j) \in \mathcal{A}$, modes are referenced by $m \in \mathcal{M}$. In this model, three modes are considered: $\mathcal{M} \in \{\text{car, public transport, bicycle}\}$. Travelers are distinguished by their origin-destination pair $(o, d) \in \mathcal{OD}$. The set of origins and destinations is a subset of the set of nodes, i.e., $\mathcal{OD} \subseteq \mathcal{N}$.

In this macroscopic model, travelers make up to two choices. First, they choose their mode m. Second, all users choosing the car also choose their route. The equilibrium condition follows the Wardropian user equilibrium (Wardrop, 1952). The presented multimodal extension is a generalization of the seminal mathematical formulation presented by Yang & Wang (2011). The model defined in the following is formulated as a mixed-complementarity problem (MCP) (Ferris et al., 1999) and is implemented in GAMS (GAMS Development Corporation, 2018). The model's variables and parameters are summarized in Table 1.

The overall demand d_{od} between origin o and destination d is fixed and exogenous. This demand is distributed across modes using a logit based assignment. As shown in Eqn. 1, the choice of modes depends on the minimum travel costs W_{odm} between o and d using mode m and a scale parameter μ.

$$X_{odm} = \frac{\exp(-\mu W_{odm})}{\sum_{m' \in \mathcal{M}} \exp(-\mu W_{odm'})} \tag{1}$$

In the proposed model, cars experience congestion effects as a function of the flow of vehicles, while public transport and bicycles have fixed travel times. Thus, the minimum travel cost depends on the chosen mode as defined in Eqn. 2. The minimum travel cost for cars results from the network assignment of all cars, where M_{od} is the resulting minimum origin-destination travel cost which includes all MobilityCoins link charges. For public transport and bicycles, the minimum travel costs comprises the fixed origin-destination travel times τ_{odm} and the origin-destination specific MobilityCoins charges λ_{odm} valued at the MobilityCoins market price P.

$$W_{odm} = \begin{cases} M_{od}, & m = \text{car} \\ \tau_{odm} + P \cdot \lambda_{odm}, & \text{otherwise} \end{cases} \tag{2}$$

The car travel costs C_{ij} on link i-j comprises two elements. First, the travel time T_{ij} and second the MobilityCoins link charges κ_{ij} valued at the MobilityCoins market price P. The link travel time is defined in Eqn. 3 and follows the Bureau-of-Public-Roads (BPR) function (Bureau of Public Roads, 1964) with the usual parameters and is a function of link flow Q_{ij}.

$$T_{ij} = t^0_{ij} \left(1 + \beta \left(\frac{Q_{ij}}{c_{ij}} \right)^n \right) \tag{3}$$

This then leads to the link car travel costs C_{ij} being computed as defined in Eqn. 4.

$$C_{ij} = T_{ij} + P \cdot \kappa_{ij} \tag{4}$$

The arbitrage condition for car drivers to use link (i, j) follows the Wardropian user equilibrium (Wardrop, 1952). It is formulated in the model as shown in Eqn. 5, where Y_{ijk} are the partial flows on that link towards k. Only when the minimum travel costs from node i to k over j equal the minimum travel costs from node i to k, the link is used for car drivers towards k.

$$C_{ij} + M_{jk} \geq M_{ik} \quad \perp \quad Y_{ijk} \geq 0 \tag{5}$$

The partial link flows Y_{ijk} can then be aggregated to link flows Q_{ij} as the sum over all partial flows along that links as defined in Eqn. 6.

$$Q_{ij} = \sum_k Y_{ijk} \tag{6}$$

In the model, it must be ensured that the inflows and outflows at each node in the network are balanced. This is ensured by Eqn. 7.

$$d_{od} X_{od\text{car}} = \sum_{(o,j) \in \mathcal{A}} Y_{ojd} - \sum_{(j,o) \in \mathcal{A}} Y_{jod} \tag{7}$$

Last, as the MobilityCoins scheme is a market-based system, Eqn. 8 resembles the market clearing condition. Here γ is amount of credits initially issued per traveler. In other words, the left-hand side of Eqn. 8 results into the total market volume of MobilityCoins. κ_{ij} is the MobilityCoins link charge for car travelers and λ_{odm} is a origin-destination mode-specific charge for all other travelers. The complementarity conditions ensures that the MobilityCoins market price P is only non-zero when supply and demand are balanced. If the market is over-supplied, the market price would be consequently zero.

