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Design and classification of tradable mobility credit schemes

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ABSTRACT

The ongoing research on tradable credit schemes (TCS) in mobility has captured the attention of policymakers, authorities and academics. Even though several studies have demonstrated the potential of such schemes, key policy design aspects that are relevant for real world implementation have been overlooked. There exists insofar no blueprint for an actual application of a TCS. We therefore propose a single all-encompassing framework for designing a TCS based on three dimensions: *ownership*, *transfer* and *consumption*. This framework has been developed through the extraction of policy design questions in the existing literature on TCS as well as alternative demand management schemes. Literature on the design of central bank digital currencies (CBDC) and digital tokens has been used to derive additional decisions regarding technical implementation and regulation. The decisions that are incorporated in the framework facilitate the comparison of different scheme designs in a three-dimensional space, addressing aspects of security, anonymity, centralization and technical feasibility. Hence, it provides policymakers and responsible authorities with a comprehensive framework on the essential decisions that need to be made upon practical application of a tradable credit scheme. It also serves as a means to classify existing work and develop new (or more realistic) variants of TCS that can be studied in future research endeavors. Based on the proposed framework, we devise an extensive research agenda describing directions for future research on tradable credit schemes across a variety of themes.

1. Introduction

Contemporary mobility systems face large challenges in combating the negative externalities caused by congestion. Such externalities, including time losses and environmental damage, have a significant impact on the quality of life and the economy in urban areas. It is likely that these issues will worsen unless appropriate policy instruments and control mechanisms are applied. Demand management measures are an example of such policy instruments which can reduce or redistribute travel demand across time, space and modality.

Insofar measures of demand management have been mainly aimed at restricting access to the transportation system (e.g., license plate rationing) or charging travelers for their use of infrastructure (e.g., tolls and congestion pricing). In currently operational pricing-based measures, for instance in London, Stockholm and Singapore, the authorities decide upon the exact pricing of the infrastructure (de Palma and Lindsey, 2011). Pricing levels in such schemes are fully determined given a zone and time slot, and therefore pricing does not adequately represent the true cost of externalities caused by a specific traveler's infrastructure usage. Additionally, given that pricing is centrally determined, it may be difficult to understand the composition of pricing levels for specific zones and times and the rationale behind them, thereby hampering transparency and public acceptance. In addition, issues pertaining to the equitability and fairness of such pricing policies can only be resolved through patchwork in the form of exemptions and concessions.

The tradable credit scheme (TCS) is regarded by a growing number of researchers as a potentially powerful and effective alternative to conventional congestion charging (Verhoef et al., 1997; Grant-Muller and Xu, 2014; Dogterom et al., 2017). In the commonly envisioned concept of TCS, travelers consume credits in accordance with their use of the transport system. After receiving an initial allocation of credits, travelers can trade credits between each other in a marketplace. The resulting market mechanism will lead to credits flowing towards heavy users, while light users (or those who use less congested and more sustainable alternatives) can benefit from the scheme by selling credits. In contrast to congestion pricing, there is no flow of money from travelers to the authority. Moreover, TCS allows policymakers to directly address equity concerns by providing different credit allocations based on socioeconomic variables, mitigating the need for complicated exemptions and deductions which are inherent to conventional demand management measures.

A large body of research is available regarding different variants of the TCS. The majority of these works are modeling studies, with

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few others considering the social acceptability (Dogterom et al., 2018; Krabbenborg et al., 2021) and political feasibility (Krabbenborg et al., 2021) of the scheme. Notwithstanding, many studies disregard design decisions that could specifically address equity concerns and multi-modality, even though these can be regarded as potential strengths of the TCS in practice. Some of the fundamental studies on the concept of tradable credit and permit schemes consider design considerations that are relevant upon practical application (Verhoef et al., 1997; Raux, 2002, 2004; Raux and Marlot, 2005), but the scope is often broad and interactions or causalities between individual design choices are mostly left out of consideration. Furthermore, the literature disregards implications of specific design elements on (de)centralization levels, practical feasibility, and potential security issues. Most studies assume a specific model of the TCS which fits the context and scope of that study (Lessan and Fu, 2019). This leads to disparities among TCS variants that are used in literature. For instance, many studies define charging amounts to be link-specific (Yang and Wang, 2011; Miralinaghi and Peeta, 2016; Liu and Nie, 2017), whereas others define them on an OD-specific basis (Xiao et al., 2015; Shirmohammadi and Yin, 2016). Another example of this can be illustrated through the different types of credit allocation that are assumed in existing literature: in most studies, credits are allocated evenly among all eligible individuals (He et al., 2013; Miralinaghi and Peeta, 2016), while others assume a per-household allocation (Xu et al., 2018). There are only few studies where auction-based distribution is applied (Nie, 2012; Tian and Chiu, 2015), while heterogeneous allocation methods (i.e., where the allocated amount is differentiated on an individual basis) have been discarded altogether. Thorough reasoning about the design decisions that underlie the modeling assumptions is absent in most literature. This presents difficulties in classifying and comparing the studies, making it nearly impossible to analyze the effectiveness of different scheme designs from the perspective of policymakers.

The fact that TCS is modeled with varying scope across the literature means that particular design elements might be overlooked. These design elements could potentially be influential in studies that utilize more complex models or take a different perspective (e.g., financial viability or social acceptability). Specific elements of the scheme, such as non-uniform credit allocation, mode-dependency, intervention and regulation have not been considered in earlier works, even though they could arguably have a considerable influence on traveler behavior, technical requirements and feasibility, economic viability and social acceptability (Chen et al., 2021). For example, price regulation by the authority (e.g., in the form of a price floor or ceiling) could influence trading behavior in the credit market and, consequently, the distribution of wealth among individuals. Also, the technical implementation of the credit scheme has a considerable impact on the possible objectives of the scheme and the ability of the authority to regulate the market. To illustrate, a fully decentralized token-based scheme would exclude the possibility to use the scheme as a tax substitute since a revenue stream to the authority cannot be established. Also, it would remove many of the authority's intervention capacity in supporting fairness and equity considerations.

The framework proposed in this paper addresses design decisions that need to be made prior to the application of a tradable credit scheme. The main purpose of this work is therefore to provide policymakers with guidelines for designing a TCS along the designated socioeconomic objectives and constraints. It also serves as a means of classification for existing work and a reference for the development and evaluation of new TCS variants in future research. Naturally, not all design decisions that will be proposed in this framework are directly relevant within the respective scope of each individual study. Notwithstanding, they can be useful for performing an analysis on the feasibility and implications of a proposed scheme prior to its field application. Altogether, the contributions of the proposed design framework can be summarized as follows:

- Provide policymakers and responsible authorities with a comprehensive and transparent framework on how a tradable credit scheme can be designed in accordance with varying socioeconomic objectives and constraints.
- Provide a means of classification of existing schemes. This allows for better comparison and analysis across studies.
- Analyze and understand the practical implications of design decisions on the effectiveness and feasibility of specific TCS variants proposed in the literature.
- Obtain a broader and more realistic overview of design considerations that have not yet been considered in the literature, thereby making it possible for novel research directions to be defined and, consequently, to set up a research agenda.

The further contents of this paper are structured into three sections. Firstly, in Section 2, we explain the rationale behind the formation of the three design dimensions based on literature from the field of TCS and related credit- or token-based systems. Also, we explain the structure of our framework for every dimension. This is followed in Section 3 by a specification of the dimensions and the individual design choices that can be classified within those dimensions, as well as the interactions between those design choices. Lastly, we conclude this paper by identifying directions for further research based on the developed framework.

