# MobilityCoins - Dynamics of a Multi-Modal, Multi-Period Tradable Credit Scheme for Munich

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## ABSTRACT

Tradable mobility credits have gained significant attention as a viable economic instrument for traffic and travel demand management. This paper introduces the MobilityCoin System, a novel scheme built on Tradable Credit Schemes (TCS), designed with three key features: (i) mobility, where credits are earned and spent based on travel behavior; (ii) trading, enabling the transfer of credits among users to enhance efficiency; and (iii) crowdfunding, facilitating the reinvestment of credits into transportation projects. A mode-choice logit model is constructed using stated-preference survey data from over 1000 users to assess the potential impacts of the MobilityCoin System on travel behavior. The model, which integrates traffic assignment and market-clearing mechanisms, is solved using a Mixed Complementarity Problem formulation. Our results provide a proof of concept for the MobilityCoin System, demonstrating its potential effects on market price and mode-specific demand, thereby indicating its feasibility as a practical tool for travel demand management. Navigating the complexity of multi-modal, multi-period network optimization is the pivotal challenge in calibrating and balancing the system, in search for a coherent interaction of parameters.



*Keywords*: tradable credit scheme; network optimization; multi-modal; multi-period

# INTRODUCTION

Transport sector requires economic instruments to achieve climate targets and limit traffic externalities. However, economists have had only limited success in promoting effective economic measures (*1*). Tradable credit schemes (TCS) are considered promising instruments. As cap-and-trade systems, they allow to set outcomes overall emission targets and people collectively distribute those resources efficiently. TCS, as they can be found in literature so far, cover mobility and market features. Those measures reflect short-term decisions by users. Either credits are used to fulfill mobility demands or are traded on the market to get another currency in return for a specific market price. Thus, TCS remain a traffic and travel demand management scheme so far (*2, 3*). The link of TCS to long-term decisions in the transportation system, e.g., infrastructure projects, has so far received little attention.

In this paper, we first provide a comprehensive overview of tradable credit schemes, setting the groundwork for understanding their function and significance in our research. We then delve into the heart of our approach, introducing the methodology and mathematical model behind our studies. This includes a thorough explanation of the charging scheme, the mode-choice model, and the traffic assignment model, all of which have been designed with a focus on market clearing. Following this, we discuss the data utilized in our study. The application of the methodology to the Munich transportation system is presented. Subsequently, we introduce and exhibit the various scenarios tested, each exploring different aspects of the system's operation. Finally, we engage in a critical discussion of the results, drawing conclusions from our findings and offering an outlook for future exploration.

# STATE OF THE ART

Based on the idea of TCS, first introduced by (*2*), we propose an extended generic policy instrument. Every user receives an initial credit budget at the beginning of each period which can be utilized in three main ways: mobility (demand), market (trading) and crowdfunding (supply). First, for mobility, credits can be used for a trip while charges depend on expected externalities. Second, instead of spending credits on mobility, they can be traded among users of the system. Due to the limited supply of credits, a market price is established that serves as an economic incentive to encourage the adoption of environmentally friendly, less expensive modes of transportation. Once users run out of credits, they have the choice to buy additional credits on the market, while users with a surplus in credits can monetize them. Third, credits can also be invested in supply-side measures defined by the agency to improve the travelers' generalized cost of travel, e.g. free flow speed improvements. The latter also gives users the opportunity to actively participate in the supply-side design, which can improve public support for such a policy tool (*4*)(*5*). Public acceptability of carbon pricing can be further improved through a tangible application and proper utilization of the revenues raised, e.g. for the crowdfunding of infrastructure (*6*). However, the idea of crowdfunding public infrastructure is not new and already present in the sustainable energy sector (*7, 8*). It has also been reported a few times in transport, e.g., public transport (*9*) or for bicycle infrastructure (*10*), but as yet it remains a niche.

## Tradable credit schemes

As mentioned before, the novel approach goes back to the idea of a tradable credit schemes (*11*). It is a cap-and-trade system for mobility, which originally refers to (*12*). (*2*) were the ones who originally suggested using tradable credits in road traffic management. In general, a distinction can be made between tradable credit schemes and mobility permit schemes. The former entails that qualified users receive an initial credit budget from which they pay the charges for any of their trips (*11*). The latter requires that travelers have to bid for or buy the necessary permits for a specific link (e.g. a bottleneck) within a specific time period (*13*). (*14*) was one of the first using tradable permits to control vehicle emissions, congestion and urban decentralization and (*3*) were the first to algebraically express tradable credit schemes in small transportation networks. In recent years, numerous methodologies with varying characteristics in terms of user heterogeneity, validity, or allocation emerged and were applied to various kinds of networks. While certain schemes permit the transfer of remaining credits to the upcoming period, the majority of schemes contemplate a smaller period of expiration. Above all, in theory, tradable credits proved successful in achieving a congestion reduction goal (*3*)(*15*), and could also help to meet climate targets (*16*). While describing it as a potential promising (theoretical) instrument, (*17*) highlight that a TCS for mobility is still far from applicable to our present mobility system. Incorporating the transportation supply side, (*18*) applies a TCS with steps to increase road capacity and (*19*) combined a TCS and link capacity improvement measures in a bi-objective bi-level model to compare economic growth and environmental management. (*20*) analyzed travel demand management for an autonomous vehicle enabled TCS and lane management strategies to reduce overall travel time under user equity constraints. (*21*) focuses on market design aspects such as allocation/expiration of credits, rules governing trading, transaction fees, and regulator intervention.

Every TCS system is targeting one or several objectives. It is not just congestion that is taken into consideration when determining the overall allocation and mobility pricing. In order to reduce greenhouse gas (GHG) emissions, the system can also be configured to influence emission externalities. (*22*) introduced market-based implementations for emissions standard attainment proposing origin-destination based pollution permits. (*23*) worked on a TCS system that redistributes link flow patterns to obtain minimum emissions for the whole network, and extend it to bi-objectives (low emissions and low travel times). (*24*) considered a vehicle type specific and OD-based credit allocation in a multi-period TCS framework. In addition, they suggested a pricing structure based on the type of vehicle (zero-emission versus internal combustion engine vehicles) and the links travelers are using linked to their vehicle type. The latter work encourages the use of zero-emission vehicles, while the former redistributes flows to achieve a dual goal of minimum emissions and minimum travel time.

## THE MOBILITYCOIN SYSTEM

This section introduces the MobilityCoin System. The MobilityCoin represents a novel and comprehensive system that aims to manage multi-modal urban transportation. It is based on a tradeable credit scheme and covers the entire trip, seeking to optimize the supply and demand side of mobility in metropolitan areas. The MobilityCoin is a holistic instrument for the transportation system. The two major innovations are the central agency's capability to offer incentives for single modes to catalyze mode-shift to greener modes. Additionally, the user has the option to spend parts of the budget for infrastructure improvements instead of using them solely for mobility or monetizing them. Latter enables user to crowdfund for improving supply side of the transportation system. Both innovations distinguish the MobilityCoin System from the initial concept of tradable credits. It is illustrated in fig. 1.

Every user of the MobilityCoin System is initially provided with a budget of MobilityCoins, illustrated in fig. 2. The decision-making process of the users usually begins with a pre-trip

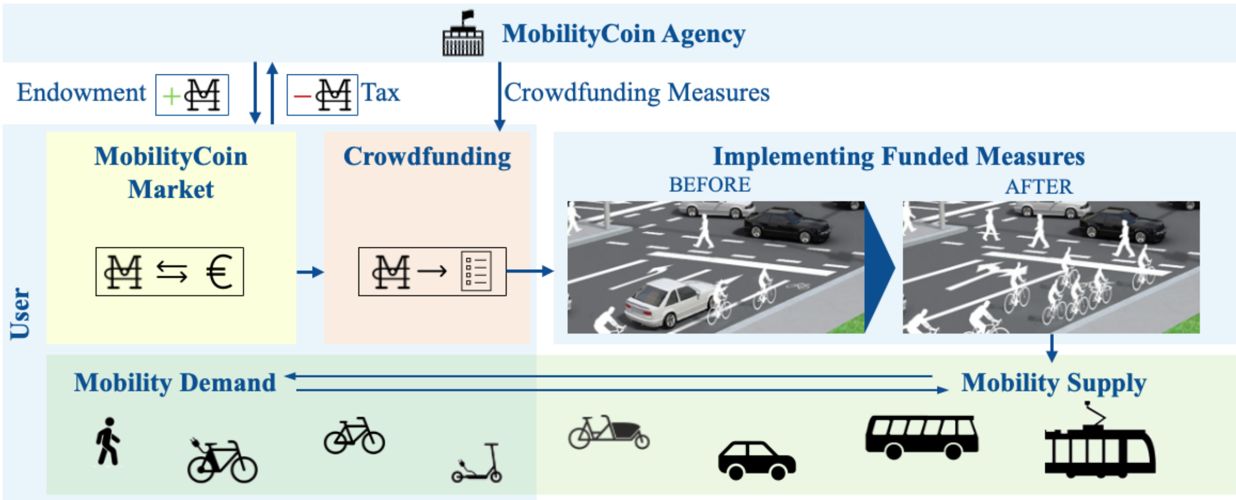


**FIGURE 1** : Major building blocks of the MobilityCoin System (*25*).

decision, which involves selecting the mode of transportation for the upcoming trip, deciding on the route and start-time window, and considering the trip costs. These can be positive or negative depending on strategic decisions of the agency and the externalities caused, such as GHG emissions or space consumption. A negative price indicates a payback, which serves as a strategic incentive for choosing greener modes. This encourages users to carefully (re-)consider their mode of transportation, switch to more eco-friendly routes, or adjust their departure times, all of which support the essential goal of the MobilityCoin System. Thus, the system aims to optimize the existing options rather than instigate fundamental transformation, subsequently aiming on effectiveness in the short term.

