

# MobilityCoins - an integrated multimodal Wardropian model

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## Abstract

MobilityCoins are a tradable mobility credit (TMC) system. They correspond to road user charges and are an alternative to existing schemes like congestion pricing and fuel taxes. Their design as a cap-and-trade scheme means that a fixed market volume is defined based on a to-be-regulated quantity, e.g., externalities. MobilityCoins are distributed to all travelers, who use these credits to pay for their mobility or sell them on a market to get additional income in case they own a surplus of them. In this paper, we develop an multimodal Wardropian transport model with integrated MobilityCoins scheme. Travelers have the choice between cars, public transport and bicycles, where the first experiences the usual congestion effects, the latter two have invariant origin-destination travel times. The TMC scheme has origin-destination-specific charges for all considered modes of transport and additionally link-specific charges for cars to accommodate the flexibility to react to congestion. Charges can be positive or negative in case incentives should be provided. 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, and in comparison to a conventional TMC scheme and road user charging scheme.

## 1 Introduction

It has been argued that “economists have had limited success in promoting economically efficient transportation and environmental externality policies” [1]. The state-of-the-art policies, if one may call 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” [2].

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 [3]. Here, Dales was one of the first proposing such a quantitative instrument to manage external costs using a cap-and-trade scheme [4]. In transport, such policy instrument based on tradable mobility credits (TMC) has been put forward by Verhoef et al. to regulate externalities [5], 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 [6] and to promote green energy deployment [7]. 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 [8] also in a multimodal context [9], compared its effectiveness to common road pricing [10], and studied user perceptions, the system’s acceptance and its feasibility [11, 12, 13]. 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 [14, 15]. In the following, we build on this particular implementation of a TMC scheme.

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.

Variables	Explanation
$P$	Tradable mobility credit market price
$X_{od}$	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 $j$
$\mu$	Mode choice scale parameter
$\gamma$	Initially issued credits per traveler
$\lambda_{odm}$	Origin-destination-specific MobilityCoins charges
$\kappa_{ij}$	Link-specific MobilityCoins charges
$\tau_{odm}$	Free-flow travel time between origin $o$ and destination $d$ using mode $m$
$t_{ij}^0$	Free-flow travel time on link $i$ - $j$
$c_{ij}$	Capacity on link $i$ - $j$
$\beta$	BPR function parameter
$n$	BPR function parameter

Table 1: Variables and parameters in the model

Travel times for public transport and bicycles are fixed, while car travel times incorporate congestion effects. The overall travel demand is distributed to modes using 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 [16]. The presented multimodal extension is a generalization of the seminal mathematical formulation presented by [8]. The model defined in the following is formulated as a mixed-complementarity problem (MCP) [17] and is implemented in GAMS [18]. 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  $\mu$ .

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

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  $\tau_{odm}$  and the origin-destination specific MobilityCoins charges  $\lambda_{odm}$  valued at the MobilityCoins market price  $P$ .

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

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  $\kappa_{ij}$  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 [19] with the usual parameters and is a function of link flow  $Q_{ij}$ .

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

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

$$C_{ij} = T_{ij} + P \cdot \kappa_{ij} \quad (4)$$

The arbitrage condition for car drivers to use link  $(i, j)$  follows the Wardropian user equilibrium [16]. 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  $k$ .

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

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.

$$Q_{ij} = \sum_k Y_{ijk} \quad (6)$$

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.

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

Last, as the MobilityCoins scheme is a market-based system, Eqn. 8 resembles the market clearing condition. Here  $\gamma$  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.  $\kappa_{ij}$  is the MobilityCoins link charge for car travelers and  $\lambda_{odm}$  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.

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

### 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 links in the network have the parameters listed in Table 2. We randomly generate an origin and destination matrix that is shown in Table 3. Nevertheless, the matrix can be adjusted, e.g., to accommodate the travel behavior in a monocentric city as the design of the network has the flexibility to describe such a situation as well.

We set the scale parameter in the mode choice to  $\mu = 0.01$  and the origin-destination travel times  $\tau_{odm}$  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 transport travel times  $\tau_{od,pt}$  on each origin-destination pair and the bicycle travel times  $\tau_{od,bicycle}$  to a multiple of the car free-flow travel times. Third, we sample this multiplier for the public transport travel times from the