2. Framework for design dimensions

To the best of our knowledge, there has been no study which has proposed a comprehensive framework for the design of tradable credit schemes as a policy instrument for demand management. One of the most relevant studies is a state-of-the-art review regarding credit- and permit-based demand management methods (Lessan and Fu, 2019). In their study, the authors classify the relevant body of literature and identify three specific problem categories arising from these schemes — *pricing*, *allocation* and *charging*. Even though the study could be useful to distinguish different forms of TCS that have been proposed in literature, we observe that the study is focused largely on modeling aspects while practical and fundamental design elements from the policy design perspective are left out of consideration. We argue that, when considering comprehensive policy design, modeling aspects should be regarded as secondary to the main design elements of the policy (which are subject to objectives and constraints that usually originate from the political sphere). After all, such fundamental design elements have a large impact on relevant modeling aspects, and consequently, the scope in which the resulting experiments can be considered as valid and representative for a real-world scenario. Hence, in our proposed framework, we employ a top-down approach from the perspective of policymakers and authorities, and discuss the implications that policy design decisions have on modeling and in a practical application.

Market design aspects have been covered in the context of tradable permit schemes (TPS), albeit to a limited extent. Even though the limited number of relevant studies do provide reasoning for the different design decisions that were made for the conceptual set-up of the scheme, it does not provide an exhaustive overview of all design aspects that are relevant for a practical application from the policymaker's perspective (Wada and Akamatsu, 2013; Liu et al., 2015). In Brands et al. (2020), such aspects are considered, yet the authors use them while reasoning about their choice for a specific market design. Even though the study provides guidelines "to extend and adjust [the proposed design] for specific real-world settings", some assumptions were inevitably made by the authors: for instance, the proposed market design uses a *virtual bank* as an intermediary for setting permit prices. The authors also decide upon limited validity of permits. These assumptions can, in fact, be seen as a relevant and highly influential design considerations which influence price dynamics as well as the level of centralization of the scheme. Once more, this underlines the need for a

framework that provides policymakers and authorities with a broader and more comprehensive overview of conceptual and practical design decisions, as well as their implications.

In Krabbenborg et al. (2021), a study is performed on the feasibility of tradable credits for congestion management in road transportation. The authors have interviewed a total of 16 experts from a variety of backgrounds, including policymakers and transport engineers. The study provides useful insights into some relevant design choices of the TCS from a policy design perspective. Multiple essential questions are raised by interviewees, such as: how often (and by whom) credits are allocated, how the cap is determined, how the scheme will be regulated, and how often users will be required to trade. However, we observe that the interdependencies between these design elements are not highlighted, and that more technically in-depth design choices are largely avoided. For instance, choosing a specific payment infrastructure restricts the possible instruments that the authority can use for regulatory purposes. We therefore aim to include aspects that were considered in this study, but will add more specific design decisions regarding technical implementation and use our framework to highlight the relationships between decisions. We may draw knowledge and inspiration from literature regarding technical design considerations in digital currencies. We assume that a TCS will be implemented as a digital currency, and therefore exclude the possibility of credits being held and paid in physical form since this would arguably make the scheme technically infeasible. The presence of information and communication technologies is the main reason why TCS can now be brought into practice.

We observe that properties of a TCS bear resemblance to those of so-called *central bank digital currencies* (CBDC) — the main difference being that mobility credits are only valuable in the specific context of transportation whereas a CBDC would be more widely accepted as a ubiquitous medium of exchange. Even though many design elements in CBDCs are not necessarily relevant in the context of TCS, large aspects of it provide useful questions about the technical implementation of the TCS. The literature base on CBDCs has grown rapidly in recent years and can be used to distill essential decisions about the conceptual and technical design of such currencies (Yao, 2017; Parra-Moyano et al., 2018; Agur et al., 2022). Literature on the design of digital tokens was also used for this purpose, given its similar relevance to the technical implementation of a TCS (Schubert et al., 2021; Freni et al., 2022). The interdependencies between decisions were established, after which we attempted to cluster decisions between which the most dependencies exist. This results in multiple (largely) independent categories, called *design dimensions*. This definition was chosen because the combined decision-making in all categories determines a scheme design's position in an n-dimensional space, allowing for an intuitive comparison between different variants based on key characteristics.

Using this approach, we identified three dimensions along which a tradable credit scheme can be designed and classified. Within each of those dimensions, a set of design choices need to be made. These decisions are mostly dependent on other choices made within the same dimension. Each dimension therefore involves a separate decision tree which can be used to design specific components of the scheme. However, decisions made at different levels in the TCS design process also exercise interdependencies. This means that design dimensions cannot be completely viewed in isolation (i.e., the decisions in one dimension might depend on the decisions made in another dimension). Through experimentation with different structures and hierarchies of the framework, we have determined that every dimension requires separate design decisions regarding governance and regulation. Such decisions often flow from (or are highly influenced by) the main formative decisions made in the earlier stages, and therefore we have decided that it is most logical to group them and place them at the bottom end of each decision tree. Correspondingly, we describe these decisions in a separate *Governance & regulation* section for every dimension.

The combined positioning along the three spectra defines the global characteristics of the scheme. Foremost, it determines the level of (de)centralization: if the decisions result in positions towards the left side of the spectra, the scheme is more decentralized and the authority adopts a *laissez-faire* approach to regulating the scheme. Conversely, if they are placed more towards the right, there is a higher level of involvement of the authority required, yielding a more centralized and interventionist scheme. The increased intervention by the authority (e.g., for facilitating the necessary infrastructure but also regulation and intervention) implies a higher cost of implementation and maintenance. Hence, generally speaking, the combined positioning of design decisions on the spectra can also be used as a measure for the complexity and cost involved in implementing and operating the scheme (where positions towards the right on the global spectrum imply higher complexity and cost). The question of security in centralized versus decentralized schemes can be approached from different angles (Parra-Moyano et al., 2018). In many ways, proponents of decentralization will argue that transactions occur in a more secure way, without dependence on central systems which are inherently more vulnerable to attacks. Also, the fact that no (or less) personal information needs to be collected leads to a lower vulnerability to data breaches. However, from a user's perspective, a decentralized scheme (e.g., in the form of a cryptocurrency) might be perceived as less secure, given that the authority has less oversight and instruments to intervene in case of fraud or data loss. Hence, since the definition of security might be considered ambiguous in the context of a TCS, we avoid classifying designs along a global spectrum of security, but rather highlight the individual risks that are relevant for specific design considerations.