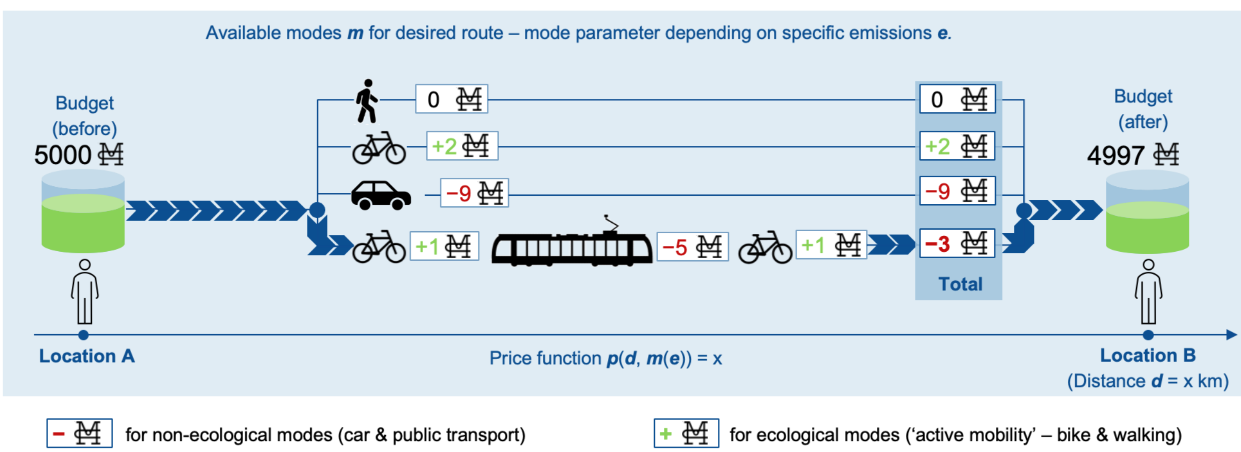


**FIGURE 2** : Mobility feature of the MobilityCoin System (*25*).

The MobilityCoin System suggests an initial coin allocation based on the following assumptions: The agency issues the coins through free allocation, and the total quantity is limited by an emission reduction target. The target can be derived via the TCS sizing methodology by (*26*). The decision to use free allocation is based on its potential to enhance the system's social acceptability and reduce its complexity (*27*). The individual coin allocation for each user is determined by personal attributes, such as health (e.g., an allocation bonus for mobility-impaired individuals), accessibility to public transport, and the balance between jobs and housing. Work-related trip frequency or necessity is not factored into the allocation process, as companies may receive specific coin budgets for their employees. Eligible recipients of the coin budget are individuals residing within the predetermined system borders (e.g., a metropolitan area) who are over 18 years of age. The budget is valid for a specific period, e.g., one year to align the system with other societal systems, such as insurance costs and tax declarations, and cannot be accumulated over consecutive years in order to reduce speculation. The budget expires after one year, and the allocation process begins anew. Users must use their coin budget to pay for the external costs of trips, following the polluter pays principle, using all eligible modes in the system, such as cars, public transport, bikes, and sharing services.

As aforementioned, the overall objective of the MobilityCoin System is the mitigation of GHG emissions in transport sector. Every additional feature to spend coins can be expended based on this framework, as long as the main target is secured. Thus, we will mainly focus on the mobility part of the MobilityCoin System, especially the balancing between charges and incentives. Within the following section, the essential examination involves studying the inter-dependencies between core parameters *initial allocation*, *coin charges, respectively incentives*, and *market price*, as well as the resulting demand shift. These factors collectively contribute to a dynamic ecosystem, where the interplay between them significantly impacts the overall efficiency, effectiveness and sustainability of the system. A comprehensive understanding of these relationships is crucial for optimizing the performance of the MobilityCoin System.

## A MATHEMATICAL MODEL FOR THE MOBILITYCOIN SYSTEM

To investigate and illustrate the fundamental behavior of the MobilityCoin System, we describe the system mathematically. Table 1 summaries the indices, parameters and variables. We use basic and well-known building blocks for establishing the linkage between traffic assignment and market behavior to demonstrate the scheme as a proof of concept. Originating from the model proposed by Yang and Wang (*3*), we formulate the MobilityCoin System as an equilibrium problem in mixed complementarity problem (MCP) representation (*28, 29*). This equilibrium problem is embedded into the modeling sequence shown in Figure to model the interactions between TCS and crowdfunding of the benefit gap of a proposed transport project. In the following, we discuss each building block before discussing the policy scenario.

### Charging scheme

The idea of the MobilityCoin System charging scheme is the internalisation of externalities, especially greenhouse gas emissions. A distance-based, mode-specific function computes the link charges per mode. Therefore, the mode-specific parameters out of fig. 3 are exploited.

The link price in MobilityCoins is calculated via eq. 1, the mode-specific coin charge $\kappa_{ijm}$ multiplied by the MobilityCoin market price $MP_{coin}$. While the coin charge comes from multiplying the link length $\delta_{ijm}$ by mode-specific externalities $e_m$, and coin-$CO_2$-ratio $r_{CO2}$ as shown in eq. 2.

$$p_{ijm} = \kappa_{ijm} * MP_{coin} \tag{1}$$

$$\kappa_{ijm} = \delta_{ij} * e_m * r_{CO2} \tag{2}$$

| Indices | Definition |
|---|---|
| $i,\ j,\ k$ | Node identifier |
| $m$ | Mode (car,bus,bike) |
| **Parameter** | **Definition** |
| $a_m,\ b_m$ | Mode-specific parameters of the BPR function. |
| $\beta_m$ | Mode-choice coefficients of modal attributes. |
| $\delta_{ij}$ | Link length from node $i$ to $j$. |
| $e_m$ | Mode specific externalities. |
| $I$ | Initial MobilityCoin endowment. |
| $K_{ijm}$ | Link capacity by mode $m$ from $i$ to $j$. |
| $\kappa_{ijm}$ | Basic coin charge by mode $m$ from node $i$ to $j$. |
| $OD_{jkm}$ | Demand by mode $m$ from node $j$ to $k$. |
| $p_{ijm}$ | Link price by mode $m$ from node $i$ to $j$ in coins. |
| $r_{C}O2$ | Coin-$CO_2$-ratio. |
| $t_{ijm}$ | Free flow travel time by mode $m$ from node $i$ to $j$. |
| **Variable** | **Definition** |
| $U_{ijm}$ | Utility by mode $m$ from $i$ to $j$. |
| $T_{ijm}$ | Travel time by mode $m$ from $i$ to $j$. |
| $C_{ijm}$ | Travel costs by mode $m$ from $i$ to $j$. |
| $MC_{ijm}$ | Minimum path costs by mode $m$ from $i$ to $j$. |
| $Q_{ijm}$ | Link flow by mode $m$ from $i$ to $j$. |
| $Y_{ijkm}$ | Link flow by mode $m$ from $i$ via $j$ to destination $k$. |
| $MP_{coin}$ | MobilityCoin market price. |

**TABLE 1** : Mode-choice model parameters.

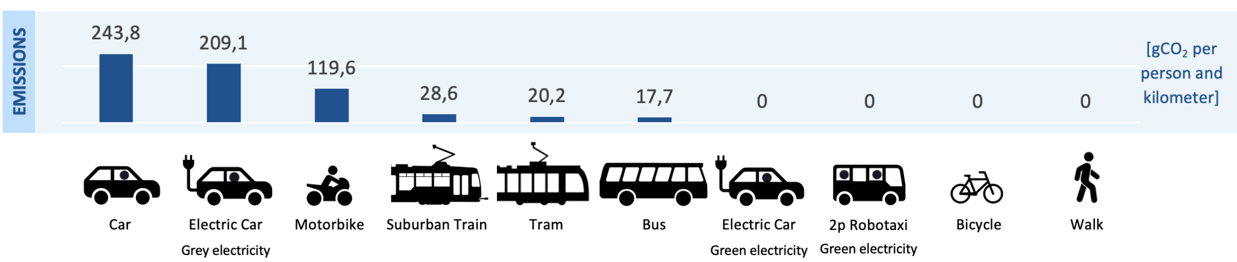


**FIGURE 3** : Specific emissions for different modes of transport (*30*).

**Mode-choice model**

The mode-choice model is derived out of a stated-preference survey conducted at the chair of traffic engineering and control at Technical University (TU) Munich with a sample size of n = 1249 individuals between 18 and 80 years of age. The stated preferences are statistically linked to the scenarios and analyzed using a multinomial logit modal to estimate parameters that give the relative importance of different factors in influencing mode choice (*31*).