$$\gamma \cdot \sum_{(o,d) \in \mathcal{OD}} d_{od} \geq \sum_{(i,j) \in \mathcal{A}} \kappa_{ij} Q_{ij} + \sum_{(o,d,m) \in \mathcal{OD}} \lambda_{odm} * d_{od} * X_{odm} \quad \perp \quad P \geq 0 \tag{8}$$

3 A CASE STUDY

To illustrative the primary transport and economic mechanisms of a MobilityCoins scheme, we apply the model developed in Section 2 to the simple network shown in Figure 1. The network has 17 nodes of which 13 are origin and destination nodes and four are through nodes, i.e., the demand entering or exiting the network at these nodes is 0. The network has directed arcs as shown in Figure 1.

This network is centered around node "9", while having symmetry with the line from nodes "2", "10", "9", "11", "7". The full list of network and demand parameters will be provided in the full paper, but network parameters and origin-destination matrix are similar to the values present in the familiar Sioux Falls network. We set the scale parameter in the mode choice to $\mu = 0.01$ and the origin-destination travel times τ_{odm} for public transport and bicycles as follows. First, we calculate the car free-flow travel times in the network shown in Figure 1. Second, we set the public

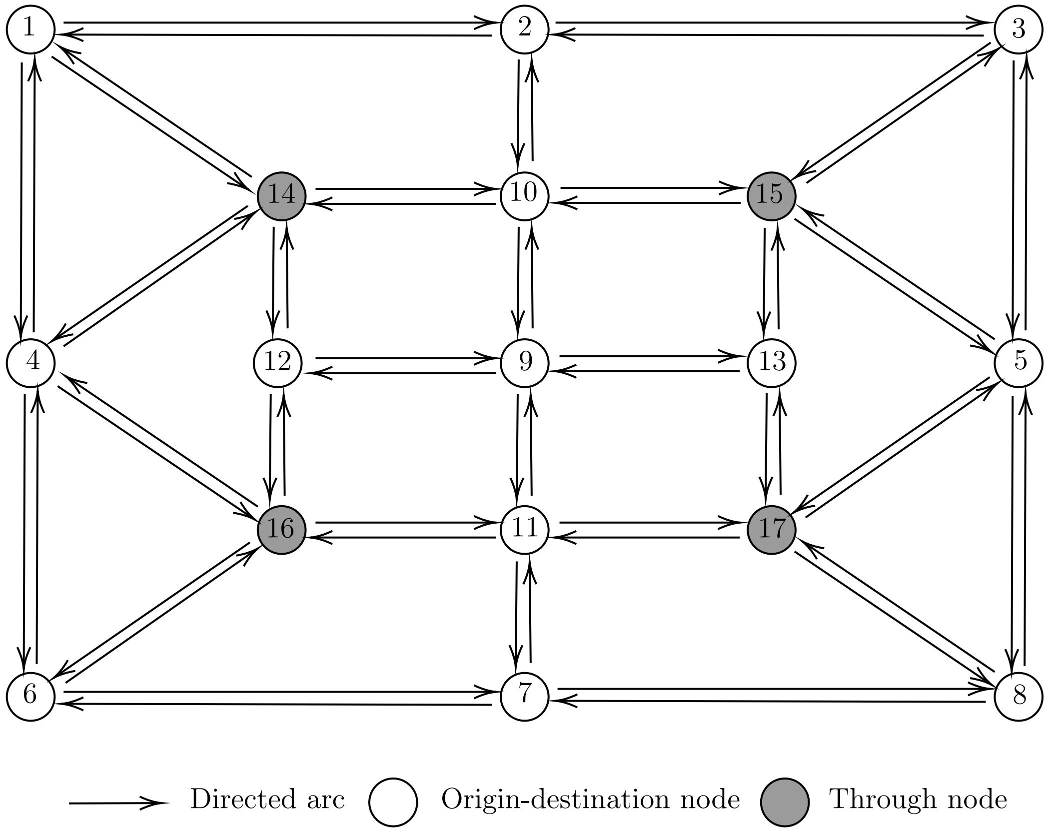

Figure 1: Case study network

transport travel times $\tau_{od,\text{pt}}$ on each origin-destination pair and the bicycle travel times $\tau_{od,\text{bicycle}}$ to a multiple of the car free-flow travel times. Third, we sample this multiplier for the public transport travel times from the uniform distribution in 1.35 to 1.45 and the bicycle travel times from the uniform distribution in 1.40 to 1.50.
In the case study, we define four scenarios. These are defined as follows.