3. Design choices & regulatory considerations

We propose a design framework consisting of three dimensions: *ownership*, *transfer* and *consumption*. The **Ownership** dimension deals with the possession of credits and determines how credits are held from a user perspective, how ownership is recorded and verified in a ledger, and how credits are distributed and allocated to users. This dimension therefore mainly influences the level of anonymity and identity-dependency (i.e., ranging on a spectrum from *anonymous* to *differentiated*) maintained in relation to the ownership and allocation of credits, and consequently affects the extent of potential privacy and security concerns that could be raised by the scheme. It also affects the options for intervention that the authority possesses to address equity concerns through variable allocation. The **Transfer** dimension involves the design of digital infrastructure that facilitates the movement of credits between users of the scheme, which is needed for making payments, trading and receiving allocations. This has consequences for the role of a central entity as an intermediary which facilitates the transfer of credits between users, with potential privacy and security risks as a consequence. This dimension therefore determines the position of the scheme on a spectrum ranging between *peer-to-peer* and *through intermediary*. Lastly, the **Consumption** dimension determines how users will spend their credits based on their usage of the transportation system, as well as the methods for enforcement of credit expenditure. It determines the position of the scheme on a spectrum ranging between *uniform* (i.e., where every user spends the same, independent of their travel behavior) and *refined* (i.e., based on one or multiple parameters, possibly through a model of externalities as a function of behavior) credit consumption. The resulting framework is schematically visualized in Fig. 1.

3.1. Ownership

This dimension covers design decisions that determine how credits are owned, held by and allocated to users of the scheme. Its corresponding decision tree is displayed in Fig. 2. The first decision that needs to be made regarding the ownership of credits concerns the way the

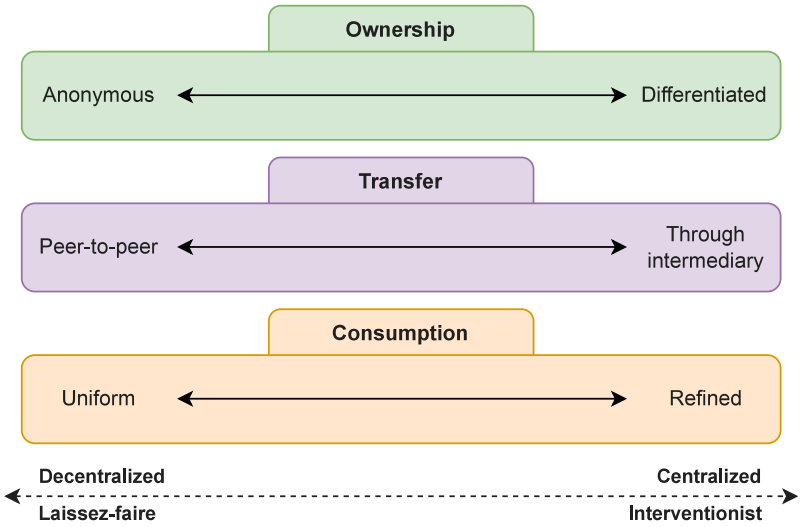

Fig. 1. The proposed framework consisting of the three primary dimensions along which a TCS should be designed.

credits are held by users of the scheme. In a token-based approach, the holding of credits is analogous to the possession of banknotes and coins in the context of a conventional government-issued currency. Every credit is represented as a token with a specific denomination. Ownership is therefore not proven through the verification of owners' identity, but rather through demonstrating that the credits are genuine and valid, i.e. like Euro coins or notes upon payment at the supermarket. This makes a token-based TCS highly anonymous since a specific token cannot be coupled to an identity. In theory, unlimited wallets can be held by a single individual. Also, since a token-based scheme only requires proof of validity and not an identity check, no intermediary is necessary, thus increasing the level of decentralization. Conversely, in an account-based approach, each user of the TCS holds an account that is managed by the central authority or a commercial bank. A potential advantage of the account-based approach is that the authority has more ability to regulate and intervene in case of fraud. However, the fact that a bank or central authority manages all accounts also means that this approach is more centralized, leading to potential privacy and security risks.

In the case of a token-based credit scheme, another decision should be made regarding the type of ledger, i.e., the database in which transactions are stored and from which the rightful ownership of tokens can be determined. The traditional approach is to implement a *centralized ledger* which is managed by the central authority or a bank. It is relatively easy to implement and requires little effort to perform and verify a transfer of ownership, but the centralized nature means that this approach is relatively prone to attacks or malfunctions. Recent technological advancements have allowed for the emergence of *distributed ledgers*, in which the transaction data is replicated, shared and synchronized across different locations. Generally, such systems provide more transparency and robustness, even though the implementation can be complex. Also, the computational cost of validating transactions can be high, possibly leading to limited scalability and slow credit transfers. In case a distributed ledger approach is preferred, a further decision needs be made on the type of wallets that is supported in the scheme. In most blockchain-based token systems, wallets are digital and their private keys are stored on the user's personal device. Another option is the use of hardware wallets, which store the private keys offline. This makes them less vulnerable to theft, but also increases the responsibility of the user to physically protect the wallet. Depending on the decisions made in the 'consumption' dimension, one option could be to integrate a hardware token wallet in the personal vehicle. In a scheme where only hardware wallets are used, the authority is responsible for providing such devices to users, which would drastically increase operational costs. A hybrid between digital and hardware wallets could be a solution that allows users to select their preferred method for holding mobility credits.

In an account-based credit scheme, a decision needs to be made on the responsible entity for managing the accounts. The first and most centralized option is that the central authority fulfills this role. This likely increases the ease of implementation of the scheme but increases the vulnerability of the system. Also, since all responsibility for the secure handling of accounts and identities of the users will reside with the authority, special attention should be devoted to issues of trust and transparency. Allowing banks to manage user accounts could lead to higher robustness of the overall system. However, this approach comes with many additional issues, since banks would need to be subjected to strict regulation that needs to be devised by the authority. Also, the governing authority needs to ensure that participating in the scheme is commercially attractive to the banks in order to maintain enough competition in the market, impacting the financial efficiency of the scheme.

The distribution of credits forms a useful instrument for policymakers to address equity issues induced by the tradable credit scheme. One of the largest objections against a tradable credit scheme is the fact that it might lead to inequality, since wealthy users (or businesses) might end up buying large amounts of credits to ensure their ability to travel while poorer users (or individual citizens) are forced to pay high prices or abandon their travel plans altogether. We argue, however, that the other side of the coin (or credit) is that the tradable credit scheme provides powerful tools to combat so-called 'mobility poverty', provided that the scheme is properly designed. We therefore cover design decisions which make it possible to implement so-called variable allocations as a distribution method, based on socioeconomic status of the user. It should be noted that token-based mechanisms will make it nearly impossible for the central authority to influence credit issuance and distribution over time, unless it takes an active part in the mining or staking process (which is potentially a costly endeavor). The number of credits in circulation is directly dependent on the assets that external participants invest. Hence, even though blockchain-based credit schemes can be regarded as a highly secure and anonymous approach, they lack options for the authority to regulate, intervene or influence the distribution of wealth. Implementing an account-based credit scheme implies that the authority has more abilities to distribute credits in a differentiated (i.e., individual-specific) manner.