The logit mode-choice model applied in this paper focuses mainly on travel time and Mo-

| Parameter | Value |
|---|---|
| $\beta_{0pt}$ | 0.00000 |
| $\beta_{0c}$ | 0.52233 |
| $\beta_{0b}$ | 0.30734 |
| $\beta_{pt}^{tt}$ | −0.03438 |
| $\beta_{c}^{tt}$ | −0.03394 |
| $\beta_{b}^{tt}$ | −0.03955 |
| $\varepsilon^{\mathrm{tt}}$ | −0.21299 |
| $\beta^{\mathrm{moco\_gain}}$ | 0.27266 |
| $\varepsilon^{\mathrm{moco\_gain}}$ | −0.27137 |
| $\beta_m^{moco\_loss}$ | −0.02988 |
| $\varepsilon^{moco\_loss}$ | −0.70737 |
| $\delta^{\mathrm{mean}}$ | 7.25634 |
| $\Phi^{\mathrm{nomoco}}$ | 1.000 |
| $\Phi^{\mathrm{moco}}$ | 0.85716 |

**TABLE 2** : Model indices, parameters and variables.

bilityCoin gain and loss aversion. Thus, two utility functions are derived. Eq. 3 shows the utility for car and bus mode which consume MobilityCoins, and eq. 4 that reflects bike incentives and as a result a gain in coins. Both utility functions take the link prices into account, which implies that the market prices are reflected as well, as mentioned before in eq. 1.

$$\mathrm{U_{ijm}} = \Phi^{moco} \cdot \left(\beta_{0m} + \mathrm{t}_{ijm} \cdot \left(\beta_m^{tt} \cdot \left(\frac{\delta_{ij}}{\delta^{mean}}\right)^{\varepsilon^{tt}}\right) + p_{ijm} \cdot \left(\beta_m^{moco\_loss} \cdot \left(\frac{\delta_{ij}}{\delta_{mean}}\right)^{\varepsilon^{moco\_loss}}\right)\right) \tag{3}$$

$$\mathrm{U_{ijm}} = \Phi^{moco} \cdot \left(\beta_{0b} + \mathrm{t}_{ijm} \cdot \left(\beta_b^{tt} \cdot \left(\frac{\delta_{ij}}{\delta^{mean}}\right)^{\varepsilon^{tt}}\right) + p_{ijb} \cdot \left(\beta_b^{moco\_gain} \cdot \left(\frac{\delta_{ij}}{\delta_{mean}}\right)^{\varepsilon^{moco\_gain}}\right)\right) \tag{4}$$

The mode-related demand coming from the Munich Visum model is summarized, creating a total demand pool. Overall demand is then distributed across modes based on the logit model. In the first run, the mode specific utilities are expressed as deterministic components of a parameter function of modal attributes of travel time $t_{\mathrm{ijm}}$. After introducing the coin system, the utility function gets extended by the mode specific link prices, respectively incentives $p_{\mathrm{ijm}}$. After the first run the MobilityCoin market price is taken into consideration as well. The choice probabilities are established through a maximum-likelihood estimation in a logit-modeling framework, assuming that users are aware about the coin charges and market price a priori (*32*).

Following the generic utility function 3, 4 and probability function 5, the OD-pair values for each mode are computed. Altogether we get mode specific utilities $\mathrm{U_{ijm}}$ for each OD-pair $i, j$. For the utility function, the coefficients of modal attributes $\beta$ are shown in tab. 2

$$P_{\mathrm{ijm}} = \frac{e^{U_{\mathrm{ijm}}}}{e^{U_{\mathrm{ij,car}}} + e^{U_{\mathrm{ij,,bus}}} + e^{U_{\mathrm{ij,bike}}}} \tag{5}$$

### Traffic assignment with MobilityCoin market clearing condition

The traffic assignment module of the model refers to the algebraic TCS description of (*3*). The BPR function 9 is applied as volume delay function for the means of transport car. Bus and bike mode is not affected by congestion. The user equilibrium (UE) is described and computed as a link-flow mixed complementarity problem (MCP) (*28*, *29*, *33*). The governing Equation is Wardrop's condition for the user equilibrium (*34*) shown in Equation 6. On the left hand side of Equation 6 we have the sum of the travel costs $C_{\text{ijm}}$ starting at node $i$ to any adjacent nodes $j$ and the minimal costs $MC_{\text{jkm}}$ for travelling from any adjacent node $j$ to destination node $k$ with mode $m$ that should be greater than or equal to the minimal costs $MC_{\text{ikm}}$ travelling from node $i$ to node $k$. The non-negative flow variable $Y_{\text{ijkm}}$ is associated to this time minimization equation and is only positive for those neighboring nodes where the generalized costs are minimal.

$$C_{\text{ijm}} + MC_{\text{jkm}} \geq MC_{\text{ikm}} \perp Y_{\text{ijkm}} \tag{6}$$

For the number of agents travelling from every node $j$ to a destination $k$ is given by the flow conservation on the left side of Equation 7. This equation is associated with the minimal costs variable $MC_{\text{jkm}}$.

$$\sum Y_{\text{ijkm}} - \sum Y_{\text{jikm}} = OD_{\text{jkm}} \perp MC_{\text{jkm}} \tag{7}$$

We add a third condition to the MCP for integrating the MobilityCoin Market in the traffic assignment module. Therefore, we first have to add the MobilityCoin trip charge $p_{ijm}$ and market price $MP_{\text{coin}}$ to the generalized travel costs, as shown in Equation 8.

$$C_{\text{ijm}} = T_{\text{ijm}} + p_{\text{ijm}} * MP_{\text{coin}} \tag{8}$$

The travel times $T_{ijm}$ are defined according to the BPR function as shown in Equation 9.

$$T_{ijm} = t_{ijm}\left(1 + b_m\left(\frac{Q_{ijm}}{K_{ijm}}\right)^{a_m}\right) \tag{9}$$

Subsequently, we associate the market clearing condition shown in Equation 10 with the market price which is only positive if and only if all coins of the initial endowment $I$ as well as bike incentives - reflected in negative prices $p_{ijm}$ - are charged for mobility purposes by using all three modes, while $p_{ijm}$ is positive for MIT and PT and negative for cycling, since it generates coins. In Equation 10, $\mathscr{A}$ defines the set of arcs in the network.

$$I - \left(\sum_{ij \in \mathscr{A}} Q_{\text{ijm}} * p_{\text{ijm}}\right) = 0 \perp MP_{\text{coin}} \tag{10}$$

## DATA: MULTI-MODAL NETWORK OF THE CITY OF MUNICH

Prior to introducing the assumed policy scenario, we give an overview about the underlying data. We use a sub-network of the Transportation Model of the City of Munich.