S1 Computes the status-quo scenario without any pricing, i.e., $\gamma = 0$ and $P \equiv 0$.

S2 Imposes link charges for car travelers, i.e., $\kappa_{ij} \geq 0$, but no origin-destination specific charges for other modes of transport, i.e., $\lambda_{odm} = 0$. The charges κ_{ij} are set to 1.0 for $(i, j) \in \mathcal{N} \setminus \{9\}$ and 3.0 for $i \in \{9\} \vee j \in \{9\}$ to incentivize avoiding car travel in the inner zone of the network. The per-capita initial issue of MobilityCoins is evaluated at $\gamma \in \{1; 0.9; 0.8; 0.7; 0.6; 0.5\}$ to investigate transport outcomes when the overall budget of MobilityCoins is reduced. In other words, at the highest individual issue of MobilityCoins car travelers can travel one link outside the inner zone without acquiring additional MobilityCoins from the market.

S3 Impose link charges for car travelers, i.e., $\kappa_{ij} \geq 0$, and allow as an incentive negative origin-destination specific charges for other modes of transport, i.e., $\lambda_{odm} \leq 0$. The values for κ_{ij} and γ are taken from $S2$. λ_{odm} is set for bicycles to -0.25 on all origin-destination pairs and to 0 for all public transport origin-destination pairs.

S4 as a comparison we implement a congestion tax on all links from and to node “9”, i.e., fixing the product of $P \cdot \kappa_{ij}$. Considering the free-flow travel times o of around 100 time units, we set $P \cdot \kappa_{ij} \in \{100; 200; 300; 400\}$ as these values increase the travel costs on these links considerably. All other links receive a charge one third of charges on the links from and to node “9”.

The results are of the scenario analysis is presented in Section 4 along with their discussion.

Mode of transport	**Trips**		**Travel time**	
	Total	Share	Total (10e6)	Share
Car	84,409.6	27.5%	3.461	52.2%
Public transport	111,548.2	36.4%	1.624	24.0%
Bicycle	110,879.2	36.1%	1.676	24.8%
Total	306,837.0	100.0%	6.760	100.0%

Table 2: Trips and travel time in the status-quo scenario

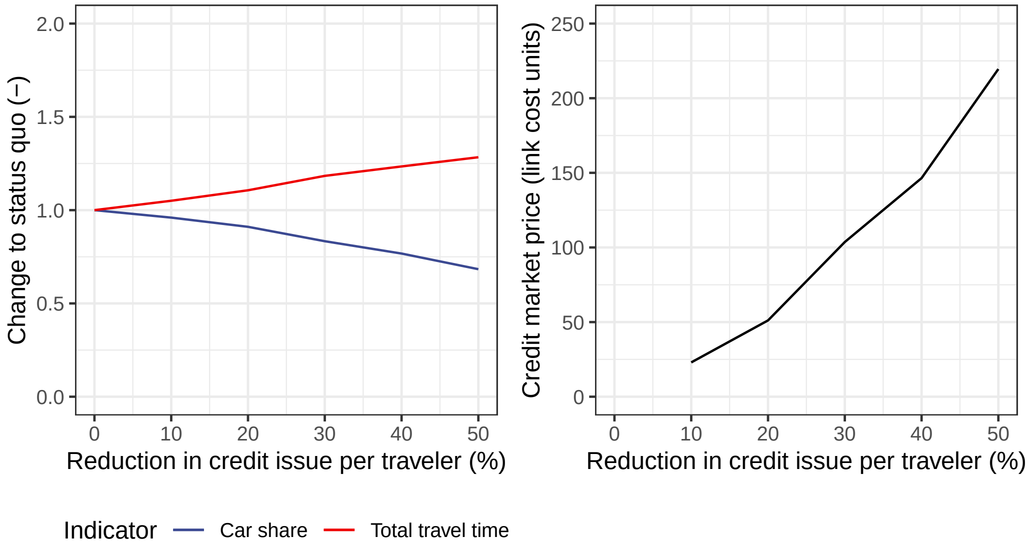

Figure 2: Changes of travel time, car share and credit price in a tradable credit scheme when the initial issue of credits is reduced.