In an account-based scheme where the central authority is responsible for issuing the credits and the management of accounts, one

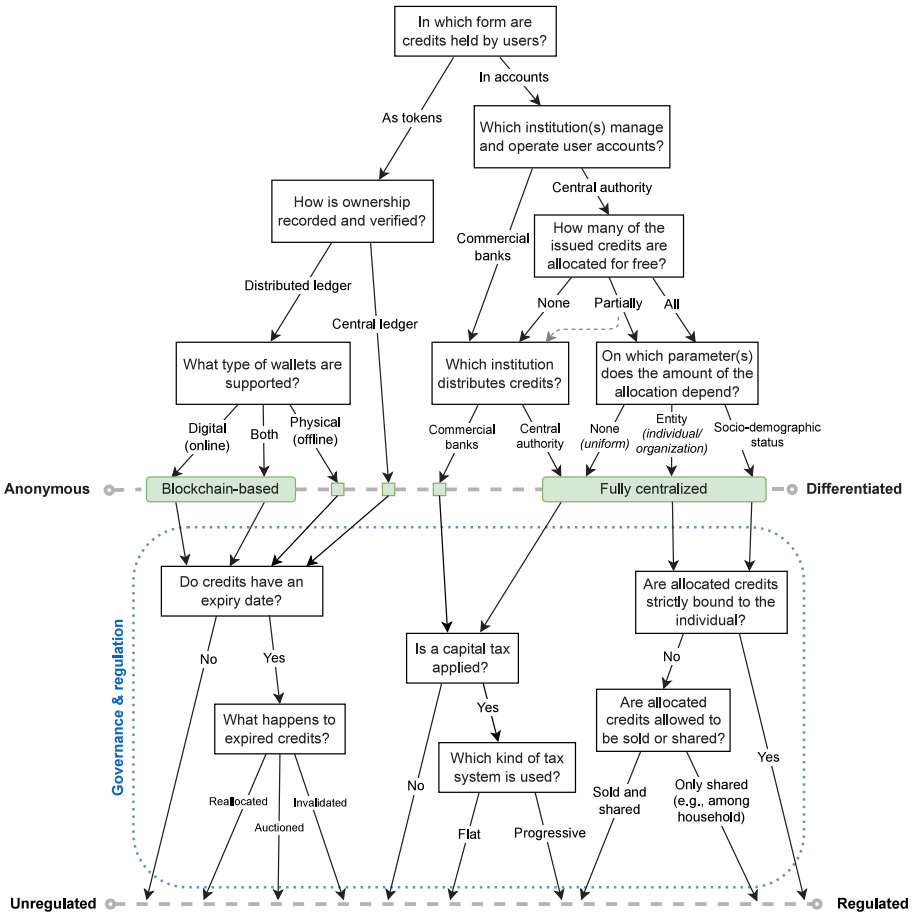

Fig. 2. Decision tree illustrating the relevant design decisions and their inter-dependencies in the *Ownership* dimension.

can decide to allocate credits for free. In the case that all credits are subject to free allocation, we can define the scheme as *revenue-neutral*. In this variant, there is no stream of money flowing to the authority, which could potentially increase acceptance among the public. Another potential strength of the TCS could be its ability to act as a substitute for conventional road taxes or public transport ticket fees, but this would sacrifice revenue-neutrality. However, a *tax-substitutive* TCS could possibly increase public acceptance in a different manner, as it would reduce the complexity of dealing with multiple taxation systems (i.e., existing road and vehicle taxes). To facilitate a tax-substitutive scheme, part (or all) of the credits could be distributed through auctioning and/or fixed-price selling by either the central authority or commercial banks, such that a revenue stream to the government is established. When allocating (part of) the credits for free, one also needs to decide the parameters upon which the exact allocations are determined. For any combination of parameters, it is necessary to have an account-based scheme in which the identity of the account holder is verified to ensure fair allocation. The most straightforward option is to perform a uniform allocation, in which every individual obtains the same number of credits upon issuance. More sophisticated allocation methods can be based on sociodemographic status of the recipient and the type of entity (e.g., companies and institutions could receive higher amounts of credits than private individuals). For such methods, more personal data (coupled with an identity) will be needed to classify the account holders, which might give rise to additional privacy concerns.

The amount and distribution of free credits among eligible users can arguably influence trading activity on the market as it is highly dependent on the extent to which the credit needs of individual users are already satisfied with the initial allocation. As already discussed, if a specific initial allocation of credits already suffices for the desired travel behavior, there is no need for trading. Hence, it is likely that a uniform allocation will make it necessary for users to trade, whereas an allocation depending on sociodemographic status might yield very low trading activity market liquidity. The implication for trading activity and market liquidity is that high levels can be achieved by performing free and uniform allocations, such that heavy (or unsustainable) users will need to purchase credits from light (or sustainable) users. In case that a free allocation based on socioeconomic status is preferred (e.g., to address potential equity issues), trading activity could be stimulated by limiting the amount allocated, such that users still need to trade to satisfy the credits corresponding to their desired travel behavior.

Governance & regulation. In the ownership dimension, several instruments are available for the governance and regulation of the scheme. The feasible instruments and corresponding decisions are influenced by earlier decisions that were made regarding credit ownership. In the case of a token-based credit scheme, it is impossible to apply a capital tax, as ownership (and therefore capital) cannot be linked to an individual. However, to stimulate the expenditure of credits and to reduce hoarding and speculative behavior, an alternative can be to introduce credit expiry dates. In this case, a token cannot be spent after a certain amount of time has elapsed since it was created. A disadvantage of this approach is that the market will consist of differently valued credits (due to some credits being valid longer than others), which will increase the complexity of price discovery. Furthermore, when fine-grained validity periods are utilized, the buying and selling process will become much more complicated for regular users due to the high variation in the intrinsic value of the credits. This could give rise to additional equity issues and potentially lower the public acceptance of the scheme. The use of credit expiry dates could also spur speculation, thereby increasing trading activity and market liquidity. Also,

depending on the granularity of expiry dates, the intensity of trading activity might fluctuate more over time (to illustrate, a sudden surge in activity might occur shortly before a common date on which many credits will expire, e.g. at the end of each month). If credits are brought back into circulation after expiry (for instance as a way to redistribute wealth more fairly among users), the need for trading might decrease in the short term, hence possibly decreasing trading activity and market liquidity. Another decision that needs to be made in case of an expiring-credit system is the purpose of credits after their expiration date. The credits might be brought back into circulation through auctioning or reallocation or might be invalidated and removed from circulation altogether.

For an account-based credit scheme, credits are in theory infinitely divisible and are represented digitally as a number. This means that individual tokens cannot be distinguished, unlike in a token-based system. Hence, credit expiration is impossible in an account-based scheme. In this case, a capital tax can be applied to discourage hoarding by users. The tax rates are decided by policymakers and authorities, and can differ based on the owned capital or whether the user is a private person or business. Contrary to expiry dates, this instrument can be tailored to be a *progressive tax system* where higher tax rates are applied to richer individuals. In this case, trading might be stimulated as an alternative to holding on to assets for a longer time. Hence, capital taxes could arguably increase liquidity in the market. In case that variable allocation is applied by the central authority, another method to regulate the market is restricting the use of allocated credits. Such a measure could arguably prevent allocated credits (i.e., those provided for free) from being exchanged for money, and thus making sure that the allocation is only used for consumption through usage of the transportation system. In case that the authority decides to be more lenient about usage of allocated credits, it can further decide whether selling allocated credits is allowed or if only sharing (e.g., among household or family members) is tolerated. It should however be noted that the level of strictness could have a negative effect on liquidity in the credit market.