The Munich network consists of 91 links connecting 41 nodes as shown in fig. 4. The *Landeshauptstadt München Mobilitätsreferat* serves as the primary, official network source for our transportation data. It provides information regarding supply side of various modes of transport. Respective data for cars, buses, and bikes are incorporated in the model, covering link-specific specifications and characteristics of the network layout, as well as capacities associated with these modes of transport. Additionally, it also offers data representing the demand side of the transporta-

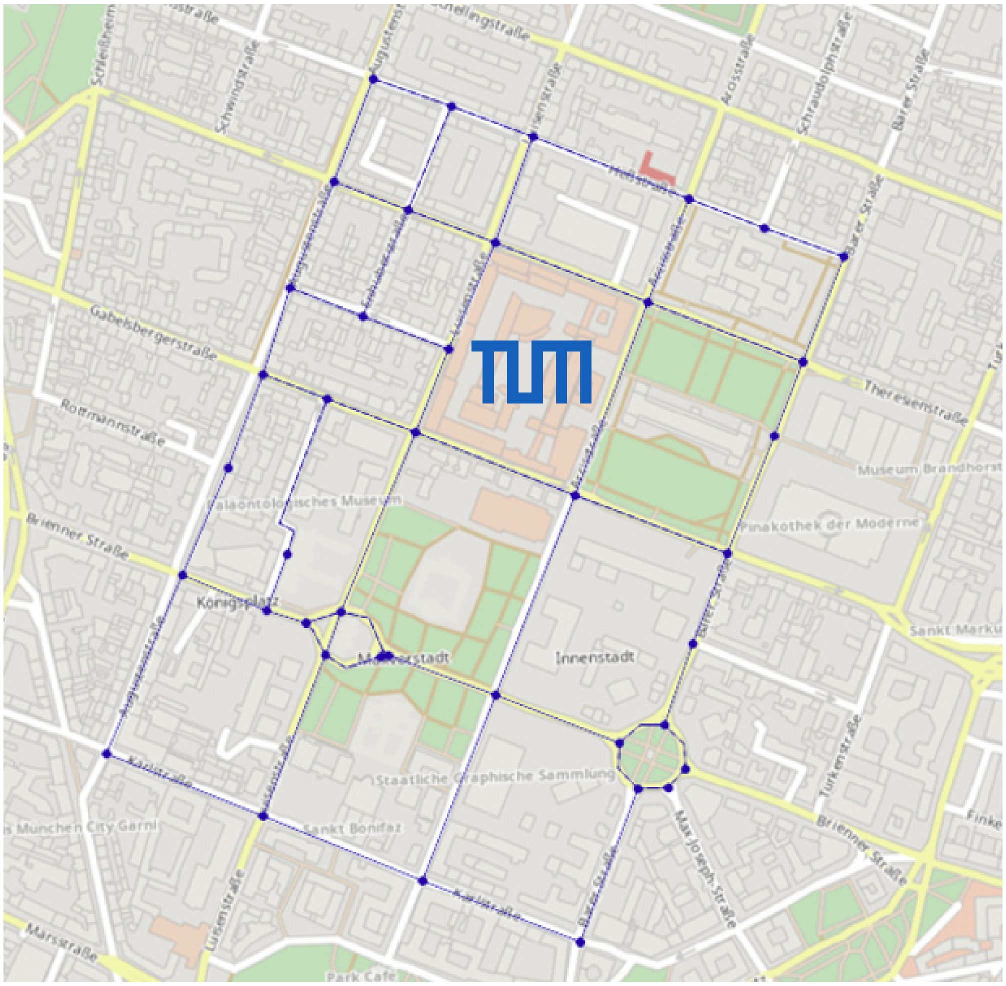


**FIGURE 4** : Munich network with 41 nodes and 91 links.

tion network. Containing origin-destination matrices for the same modes of transport, including transit, and through traffic, which are an essential source for understanding the traffic flow within the network and setting the MobilityCoin baseline.

The model comes as PTV Visum files, is processed, involving data extraction from PTV Visum, data cleaning, and finally reformatting in order to make it utilizable for the MCP. PTV Visum traffic assignment link flows are used for calibrating the MCP, first without MobilityCoin System. Following calibration of the model, it is further expended by the MobilityCoin System, enhancing its precision and applicability in diverse mobility scenarios. The MCP is computed and solved in Julia using PATHSolver and complementarity packages (*35*–*37*).

On the supply side, we set the parameters for the BPR functions of buses and bicycles as shown in Table 3, while using the BPR function parameters as provided in (*38*). We make the simplifying assumption that all modes use the same network, while not interfering each other, i.e., the volume-delay functions are separated.

In fig. 5 one can see the model building blocks and respective inter-dependencies. On the right-hand side, the computed results of each building block are indicated.

| Indices | Definition |
|---|---|
| $b_{car} = 0.15$ | B parameter for mode car. |
| $a_{car} = 4$ | Power of BPR function for mode car. |
| $b_{bus} = b_{bike} = 0$ | B parameter for modes bus and bike. |
| $a_{bus} = a_{bike} = 1$ | Power of BPR function for mode bus and bike. |
| $v_{bus} = 25$ [km/h] | Constant travelling velocity for bus. |
| $v_{wbus} = 6$ [km/h] | Constant walking velocity to bus stop. |
| $v_{bike} = 10$ [km/h] | Constant travelling velocity for bike. |

**TABLE 3** : Model indices, parameters and variables.

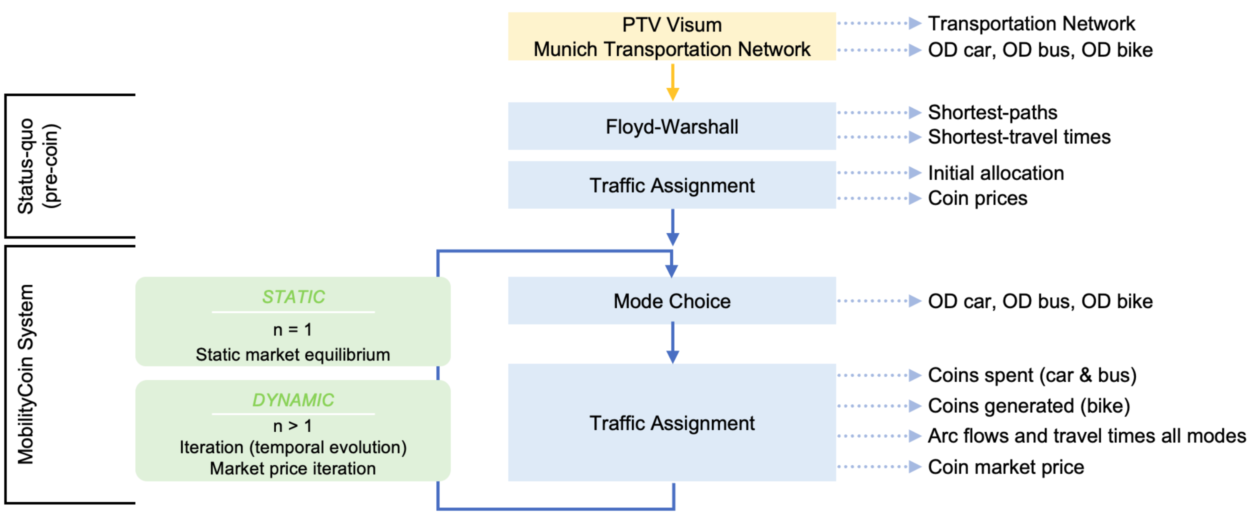


**FIGURE 5** : Building blocks of macroscopic model.

**Results for Munich MobilityCoin Scenarios**

The computed scenarios can be allocated in two major buckets. First, a *static* calculation of equilibria for varying parameters 'initial allocation', 'MobilityCoin costs per externality', and 'incentives for cycling'. In the static environment, the market price stems from a single MCP assignment and is set to $MP_{coin} = 1$ after each iteration. Second, a *dynamic* computation for mimicking temporal evolution of the MobilityCoin System under changing market prices, resulting from the MCP equilibria. This means, the market price is carried on and each loop builds on the $MP_{coin}$ results of the previous loop. That illustrates potential periodic temporal evolution starting from status-quo and developing over time. The scenarios are visualized in fig. 6.

*Scenario 'S1' (static): Increasing incentives for cycling*

Fig. 7 illustrates the variations in market price (represented on the z-coordinate) in response to adjustments in initial coin allocation (x-coordinate) and biking incentives (y-coordinate) for the static case. An observation of the slope suggests a significant role played by bike incentives in stabilizing the market. As the bike incentives are increased, a notable decrease in the slope is observed. This implies that these incentives, by driving a shift in travel behavior, can effectively dampen market volatility and support a more stable equilibrium in the market dynamics.