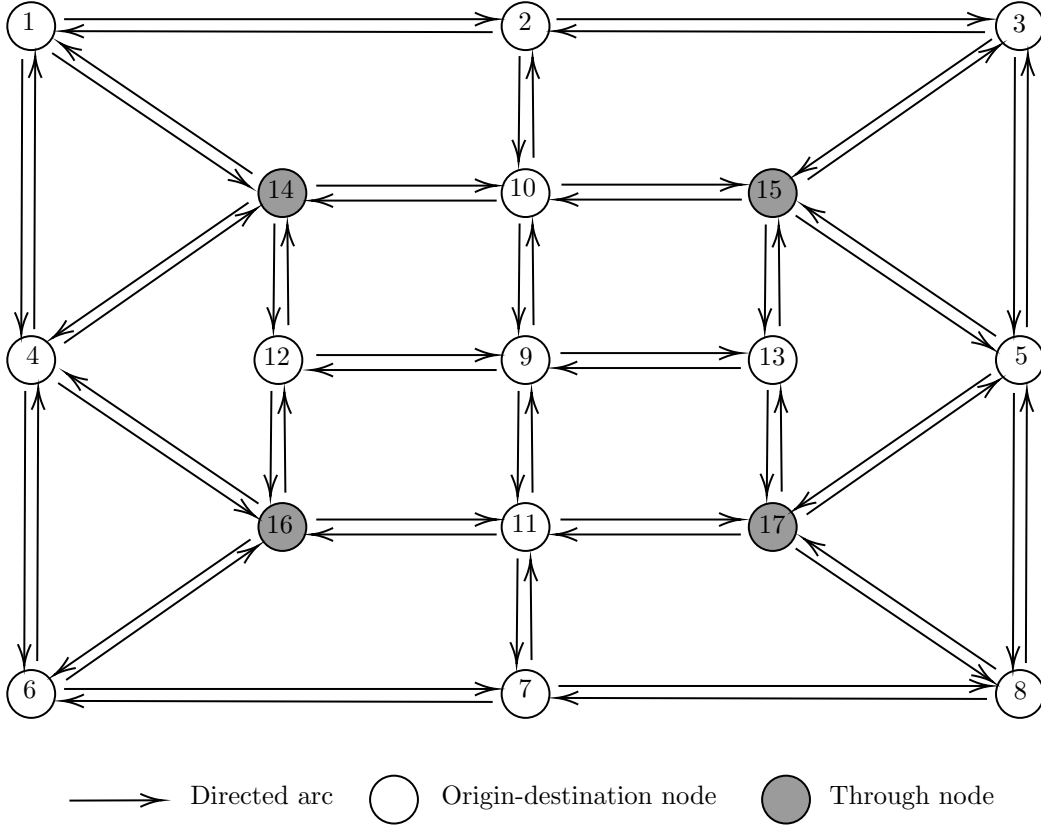


Figure 1: Case study network

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  $\kappa_{ij}$  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  $\kappa_{ij}$  and  $\gamma$  are taken from S2.  $\lambda_{odm}$  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 on these links as listed in Table 2 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 of the scenario analysis is presented in Section 4 along with their discussion.

## 4 Findings

### 4.1 Scenario 1

The transport outcomes of status-quo scenario is summarized in Table 4. 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

$i$	$j$	length	$t_{ij}^0$	$\beta$	$n$	$c_{ij}$
1	2	3000	240	0.15	4	1974
2	1	3000	240	0.15	4	2030
2	3	2900	232	0.15	4	1991
3	2	2900	232	0.15	4	2037
1	4	3100	248	0.15	4	2009
4	1	3100	248	0.15	4	2059
4	6	3000	240	0.15	4	2070
6	4	3000	240	0.15	4	1969
6	7	2900	232	0.15	4	2029
7	6	2900	232	0.15	4	1947
7	8	3100	248	0.15	4	1908
8	7	3100	248	0.15	4	1993
5	8	2900	232	0.15	4	1989
8	5	3100	248	0.15	4	2004
5	3	3000	240	0.15	4	1909
3	5	2900	232	0.15	4	1983
1	14	183	14.64	0.15	4	1731
14	1	255	20.4	0.15	4	1773
4	14	235	18.8	0.15	4	1879
14	4	279	22.32	0.15	4	1857
4	16	108	8.64	0.15	4	1876
16	6	187	14.96	0.15	4	1869
14	12	206	16.48	0.15	4	1783
12	14	113	9.04	0.15	4	1700
12	16	177	14.16	0.15	4	1899
16	12	218	17.44	0.15	4	1835
14	10	288	23.04	0.15	4	1892
10	14	218	17.44	0.15	4	1797
2	10	1498	98.05	0.15	4	4171
10	2	1501	98.25	0.15	4	3996
10	9	1474	96.48	0.15	4	4000
9	10	1519	99.43	0.15	4	3897
12	9	1550	101.45	0.15	4	3823
9	12	1462	95.70	0.15	4	4107
16	11	157	12.56	0.15	4	1713
11	16	176	14.08	0.15	4	1820
7	11	1487	97.33	0.15	4	3928
11	7	1512	98.97	0.15	4	3804
9	11	1504	98.44	0.15	4	3946
11	9	1550	101.45	0.15	4	3913
9	13	1455	95.24	0.15	4	4083
13	9	1549	101.39	0.15	4	3808
11	17	273	21.84	0.15	4	1862
17	11	143	11.44	0.15	4	1827
13	17	177	14.16	0.15	4	1776
17	13	252	20.16	0.15	4	1749
10	15	262	20.96	0.15	4	1814
15	10	238	19.04	0.15	4	1715
13	15	173	13.84	0.15	4	1875
15	13	251	20.08	0.15	4	1783
15	3	284	22.72	0.15	4	1720
3	15	183	14.64	0.15	4	1878
15	5	273	21.84	0.15	4	1865
5	15	240	19.2	0.15	4	1710
17	5	265	21.2	0.15	4	1871
5	17	243	19.44	0.15	4	1881
17	8	216	17.28	0.15	4	1847
8	17	260	20.8	0.15	4	1789