3.2. Transfer

This dimension covers design decisions that should be made regarding the movement of credits between users of the scheme, i.e., the transfer of ownership from one party to another. Its corresponding decision tree is displayed in Fig. 3. Here we largely disregard the intention behind the transfer (for instance: a transfer can be performed to settle a trade, but also to gift credits to a family member) and only consider the necessary elements for the system to execute any transfer in the credit scheme. The first decision decides whether credits are transferred via an intermediary or on a peer-to-peer basis. This is highly influenced by the decisions made in the *Ownership* dimension: if a token-based system with a distributed ledger is chosen, then the transfers are performed in a decentralized manner on the blockchain. When ownership is designed differently, transfers need to be validated and registered by a third party. This can either be done by banks or by the central authority. Giving banks the responsibility for this task could potentially increase the robustness and security of transfers, but also adds regulatory complexity and requires external (commercial) parties to be involved in the scheme. Furthermore, transactions require communication between banks and could therefore take more time, as is evident in contemporary bank transfers. Even though it is much faster and more cost-efficient, handling all transfers through the central authority potentially induces the single-point-of-failure (SPOF) risk into the system and could lead to user distrust regarding privacy and security.

If transfers are required to pass via an intermediary (i.e., banks or the central authority), one should decide whether trades are required to be made via exchange platforms. The fact that credits flow through an intermediary allows for validation of the method using which the trade was established. If trading via a regulated platform is required, this means that over-the-counter trading (i.e., direct trading between two parties) is forbidden and that every trade needs to be checked for the validity of the platform through which it was established. It should be noted that this level of regulation and enforcement puts a relatively high burden on the authority. If trading via an exchange platform is required, a follow-up design decision is whether the authority should facilitate a central exchange platform through which credits can be traded.

Governance & regulation. In case a blockchain-based token design is used for the scheme, there are still regulatory instruments that can be employed by the authority. This is also relevant when over-the-counter trading is allowed to occur in a non-blockchain-based scheme. First of all, one needs to decide whether exchange platforms and brokers should be placed under the direct supervision of the authority, meaning that these entities should adhere to strict regulations. In contrast to a scheme where only certified exchanges can be used, the transactions cannot be directly verified in the ledger, but are subject to random investigations and broader enforcement by the authority. In case exchanges and brokers are under the supervision of the authority, these institutions can be required to perform background checks and verify the identity of their customers (even in a highly anonymous blockchain-based scheme). This reflects the so-called know-your-customer (KYC) regulations that have been widely implemented in financial institutions. Such regulations allow authorities to trace fraudulent users but raise potential issues regarding the privacy and security of personal data.

In the case that a central exchange platform is implemented, the authority may decide that this trading platform is exclusive (leading to additional security and privacy risks that come with a higher degree of centralization, but more options for regulation and oversight) and that no commercial platforms are allowed to compete with it. As part of the Ownership dimension, the concept of variable allocation was described as a possible method to address the social implications of a tradable credit scheme. An alternative instrument to address equity issues can be implemented in the form of *credit price regulation*. This allows the authority to directly influence the credit price in the market and maintain an equitable system for different socioeconomic groups. One of the techniques using which prices can be regulated is through buy-backs and sell-offs, creating a lower and upper bound for the credit price. A disadvantage of this technique is that constant effort needs to be undertaken by the authority to ensure that price levels stay within the specified limits. Also, if sell-offs need to be performed from a finite pool of reserve credits, this means that the price ceiling cannot be guaranteed. Similarly, the utilization of buy-backs could mean that public money flows from the authority towards private individuals or businesses. The bought-back credits can either be invalidated or brought back into circulation for a reduced price. However, the most straightforward technique for price regulation is to directly impose price limits via the exchange platform, but this is only realistically implementable when an exclusive authority-operated exchange platform exists.

In addition to credit price regulation, transaction fees can be used as a regulative measure to combat excessive speculation. By making frequent trading movements more costly (by applying a fee for each transaction), users are discouraged to trade unless they actually need credits for their individual mobility needs. This might prevent to a certain extent speculators from entering the market and ensure that only those users are trading who actually need credits for mobility. Among these users, trading activity will be less frequent than among speculators who attempt to profit. As a consequence, this regulative measure would arguably decrease liquidity as speculators are (partially) excluded from the market.

The authority can also use exchange fees to either cover the operational costs of the platform or use the incoming funds as a tax substitute. With a tax substitute, the tradable credit scheme could function as a potential alternative to road tax and public transport ticket

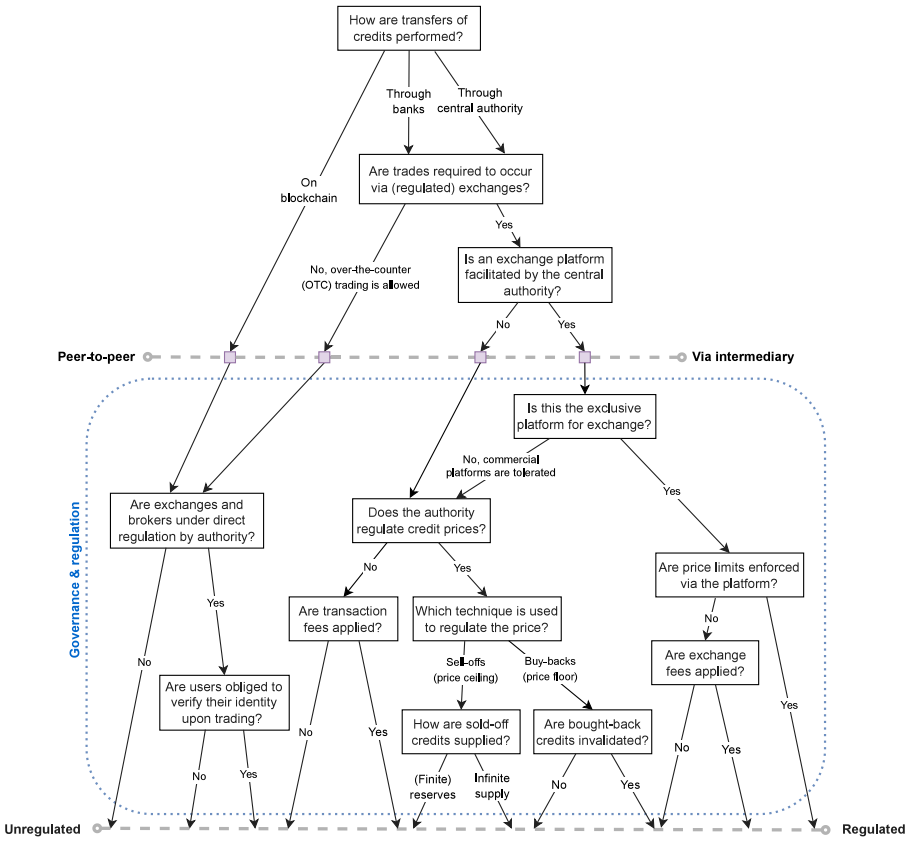

Fig. 3. Decision tree illustrating the relevant design decisions and their inter-dependencies in the *Transfer* dimension.

fees. When multiple (regulated) exchange platforms are allowed to operate, the authority can gather funds for the same purposes through transaction fees. The difference between exchange fees and transaction fees is that quittance occurs upon closing the trade (at the exchange) or upon processing the transfer (at the authority or payment service provider), respectively. Both fee structures can also act as a method for reducing speculative behavior in the market.

3.3. Consumption

This dimension determines the value of credits in the transportation system and how consumption is registered based on the individual's travel behavior. Its corresponding decision tree is displayed in Fig. 4. Design decisions in this dimension will not only have large implications for the sociopolitical objectives of the scheme, but also for the credit needs of users, and consequently, market dynamics and travel behavior. First and foremost, one needs to decide upon the parameters that determine the number of credits that a user is charged for making use of the transportation system. These parameters can be divided across four domains: *spatial*, *temporal*, *modal* and *personal*. When the credit charge is independent of any variables, we may refer to it as a *uniform* charging mechanism. When more parameters influence the credit charge, the complexity of the mechanism (and corresponding credit charge) increases, and hence and we speak of a more *refined* charging mechanism. Design choices in all four categories can be made independently of each other and in any order. This is represented in the corresponding decision tree as four boxes placed side by side with separate axes, as shown in Fig. 4.