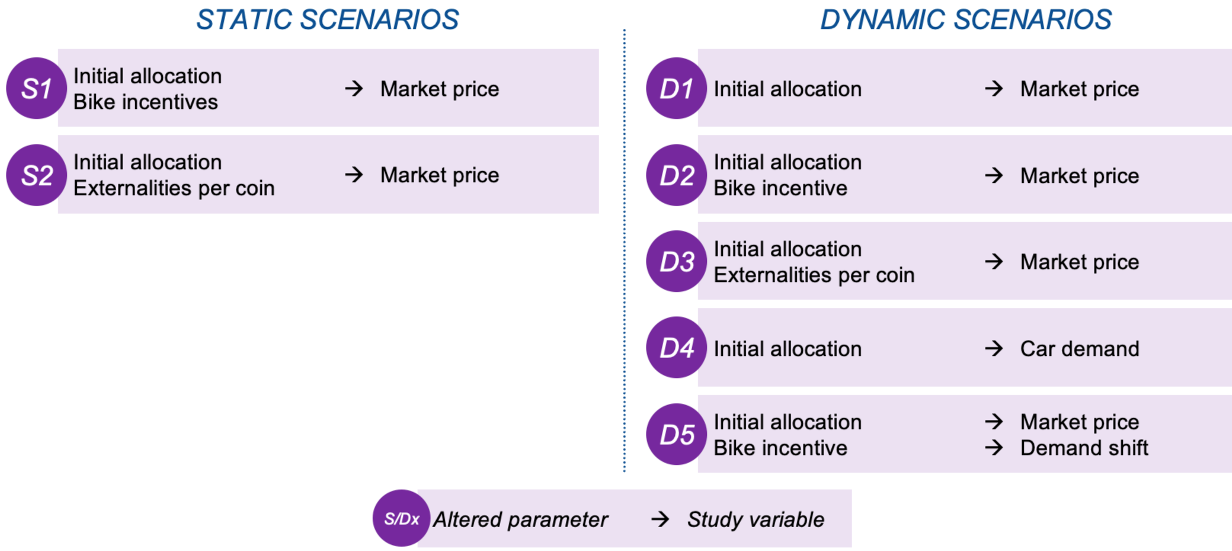


**FIGURE 6 :** Assessed scenarios.

*Scenario 'S2' (static): Rising strictness in MobilityCoin costs per externality*
A quantitative evaluation of greenhouse-gas emission targets shows that there are several feasible run-ups in MobilityCoin costs per $gCO_2e$ that lead to the desired outcome agreed by the Paris Climate Agreement (*26*). One is shown in table 4.

| Year | Costs per $gCO_2e$ in MobilityCoins |
|---|---|
| 2022 | 0.039830 |
| 2023 | 0.039852 |
| 2024 | 0.039875 |
| 2025 | 0.039897 |
| 2026 | 0,039919 |
| 2027 | 0,039941 |
| 2028 | 0,039964 |
| 2029 | 0,039986 |
| 2030 | 0.040008 |

**TABLE 4 :** Development in MobilityCoin costs from 2022 until 2030.

In the following graph, fig. 8, we represent the market price as the z-coordinate, plotted against the initial coin allocation (x-coordinate) and the coin externality ratio (y-coordinate). As the diagram makes visually evident, there exists a threshold region within which the slope experiences a rapid increase. This noticeable change in the slope within this region provides a valuable indication of the interactions and dependencies among market price, initial coin allocation, and the coin externality ratio. Through such a visual representation, the complex dynamics of our system become more tangible, aiding further interpretation and analysis of the model's behavior.

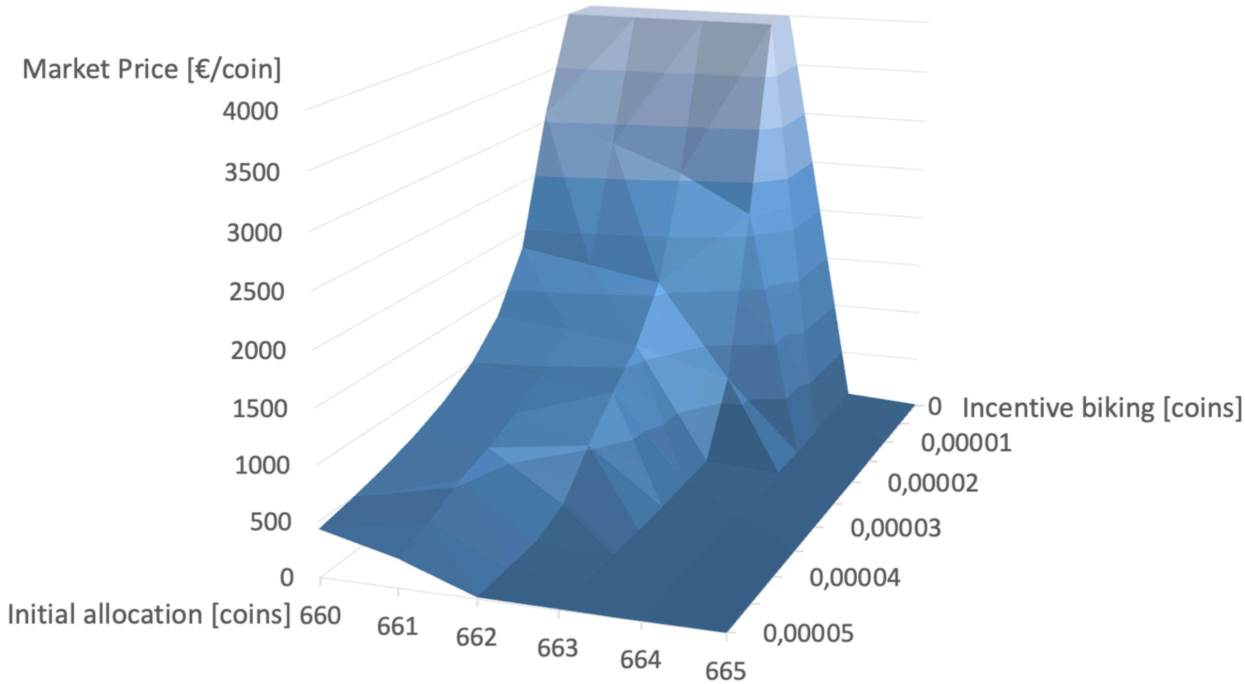


**FIGURE 7** : S1: Increasing incentives for cycling.

*Scenario 'D1' (dynamic): Altered initial allocation and effects on market price*

This study presents an iterative exploration of varying coin allocations to assess their impact on the market dynamics. The market price exhibits a sustained carryover from one iteration to the next, a consistency underlining the robustness of the model. However, the data distinctly confines a 'border' separating the areas of divergence and convergence. This border essentially represents the threshold determining whether the demand can be satisfied or not. Consequently, it alternates between high market prices, observed when demand outstrips supply, and zero, indicating a state of equilibrium when the supply matches demand. These findings offer valuable insights into the nature of market dynamics under different coin allocation scenarios.

*Scenario 'D2' (dynamic): Altered initial allocation and rising bike incentives with effects on market price*

As illustrated in the dynamic case presented in fig. 10, the market price continues to fluctuate amidst the gradual increase in biking incentives. Areas of divergence and convergence in the data trends remain clearly distinguishable despite these variations. The application of bike incentives plays a crucial role in this context, serving as a stabilizing factor for market prices from one iteration to the next. This highlights the pivotal role such incentives can have in modulating market dynamics, emphasizing their potential effectiveness as a tool in transportation policy.

*Scenario 'D3' (dynamic): Altered initial allocation and externalities per coin with effects on market price*

Contrary to the case of increasing bike incentives, when the value of a coin in terms of externalities is reduced, a stabilizing effect on the market dynamics is not observed. Specifically, when the value of a coin, as represented by its equivalent in reduced grams of CO2 emissions ($gCO_2e$), is di-