4 FINDINGS

Scenario 1

The transport outcomes of status-quo scenario is summarized in Table 2. It can be seen that cars have the lowest modal share in terms of trips, but the highest in terms of travel time. This results from the congestion effects considered for this mode of transport. However, it is important to note here that the mode choice is only based on the origin-destination path costs, but does not consider trip length, number of transfers or any unobserved preferences that are usually impacting mode choice substantially (c.f. Ortúzar & Willumsen (2011); Train (2009)).

Scenario 2

In the second scenario, a conventional tradable credit scheme is implemented as described in Section 3. Figure 2 shows the results when the per-traveler issue of credits is gradually reduced from 1 credit to 0.5 credits. It can be clearly seen that when the overall market of credits is reduced by cutting down the initial issue, while leaving the parameter of the charging scheme $\kappa_i j$ unaltered, car use declines. In this particular example with slower alternative modes, the total travel time in the system increases. This modal shift is achieved by an increasing credit market price resulting from a limited supply. In the particular example, the market price increases the travel costs on the arcs considerably when compared to the free-flow travel time.

Scenario 3

In the third scenario, a MobilityCoin system is implemented as described in Section 3. Note that the difference to the tradable credit scheme in the second scenario is that MobilityCoins are also

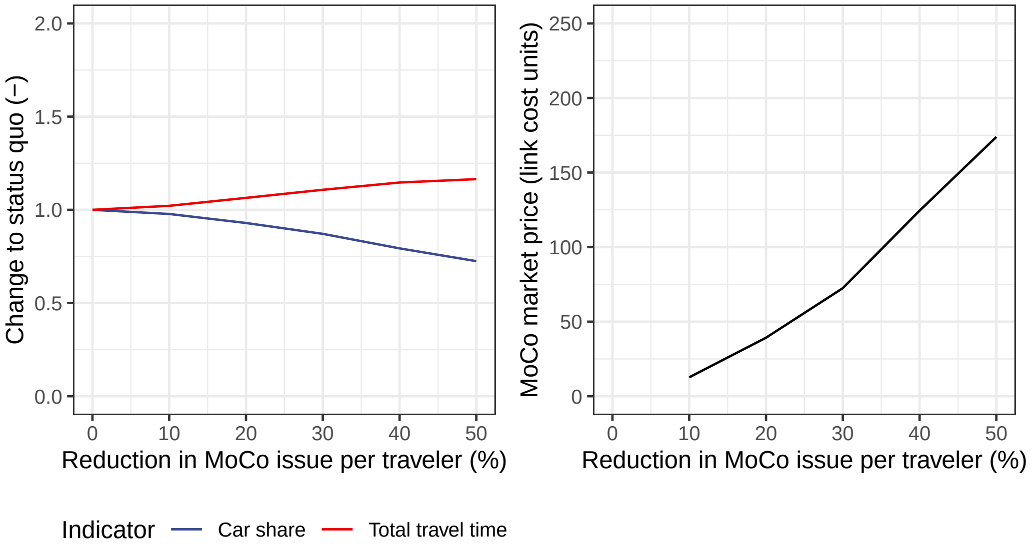

Figure 3: Changes of travel time, car share and the MobilityCoin (MoCo) market price in a MobilityCoins scheme when the initial issue of MobilityCoins is reduced.

used to incentive some mode choies, here the use of the bicycle. Figure 3 shows the results when the per-traveler issue of MobilityCoins is gradually reduced from 1 MobilityCoin to 0.5 MobilityCoins. A similar pattern is observed as for the common tradable credit scheme in Figure 2, but the changes to the transport outcomes compared to the status quo are not that strong. Arguably, using the bicycle generates additional MobilityCoins that are sold on the market; thus, the market volume is increased, leading to a lower market price compared to the second scenario and ultimately car use is not that strongly discouraged.

Scenario 4

In the fourth scenario, a conventional road user charging scheme with fixed charges is implemented as described in Section 3. Figure 4 shows the resulting impacts on the transportation system. Overall, a similar pattern as for the second (conventional TMC) and third scenario (MobilityCoins) is observed.