In the spatial domain, one of the major decisions that need to be made is whether credit charges are defined at the area level or at the link level. An *area-based* approach means that credits will be charged when the transportation system is used inside a specific area, marked by geographical boundaries. For instance, entering the city center would result in the user being charged a certain number of credits (the exact amount could additionally depend on temporal, modal and personal variables). If a *link-based* approach is chosen, the credit charge is differentiated for each link in the network. Generally, this approach allows policymakers to steer travel behavior with greater precision. However, it requires more sophisticated and complicated models for determining the exact amounts, which at present can be considered technically infeasible to implement. In the future, more precise GPS tracking techniques might allow for a solution that approaches link-based credit charging. A solution with arguably better technical feasibility is an *OD-based* approach, which means that the origin and destination location (possibly in combination with the mode of transport) are used to infer the traveled route, and consequently, the credit charge.

The main decision that needs to be made regarding dependencies in the temporal domain is whether credit charges should be static or dynamic. In a *static* charging mechanism, the credit charge remains fixed over time, whereas a *dynamic* mechanism allows for changing credit charges over time. In a dynamic mechanism, a further decision that needs to be made is whether the credit charges only depend on the point in time (i.e., time of day, day of week, or month) or also on real-time circumstances in the environment. To illustrate, in a complex dynamic mechanism, the credit charge might be dependent on the current traffic state and/or weather variables. However, it should be noted that such dependencies introduce considerable uncertainty to the credit charge levels as well as market prices, which could be considered undesirable from a social and technical perspective.

In the modal domain, one needs to decide whether credit charges are dependent on the mode of transport. Firstly, this requires a careful consideration of the modes that are included in the scheme. For instance, some policy variants might only incorporate road traffic, while others might consider integrating public transportation or mobility-on-demand services. To stimulate the use of public transport as an alternative to road transport, users might be charged a lower amount

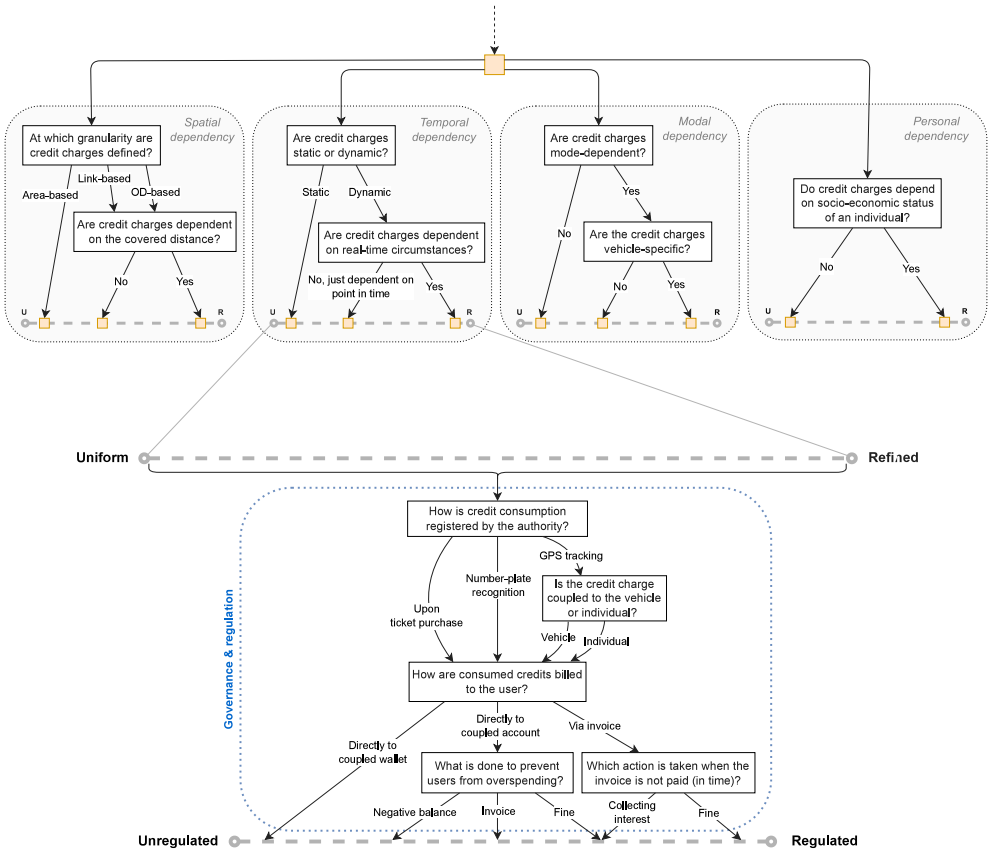

Fig. 4. Decision tree illustrating the relevant design decisions and their inter-dependencies in the *Consumption* dimension.

when they choose the train instead of the car between the same origin and destination. Additionally, credit charges can be differentiated based on the (type of) vehicle that is used. For instance, driving a large SUV car could cost more credits than driving a small electric car. Choosing a mode-dependent charging mechanism provides greater leverage to policymakers and authorities to influence travel behavior. When further differentiation is made between specific vehicle types, it could even stimulate the purchase and/or usage of more sustainable vehicles.

Credit charges could also depend on socioeconomic variables of the individual. These are considered to be dependencies in the personal domain. It should be noted that this requires an account-based scheme where the identity of account holders can directly be coupled to their socioeconomic status (see the corresponding decisions in the *Ownership* dimension). Yet, we should note that socioeconomically dependent credit charges are relatively burdensome to implement and enforce when compared to variable allocation based on individual characteristics.

A tradable credit scheme where the value of a credit represents a quantifiable external effect (caused by an individual's usage of the transportation system) is called an **externality-based** scheme. A sufficiently sophisticated model is required for an accurate representation of the externality (e.g., CO_2 or NO_x emissions) caused by the recorded travel behavior, which by definition makes the credit charge dependent on time, space and modality. For instance, per-capita CO_2 emissions of a trip depend on its duration, the speed over time (which, in turn, depends on the location and the real-time traffic state), the vehicle's emission specifications (which is mode-specific) as well as the occupancy of the vehicle (e.g. number of people riding a bus). Hence, a refined credit charging mechanism is essential for the implementation of an externality-based scheme.

The decision for increasingly refined credit charging mechanisms (link-, area-, time- and mode-based) might contribute to an increase of trading activity in the market. However, it should also be noted that the credit charging method might induce larger fluctuations in trading activity and hence liquidity. For example, in the case that credits are charged in a mode-dependent manner, and the scheme has proved to effectuate a shift towards more sustainable (and hence cheaper) transportation modes, this could reduce credit trading demand and increase its supply, possibly leading to an oversupply and a lower market price with the risk of people choosing less sustainable alternatives, if not counteracted by the agency. Lastly, a potential risk of utilizing more refined credit charging schemes is that it decreases the ability of users to plan their future credit requirements.