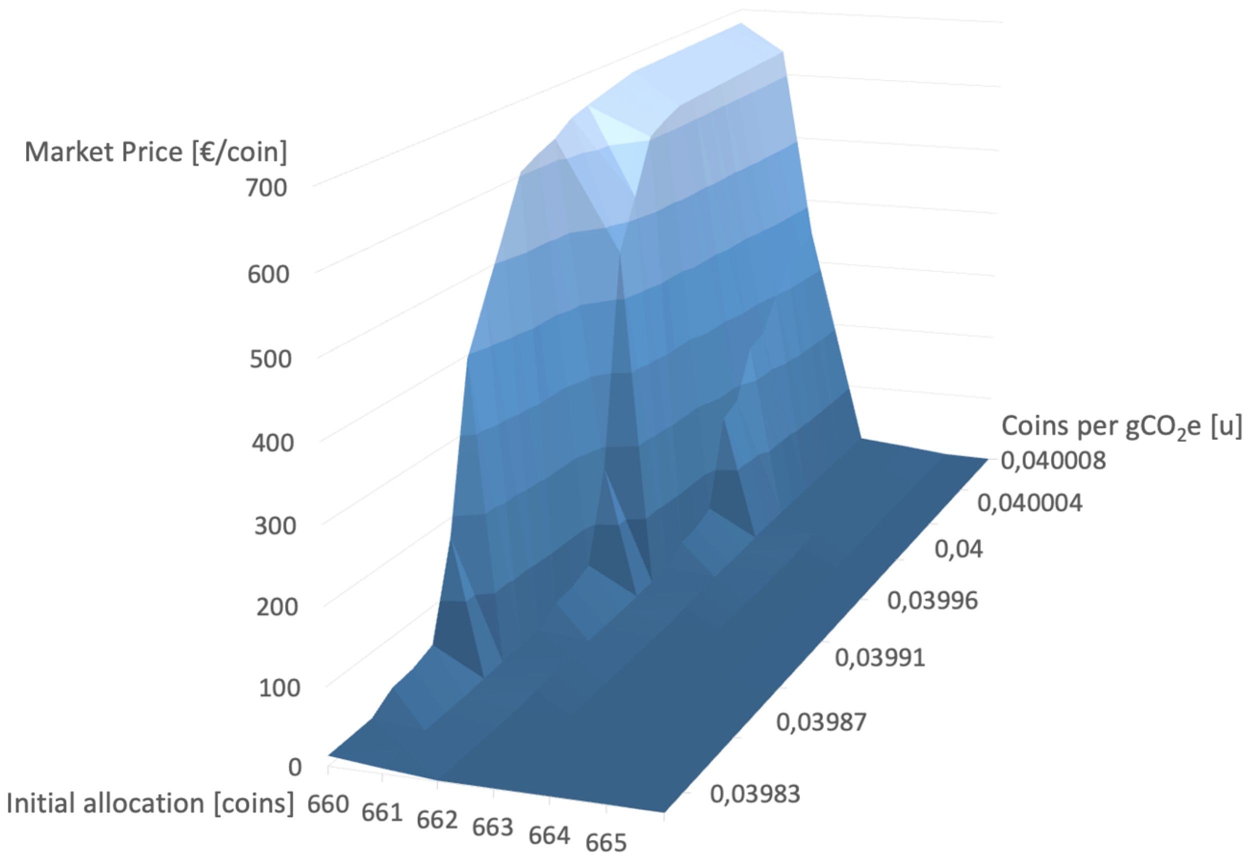


**FIGURE 8** : S2: Decreasing value of coins per $gCO_2e$.

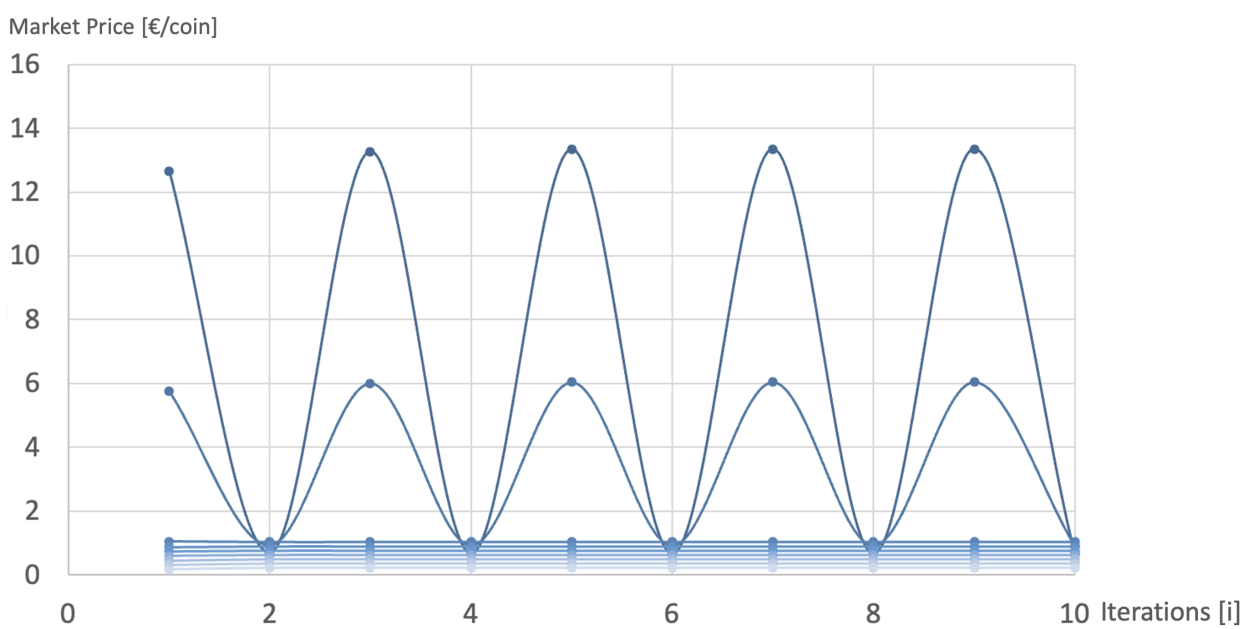


**FIGURE 9** : D1: Market price under altered initial allocation.

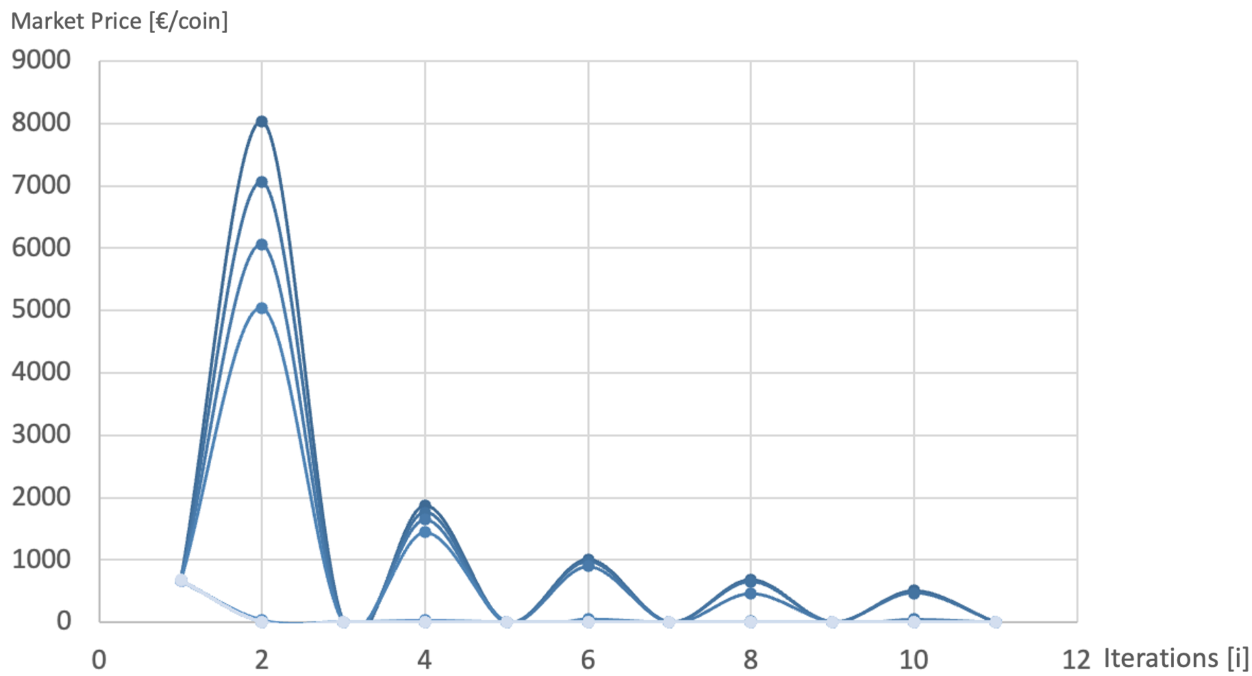


**FIGURE 10** : D2: Market price under increasing bike incentive.

minished, it leads to an unstable market price and produces varied outcomes. Basically, decreasing the value of a coin can be related to a reduction in the number of coins in circulation. This change facilitates a shift in mode-choice, resulting in a more volatile market price. The insights from this analysis underscore the importance of maintaining a robust coin value and a fair balance between incentives and charges to ensure market stability.