Table 2: Parameters of the network links shown in Figure 1.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0	1860	1404	2550	1506	2448	1104	1794	2754	1245	1740	1827	2490	0	0	0	0
2	1149	0	2406	2019	2346	918	1746	960	2034	2694	2430	2298	2145	0	0	0	0
3	1815	1743	0	2781	1365	2802	2832	1008	2556	1743	2370	2880	1194	0	0	0	0
4	2496	2250	1416	0	1743	2193	1050	2973	1989	2715	1170	1968	1761	0	0	0	0
5	1884	2601	2430	1830	0	2328	2433	2352	2088	1965	2109	2055	1293	0	0	0	0
6	2274	906	2553	2058	1038	0	1755	2160	2979	2088	987	2544	2451	0	0	0	0
7	2526	1248	1326	2643	1293	2193	0	1149	1671	2871	2943	993	1257	0	0	0	0
8	1110	2436	2565	1560	1515	2271	2364	0	1083	2028	2307	2934	1776	0	0	0	0
9	972	1530	1422	1479	1002	1557	2103	1494	0	951	2397	1401	1026	0	0	0	0
10	1953	1224	2091	2781	1212	2166	1203	2940	2448	0	1890	966	2730	0	0	0	0
11	1845	2094	1983	2271	1821	1446	2301	2691	2937	2283	0	2391	2631	0	0	0	0
12	1872	1653	2313	2121	1998	2700	2529	1608	2145	2973	1965	0	2484	0	0	0	0
13	1209	1371	1824	1578	2760	2271	1689	1371	1287	1869	2715	2997	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3: Origin and destination table for the case study

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 4: Trips and travel time in the status-quo scenario

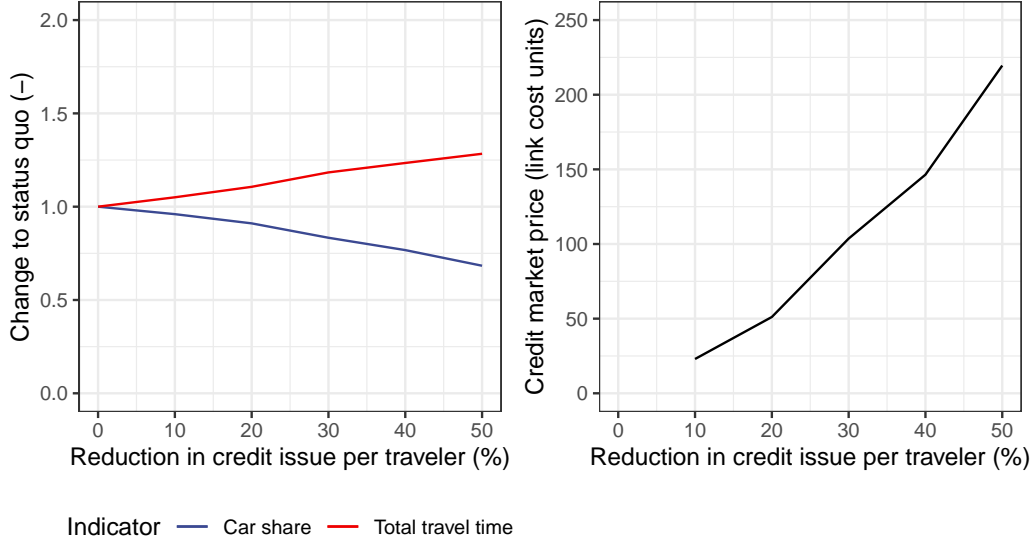


Figure 2: Changes of travel time, car share and credit price in a tradable credit scheme when the initial issue of credits is reduced.

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. [20, 21]).