Governance & regulation. Design decisions regarding governance and regulation in the *Consumption* dimension are largely independent of the variables that determine the credit charges. However, it should be noted that, as the charging mechanism becomes more refined, more precise tracking of individual travel behavior will be required. As a consequence, control and enforcement by the authority become a more complex and costly task. This could potentially raise additional privacy- and security-related issues.

The first decision that needs to be made is how credit consumption is controlled and registered by the authority. To charge users with the number of credits that corresponds to their travel behavior, the necessary data about the trip need to be registered. For road traffic, this could be done through number-plate recognition. However, this approach requires the installation of large and expensive camera equipment above roads, which might be feasible for area-based approaches but quickly becomes inconvenient in a link-based approach where high granularity is required. Therefore, the precision of the scheme is limited when number-plate recognition is used for control purposes. An alternative is GPS tracking, which can either be done at the vehicle level (e.g., through a fixed device installed in the vehicle) or the individual level (e.g., through a smartphone). The latter option would arguably

provide the most flexibility across different modes of transport, but requires the collection of privacy-sensitive data. This yields additional concerns that would need to be carefully addressed. Alternative credit consumption methods in public transportation include charging credits upon purchase of a ticket, or through the usage of smart cards.

Subsequently, one should decide how consumed credits are billed to the user. The most straightforward option is to do this through direct deduction from a wallet (in a token-based scheme) or an account (in an account-based scheme). In the case of number-plate recognition, this means that the vehicle would need to be registered to a valid wallet or account. Similarly, when GPS tracking is used at the individual level, the user's smartphone would need to be coupled to a valid wallet or account. Lastly, in public transportation, the wallet or account would need to be coupled upon purchase of a ticket at a machine, online, or at the ticket desk. Personal smart cards could also be directly coupled to a credit wallet or account. In a token-based scheme, it is almost impossible for the authority to intervene when users spend more credits than they own since the identity is unknown. Hence, enforcement would only be possible through random in-person patrols, requiring large investments in manpower and equipment for enforcement purposes. Enforcement is much easier in an account-based scheme, where an account belongs to an individual. Therefore, to prevent overspending by users, a straightforward solution could be to allow negative balances in the account. This way, a violator will be forced to settle their debt when using the transportation system again in the future. A more foolproof but also hard to implement alternative could be to send violators an invoice for the overspent credits, either at the current market price or at a fixed (higher) price. When the invoice is not paid in time, interest may be collected or a fine might be added to the invoice amount to stimulate payment by the violator. The most rigorous option to prevent overspending is to give the violator a monetary fine which is either fixed or based on the number of credits that was overspent.

4. Research agenda

The proposed framework can serve as a fundament for identifying directions for further research regarding tradable mobility credits. We therefore outline research questions that currently remain unaddressed and classify them into the three dimensions proposed by the framework: *ownership*, *transfer* and *consumption*. The research questions that were identified cover a variety of topics in the context of tradable mobility credit schemes. For instance, some relate to the factors that determine public perception and acceptance of the scheme. Others pertain to the implementation, management, and enforcement of the policy instrument by the responsible authorities are described. Lastly, many directions for further research relate to the influence of policy design choices on trading and travel behavior of users, and consequently the network-wide effectiveness and efficiency of the instrument.

In this section, we first describe some overarching research directions that need attention. From these broader directions, we can derive a more specific research agenda. In subsections 4.1–4.3 we therefore identify and classify the research questions in greater detail within the three dimensions of our framework.

Overarching research directions

We identify a number of relevant broader directions for future research endeavors. Firstly, the framework proposed in this paper provides a broad range of potential research directions regarding the acceptance and perception levels of the scheme depending on different design decisions. Insofar, there have only been a few studies that have considered acceptability and public perception of TCS (Dogterom et al., 2018; Krabbenborg et al., 2021). These studies generally studied very limited design dimensions and disregarded some of the practical design choices related to the implementation and regulation of a TCS. Hence, a promising research direction is to evaluate the impact of different policy design choices on the perception of citizens, policymakers and other stakeholders. Specifically, it is highly relevant to investigate the relationship between the level of centralization in a TCS (i.e., the extent to which the authority is involved in operating and regulating the scheme) and its acceptability among the public. Another relevant research gap pertains to the analysis of socioeconomic factors in individuals that influence social acceptability and specific policy design elements that can be applied to improve acceptability in specific social groups.

With regard to implementation, management and enforcement of the policy instrument, the proposed framework also provides a variety of research directions that remain to be addressed. This includes investigating the impact of individual policy design choices on the cost of implementation and operation of the TCS. Extending this, it could be relevant to analyze whether increased involvement of the authority (and thus an increased level of centralization) also implies higher implementation and maintenance costs for the TCS scheme. To the best of our knowledge, there has been no in-depth study into the cost-feasibility of different TCS variants. Similarly, an analysis of the technology-readiness of different scheme variants (e.g., digital infrastructure or control equipment) could be performed to address concerns regarding feasibility and reliability. In Krabbenborg et al. (2021), the authors remark that most of the interviewed experts think that a TCS is "technically feasible considering current developments in the ICT field". However, an actual technical analysis is yet to be conducted and the authors note that the actual feasibility depends on the end design of the policy. This calls for a more in-depth technical feasibility analysis of different policy variants in which specific emphasis is laid on security and reliability issues.

There is hitherto limited knowledge concerning user behavior in the market of a TCS (Grant-Muller and Xu, 2014; Dogterom et al., 2017). Therefore, one of the primary opportunities for further research is the development of a credit market model which is based on behavioral experiments with potential users. The relevant methodologies for such a study include techniques from experimental economics (for instance, collecting behavioral data through serious games) and choice modeling. Furthermore, arguably one of the most essential aspects of TCS research is to evaluate its effectiveness in reducing congestion and emissions in the transport network. Multiple works so far have used models of the transport network to show the effectiveness of the policy instrument, both for road transport exclusively (Nie and Yin, 2013; Miralinaghi and Peeta, 2016) but also for multi-modal networks (Balzer and Leclercq, 2022). However, these works do not consider the market behavior of consumers (including phenomena like speculation and hoarding) which arguably underlies the implications of introducing a TCS on the transport network. An agent-based modeling (ABM) approach, which has not been adopted in the context of TCS, could provide an opportunity to model trading and travel behavior on a more individual level. Future research should address this gap and thereby allow for a more realistic (i.e., incorporating market dynamics based on behavioral experiments) evaluation of the implications of different TCS variants on the performance of the transport system.

4.1. Ownership

Regarding the ownership and allocation of credits, the role of variable credit allocation (i.e., dependent on socioeconomic status or past travel behavior) in public perception among different segments in the population is worth investigating. Some authors have argued that equity issues arising from the initial credit allocation methods belong to the most politically and socially sensitive aspects in the design process of a tradable credit scheme (Grant-Muller and Xu, 2014; Han and Cheng, 2016). In the currently available literature, most works adopt free and uniform allocation among eligible travelers (He et al., 2013; Miralinaghi and Peeta, 2016; Lessan and Fu, 2019), or no free

allocation at all (Zhu et al., 2017). Few works have considered OD-specific allocation based on the distance from home to workplace (Yang and Wang, 2011) or based on the value-of-time (Xiao et al., 2013). However, to the best of our knowledge, allocation based on socioeconomic indicators remains unaddressed. To address equity issues that a TCS could introduce, such variable allocation techniques arguably possess the largest potential. Future research may therefore address the influence of the variable allocation on trading and traveling behavior for different socioeconomic groups.