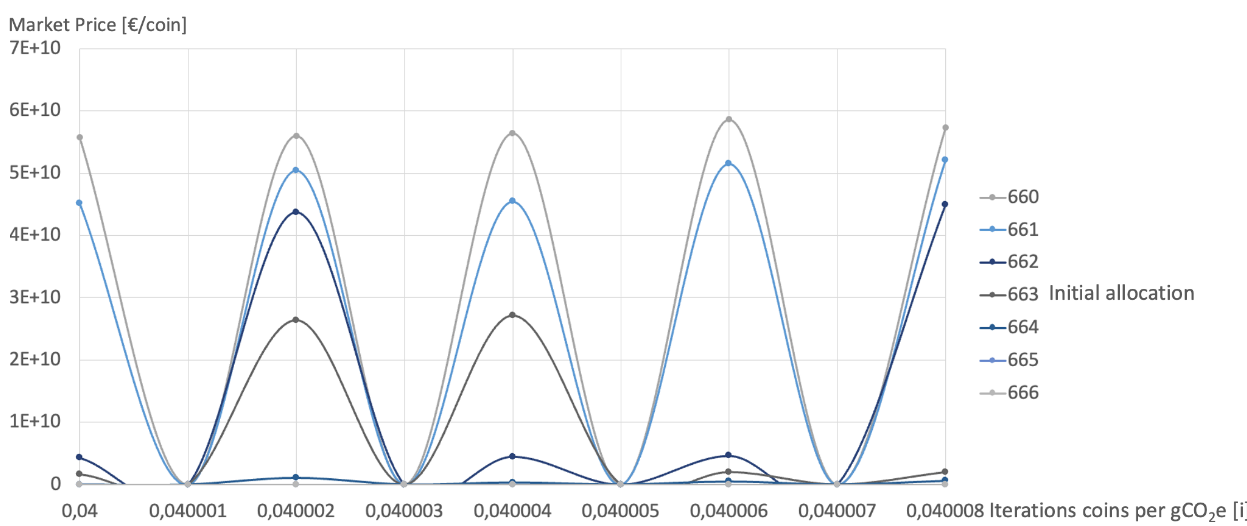


**FIGURE 11** : D3: Increasing MobilityCoin price per externality caused.

*Scenario 'D4' (dynamic): Temporal evolution of car demand under changing initial allocation*
The analysis reveals a distinct stabilizing effect on car demand brought about all alterations in initial coin allocation, with this effect becoming evident after just two iterations. Another finding is that a higher amount of allocated coins drive agents towards a more intensified use of the car mode. This suggests that the number of coins initially allocated to an agent could be a significant determinant of their choice of transportation mode, underlining the importance of a carefully considered strategy for initial coin allocation in efforts to influence sustainable transportation behavior.

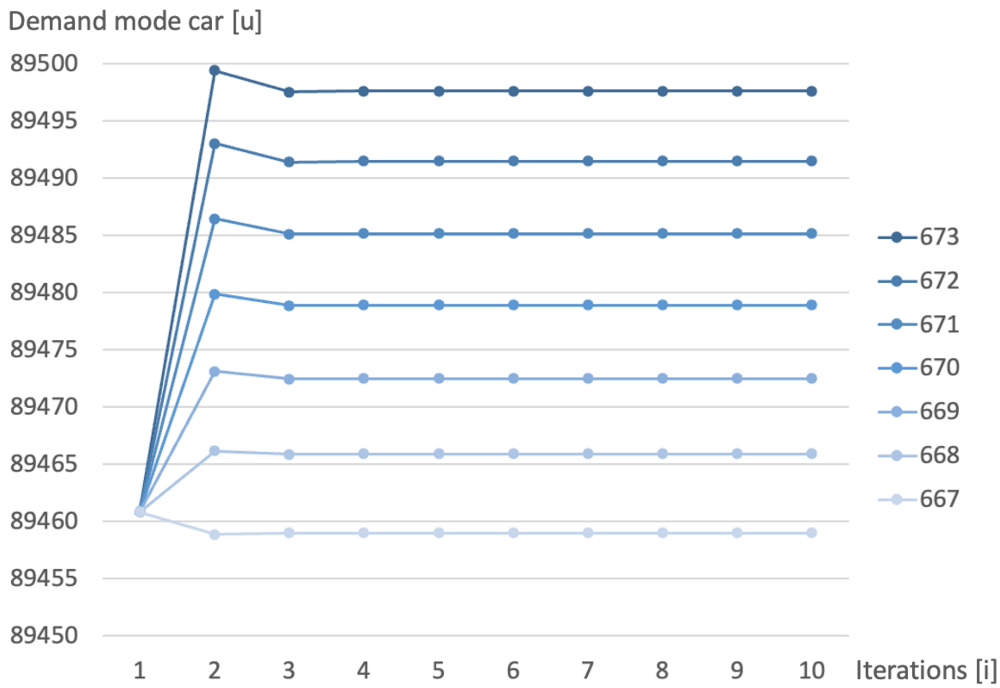


**FIGURE 12** : D4: Demand car mode under floating market price.

*Scenario 'D5' (dynamic): Temporal evolution of market price and car demand under increasing incentives for cycling*
In fig. 13, we present a dynamic case, characterized by an iterative process over increasing incentives for biking. Following the first iteration, a stable trajectory in development is observed, suggesting the effectiveness of the incentivization strategy. The incentives associated with bike mode are reinvested into the car transport mode, reinforcing its utilization. Notably, once the demand is fully satisfied, the demand for car mode does not further increase. Consequently, this leads to a market equilibrium where the market price drops to zero, underscoring the balance between supply and demand in this transport context.

**Discussion and conclusions**
The effectiveness of the MobilityCoin System has been demonstrated through its implementation within a sub-network of the Munich transportation network. In a static analysis of the system, several key effects were identified, contributing to our understanding of its underlying mechanisms. Further, the system exhibited both stability and resilience in the dynamic case, an essential attribute for its long-term sustainability. Generally speaking, the addition of coins tends to foster stability,

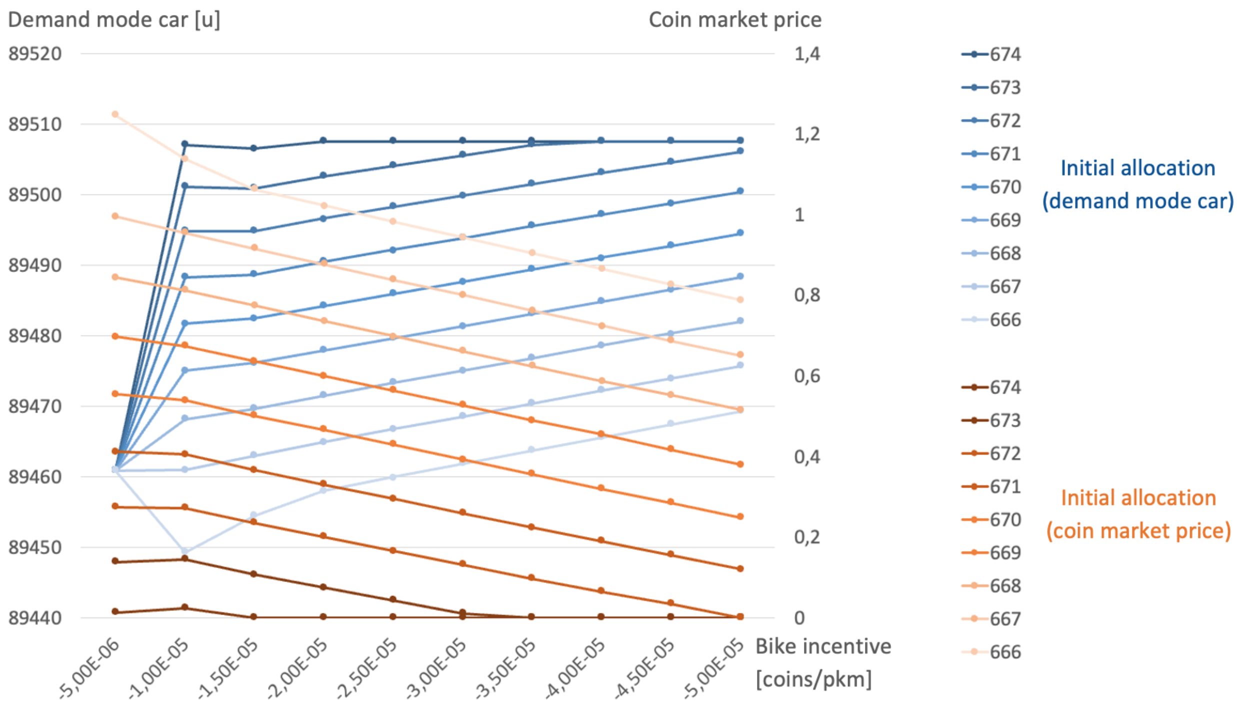


**FIGURE 13** : D5: Car demand and market price under rising incentives for cycling.

while reducing coins often leads to unstable observations. A similar trend is noticed with the increase or decrease of the value of a coin in terms of reflected externalities. It's critical to maintain a fair balance between incentives and charges within the MobilityCoin System to ensure market stability. The nuances discovered through these analyses underscore the need for thoughtful calibration of the system parameters to optimally manage and encourage desired transport behavior. Added coins are mainly used for car mode which is contrary to the overall objective of the MobilityCoin System, namely to encourage sustainable transport and reduce greenhouse gas emissions. Another reason for balancing the system thoughtfully.

In conclusion, the MobilityCoin System's effectiveness appears promising, given the insights garnered from the current study. However, it is crucial to validate these findings by applying the system to a larger subset of the Munich transportation network. As we scale the network, the parameters involved will further approach the conditions of a real-world application, thus ensuring a more robust and universally applicable solution. Additionally, extending the system to accommodate heterogeneous users in terms of mobility and coin spending behavior will further enhance its effectiveness. This diversity would render the system more inclusive and realistic, thereby elevating its potential to influence and shape sustainable transportation choices in the future.