Comparison and discussion

The three different charging schemes presented in Scenario 2, 3 and 4 can be compared regarding their ability to reduce car trips (approximately related to the reduction in negative externalities) and the impact on travel times as a measure of impact on private costs. Figure 5 shows this comparison. First, it can be seen that the TMC scheme and conventional road user charging scheme (CC) with fixed charges perform similarly. This is perhaps surprising, but as shown in (de Palma et al., 2018) both schemes are equivalent when demand is fully adaptive as in this case study. Note that demand can fully adopt just based on travel costs and no multi-period constraints are considered. However, interestingly, we find that the MobilityCoin system achieves a similar reduction in car use (negative external costs) at lower travel time increases (private costs). This can be explained by the incentives provided to cyclists which adds more attractiveness to this mode in the mode choice. Nevertheless, this finding must be further corroborated with other system design parameter configurations and better behavioral parameters before making any generalization efforts.

5 DISCUSSION

The presented results underline the impacts a tradable mobility credit scheme, here MobilityCoins , has on transport outcomes. In particular, the scheme's benefit of reducing a desired quantity to

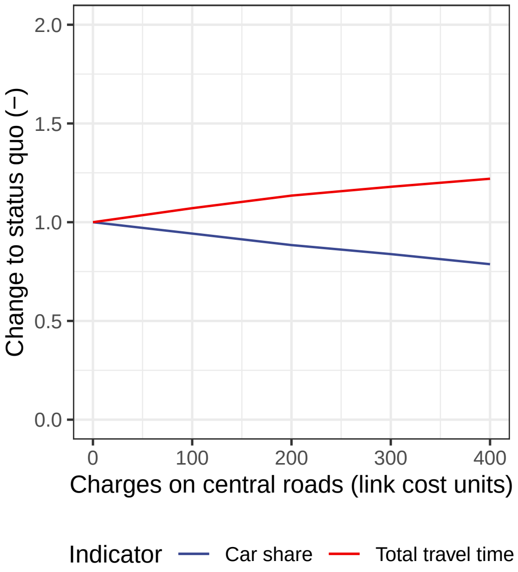

Figure 4: Changes of travel time and car share in a conventional road user charging scheme with fixed, but increasing charges.

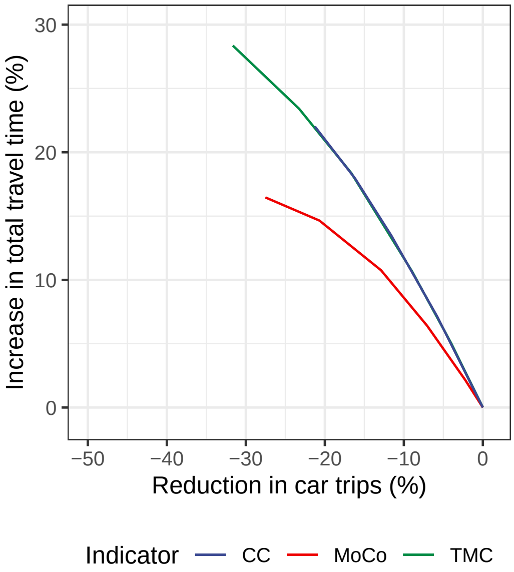

Figure 5: Comparing a conventional TMC scheme, a MobilityCoin scheme, and a conventional road user charging scheme (CC).

a target level, while providing direct financial incentives for travelers by direct transfers among themselves rather than redistributing tax revenue through a central organization. In addition, the provision of credits as an incentive, does not only increase trading activity and thus supports the market-based mechanism in general, but it seems to improve the economic allocation of resources by having more attractive alternatives.
Nevertheless, it is also apparent that a MobilityCoins or TMC scheme is not a simple system; it requires a careful policy design. Thus, for the identification of suitable policy designs future research has to start building models for real-world urban-scale cases for which appropriate choice parameters including unobserved preferences must be included (Train, 2009). In addition, the complex interactions of the key design parameters γ, κ_{ij}, λ_{odm} require the development of methods to identify those combinations - especially when considering the system's temporal evolution (Miralinaghi & Peeta, 2016) - that successfully and at little social costs lead to the desired targets. In addition, as will be an economic force in the decision making of individuals and firms, their impact on related fields like parking, housing and agglomeration should be focused on (Van Nieuwkoop et al., 2016; Loder et al., 2021; Venables, 2007).

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