## 4.2 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.

## 4.3 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 used to incentive some mode choices, 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.

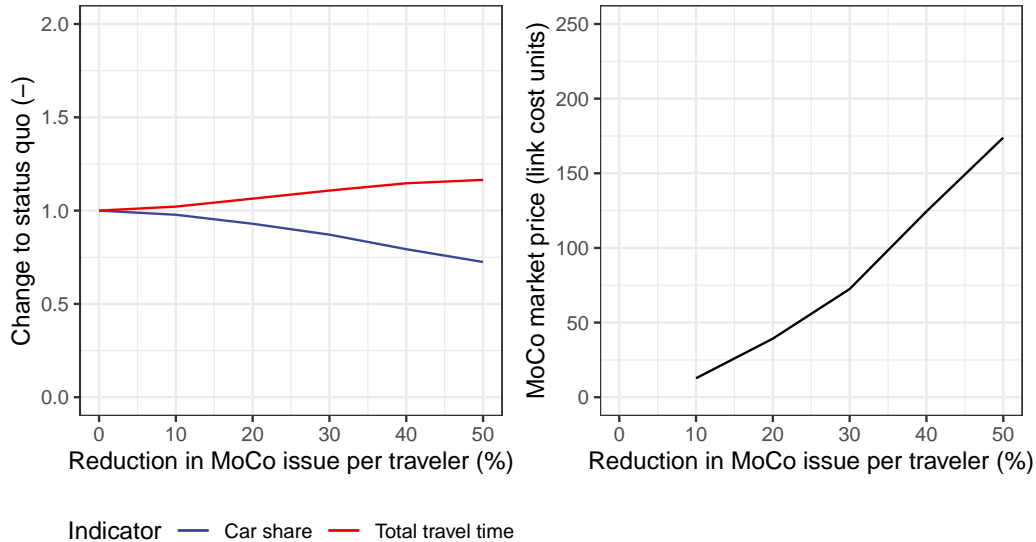


Figure 3: Changes of travel time, car share and the MobilityCoin (MoCo) market price in a MobilityCoins scheme when the initial issue of MobilityCoins is reduced.

#### 4.4 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.

#### 4.5 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 [10] 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 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 [21]. In addition, the complex interactions of the key design parameters  $\gamma$ ,  $\kappa_{ij}$ ,  $\lambda_{odm}$  require the development of methods to identify those combinations - especially when considering the system’s temporal evolution [22] -

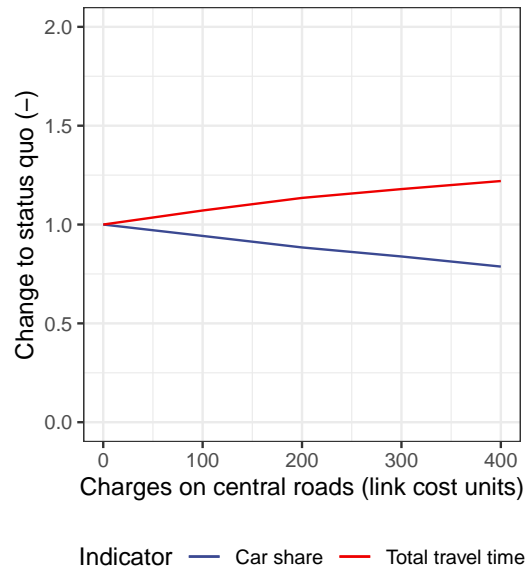


Figure 4: Changes of travel time and car share in a conventional road user charging scheme with fixed, but increasing charges.

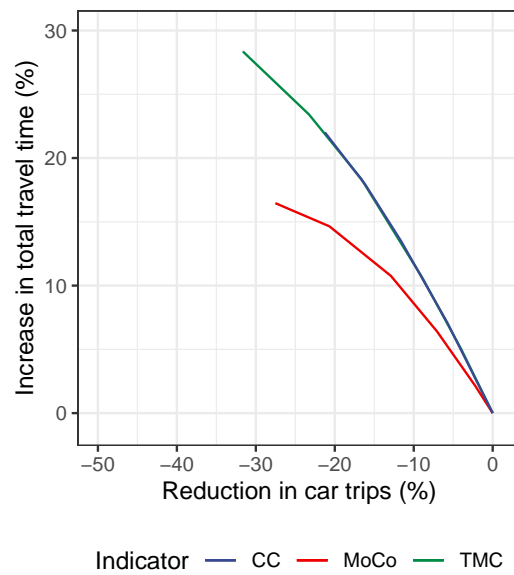


Figure 5: Comparing a conventional TMC scheme, a MobilityCoin scheme, and a conventional road user charging scheme (CC).



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 [23, 24, 25].

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