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## AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: P. Servatius, A. Loder, K. Bogenberger; data collection: P. Servatius; analysis and interpretation of results: P. Servatius, A. Loder, K. Bogenberger; draft manuscript preparation: P. Servatius., A. Loder. All authors reviewed the results and approved the final version of the manuscript.

## References


1. Lindsey, R. and G. Santos, Addressing transportation and environmental externalities with economics: Are policy makers listening? *Research in Transportation Economics*, Vol. 82, 2020, p. 100872.
2. Verhoef, E., P. Nijkamp, and P. Rietveld, Tradeable permits: Their potential in the regulation of road transport externalities. *Environment and Planning B: Planning and Design*, Vol. 24, No. 4, 1997, pp. 527–548.
3. Yang, H. and X. Wang, Managing network mobility with tradable credits. *Transportation Research Part B: Methodological*, Vol. 45, 2011, pp. 580–594.
4. Bao, Y., E. T. Verhoef, and P. Koster, Regulating dynamic congestion externalities with tradable credit schemes: Does a unique equilibrium exist? *Transportation Research Part B: Methodological*, Vol. 127, 2019, pp. 225–236.
5. Krabbenborg, L., N. Mouter, E. Molin, J. A. Annema, and B. van Wee, Exploring public perceptions of tradable credits for congestion management in urban areas. *Cities*, Vol. 107, 2020.
6. Klenert, D., L. Mattauch, E. Combet, O. Edenhofer, C. Hepburn, R. Rafaty, and N. Stern, Making carbon pricing work for citizens. *Nature Climate Change*, Vol. 8, No. 8, 2018, pp. 669–677.
7. Lam, P. T. and A. O. Law, Crowdfunding for renewable and sustainable energy projects: An exploratory case study approach. *Renewable and Sustainable Energy Reviews*, Vol. 60, 2016, pp. 11–20.
8. Vasileiadou, E., J. C. Huijben, and R. P. Raven, Three is a crowd? Exploring the potential of crowdfunding for renewable energy in the Netherlands. *Journal of Cleaner Production*, Vol. 128, 2016, pp. 142–155.
9. crowdsourced transport, *Public Transport Crowdsourcing*. crowdsourced-transport, 2022, [Accessed: 2022-06-05].
10. NEXTCITY, *Downtown Denver Could Soon Have a Crowdfunded Bike Lane*. NEXTCITY, 2014, [Accessed: 2022-06-06].
11. Grant-Muller, S. and M. Xu, The Role of Tradable Credit Schemes in Road Traffic Congestion Management. *Transport Reviews*, Vol. 34, 2014, pp. 128–149.
12. Coase, R. H., The Problem of Social Cost. *The Journal of Law and Economics*, Vol. 3, 1960, pp. 1–44, publisher: The University of Chicago Press.
13. Wada, K. and T. Akamatsu, A Hybrid Implementation Mechanism of Tradable Network Permits System Which Obviates Path Enumeration: An Auction Mechanism with Day-to-day Capacity Control. *Procedia - Social and Behavioral Sciences*, Vol. 80, 2013, pp. 304–326, 20th International Symposium on Transportation and Traffic Theory (ISTTT 2013).
14. Goddard, H. C., Using Tradeable Permits to Achieve Sustainability in the World's Large Cities Policy Design Issues and Efficiency Conditions for Controlling Vehicle Emissions, Congestion and Urban Decentralization with an Application to Mexico City. *Environmental and Resource*

*Economics*, Vol. 10, 1997, pp. 63–99.

15. de Palma, A., S. Proost, R. Seshadri, and M. Ben-Akiva, Congestion tolling - dollars versus tokens: A comparative analysis. *Transportation Research Part B: Methodological*, Vol. 108, No. July 2015, 2018, pp. 261–280.
16. Musso, A. and W. Rothengatter, Internalisation of external costs of transport–A target driven approach with a focus on climate change. *Transport policy*, Vol. 29, 2013, pp. 303–314.
17. Krabbenborg, L., E. Molin, J. A. Annema, and B. van Wee, Exploring the feasibility of tradable credits for congestion management. *Transportation planning and technology*, Vol. 44, No. 3, 2021, pp. 246–261.
18. Wang, G., Z. Gao, M. Xu, and H. Sun, Joint link-based credit charging and road capacity improvement in continuous network design problem. *Transportation Research Part A: Policy and Practice*, Vol. 67, 2014, pp. 1–14.
19. Wang, G., M. Xu, S. Grant-Muller, and Z. Gao, Combination of tradable credit scheme and link capacity improvement to balance economic growth and environmental management in sustainable-oriented transport development: A bi-objective bi-level programming approach. *Transportation Research Part A: Policy and Practice*, Vol. 137, 2020, pp. 459–471.
20. Seilabi, S. E., M. T. Tabesh, A. Davatgari, M. Miralinaghi, and S. Labi, Promoting Autonomous Vehicles Using Travel Demand and Lane Management Strategies. *Frontiers in Built Environment*, Vol. 6, 2020.
21. Chen, S., R. Seshadri, C. L. Azevedo, A. P. Akkinepally, R. Liu, A. Araldo, Y. Jiang, and M. E. Ben-Akiva, Market design for tradable mobility credits. *Transportation Research Part C: Emerging Technologies*, Vol. 151, 2023.
22. Nagurney, A., Alternative pollution permit systems for transportation networks based on origin/destination pairs and paths. *Transportation Research Part D: Transport and Environment*, Vol. 5, No. 1, 2000, pp. 37–58.
23. Abdul Aziz, H. M. and S. V. Ukkusuri, Tradable emissions credits for personal travel: a market-based approach to achieve air quality standards. *International Journal of Advances in Engineering Sciences and Applied Mathematics*, Vol. 5, No. 2, 2013, pp. 145–157.
24. Miralinaghi, M., S. Peeta, X. He, and S. V. Ukkusuri, Managing morning commute congestion with a tradable credit scheme under commuter heterogeneity and market loss aversion behavior. *Transportmetrica B: Transport Dynamics*, Vol. 7, No. 1, 2019, pp. 1780–1808.
25. Blum, P., A. Loder, L. Hamm, and K. Bogenberger, Conceptualizing an individual full-trip tradable credit scheme for multi-modal demand and supply management: the MobilityCoin System. *Frontiers in Future Transportation*, 2022.
26. Servatius, P., A. Loder, and K. Bogenberger, MobilityCoins - Navigating the Complexities of Tradable Credit Schemes. In *103rd Annual Meeting of the Transportation Research Board (TRB 2024)*, 2023.
27. Fan, W. and X. Jiang, Tradable mobility permits in roadway capacity allocation: Review and appraisal. *Transport Policy*, Vol. 30, No. s, 2013, pp. 132–142.
28. Ferris, M. C., A. Meeraus, and T. F. Rutherford, Computing Wardropian equilibria in a complementarity framework. *Optimization Methods and Software*, Vol. 10, No. 5, 1999, pp. 669–685.
29. Loder, A., M. C. Bliemer, and K. W. Axhausen, Optimal pricing and investment in a multimodal city — Introducing a macroscopic network design problem based on the MFD. *Transportation Research Part A: Policy and Practice*, Vol. 156, No. January, 2022, pp. 113–132.
30. Institute for Sensible Transport, https://sensibletransport.org.au/project/transport-and-climate-

change/. *webpage*, 2021, accessed: 2021-10-15.
31. Schatzmann, T., S. Álvarez Ossorio Martínez, A. Loder, K. W. Axhausen, and K. Bogenberger, Investigating mode choice preferences in a Tradable Mobility Credit Scheme. In *103rd Annual Meeting of the Transportation Research Board (TRB 2024)*, 2023.
32. Domencich, T. A. and D. McFadden, *Urban travel demand-a behavioral analysis*. University of California, Berkeley, 1975.
33. van Nieuwkoop, R., K. W. Axhausen, and T. F. Rutherford, A traffic equilibrium model with paid-parking search. *Journal of Transport Economics and Policy*, Vol. 50, No. 3, 2016, pp. 262–286.
34. Wardrop, J. G., Some Theoretical Aspects of Road Traffic Research. *Proceedings of the Institution of Civil Engineers*, Vol. Part II, 1952, pp. 325–378.
35. Bezanson, J., S. Karpinski, V. B. Shah, and A. Edelman, Julia: A fast dynamic language for technical computing. *arXiv preprint arXiv:1209.5145*, 2012.
36. chkwon, *PATHSolver.jl*. https://github.com/chkwon/PATHSolver.jl, 2023.
37. chkwon, *Complementarity.jl*. https://github.com/chkwon/Complementarity.jl, 2022.
38. Stabler, B., *Transportation Networks*. https://github.com/bstabler/TransportationNetworks, 2021.