Another potential research gap that arises from the proposed framework is the comparison of social acceptability towards a tax-substitute scheme versus a TCS which runs on top of the conventional transport tax structures — replacing such taxes could arguably enhance the intuitiveness and comprehensibility but could also raise concerns about the increased responsibility and involvement of the government. Similarly, an relevant research effort could be done regarding costs induced by tax-substituting versus complementary schemes, as both variants would likely require different levels of robustness, reliability and legislative efforts upon development. From a political and juridical perspective, a feasibility study can be performed to assess whether a tax-substituting scheme is feasible in practice, and with which policy design it could succeed as a suitable and reliable replacement for conventional taxes on car ownership, road usage, and public transport tickets. Even though Krabbenborg et al. (2021) performed a feasibility study for TCS from a political, economical and technical perspective, the possibility of a tax-substitute TCS variant and many design options that were discussed in the previous section have not been considered.

4.2. Transfer

Regarding the transfer of credits between scheme participants, a relevant research opportunity would be to investigate the feasibility and benefits of decentralized infrastructure for the transfer of credits, as it could reduce privacy and security risks. Research could focus on understanding the trade-offs between centralized and decentralized approaches and how to design decentralized systems that are both efficient and secure. Another relevant research gap involves performing a feasibility study of the different regulatory tools to combat hoarding and excessive speculation on the credit market (e.g., taxes, exchange/transaction fees, centralized price bounds and credit validity periods), considering aspects such as cost-effectiveness, equity, and legislative complexity. Additionally, a relevant research gap involves an analysis of the influence that such regulatory measures exert on user behavior in the market and in the transport system. Using market models, it is possible to assess the effectiveness of such measures in combating excessive speculation and hoarding. Extending this to agent-based models of the transport network, it will be possible to directly evaluate the effect of regulative measures on the capability of the TCS to reduce congestion and emissions throughout the transport network. Finally, the transfer dimension also affects the user experience of tradable mobility credit schemes. Research could focus on understanding the factors that influence the adoption and usage of such schemes, such as ease of use, security, and trust, and how these factors can be improved through the design of digital infrastructure, for instance (centralized) exchange platforms.

4.3. Consumption

The majority of works consider credit charging amounts as a parameter of the tradable credit scheme which should be optimized, whereas others argue that credit charging levels should be set in accordance with some measurable unit, such as emission levels, which is expected to increase sociopolitical acceptability and understandability of the scheme's core objectives (Krabbenborg et al., 2021). As of today, there have been no studies that have addressed the effectiveness of externality-based credit charging schemes (Lessan and Fu, 2019). Hence, a promising direction could be to investigate whether the sophistication and complexity of the credit charging method (i.e., static vs. dynamic, mode-dependent vs. mode-agnostic, externality-based, etc.) have an impact on the comprehensibility and thereby the social and political acceptance of the scheme. Models of the credit market could facilitate a study on the influence of different credit charging methods on the trading and consumption behavior of users. Such a study could demonstrate whether more complex and sophisticated charging methods can effectuate a greater behavioral shift. Overall, the research agenda resulting from the proposed framework spans a wide range of open research questions which are essential to further expand the knowledge base on innovative policy instruments for demand management.

CRediT authorship contribution statement

Jesper Provoost: Conceptualization, Methodology, Investigation, Writing – original draft. **Oded Cats:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Serge Hoogendoorn:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

de Palma, A., Lindsey, R., 2011. Traffic congestion pricing methodologies and technologies. Transp. Res. C 19 (6), 1377–1399.
Verhoef, E., Nijkamp, P., Rietveld, P., 1997. Tradeable permits: Their potential in the regulation of road transport externalities. Environ. Plan. B: Plann. Des. 24 (4), 527–548.
Grant-Muller, S., Xu, M., 2014. The role of tradable credit schemes in road traffic congestion management. Transp. Rev. 34 (2), 128–149.
Dogterom, N., Ettema, D., Dijst, M., 2017. Tradable credits for managing car travel: a review of empirical research and relevant behavioural approaches. Transp. Rev. 37 (3), 322–343.
Dogterom, N., Bao, Y., Xu, M., Ettema, D., 2018. Acceptability of a tradable driving credit scheme in the Netherlands and Beijing. Case Stud. Transp. Policy 6 (4), 499–509.
Krabbenborg, L., van Langevelde-van Bergen, C., Molin, E., 2021. Public support for tradable peak credit schemes. Transp. Res. A 145, 243–259.
Krabbenborg, L., Molin, E., Annema, J.A., van Wee, B., 2021. Exploring the feasibility of tradable credits for congestion management. Transp. Plan. Technol. 44 (3), 246–261.
Raux, C., 2002. The use of transferable permits in the transport sector. In: Implementing Domestic Tradeable Permits. Recent Developments and Future Challenges. In: OECD Proceedings, OECD, pp. 141–185.
Raux, C., 2004. The use of transferable permits in transport policy. Transp. Res. D 9 (3), 185–197.
Raux, C., Marlot, G., 2005. A system of tradable CO2 permits applied to fuel consumption by motorists. Transp. Policy 12 (3), 255–265.
Lessan, J., Fu, L., 2019. Credit- and permit-based travel demand management state-of-the-art methodological advances. Transp. A Transp. Sci. 18 (1), 5–28.
Yang, H., Wang, X., 2011. Managing network mobility with tradable credits. Transp. Res. B 45 (3), 580–594.
Miralinaghi, M., Peeta, S., 2016. Multi-period equilibrium modeling planning framework for tradable credit schemes. Transp. Res. E 93, 177–198.

Liu, Y., Nie, Y., 2017. A credit-based congestion management scheme in general two-mode networks with multiclass users. Netw. Spat. Econ. 17.
Xiao, L.-L., Huang, H.-J., Liu, R., 2015. Tradable credit scheme for rush hour travel choice with heterogeneous commuters. Adv. Mech. Eng. 7 (10).
Shirmohammadi, N., Yin, Y., 2016. Tradable credit scheme to control bottleneck queue length. Transp. Res. Rec. 2561 (1), 53–63.
He, F., Yin, Y., Shirmohammadi, N., Nie, Y.M., 2013. Tradable credit schemes on networks with mixed equilibrium behaviors. Transp. Res. B 57, 47–65.
Xu, M., Mussone, L., Grant-Muller, S., 2018. Effects of a tradable credits scheme on mobility management: A household utility based approach incorporating travel money and travel time budgets. Case Stud. Transp. Policy 6 (3), 432–438.
Nie, Y.M., 2012. Transaction costs and tradable mobility credits. Transp. Res. B 46 (1), 189–203.
Tian, Y., Chiu, Y.-C., 2015. Day-to-day market power and efficiency in tradable mobility credits. Int. J. Transp. Sci. Technol. 4 (3), 209–227, Special Issue on Travel Demand Management.
Chen, S., Seshadri, R., Azevedo, C.L., Akkinepally, A.P., Liu, R., Araldo, A., Jiang, Y., Ben-Akiva, M.E., 2021. Analysis and design of markets for tradable MobilityCredit schemes.
Wada, K., Akamatsu, T., 2013. A hybrid implementation mechanism of tradable network permits system which obviates path enumeration: An auction mechanism with day-to-day capacity control. Transp. Res. E 60 (C), 94–112.
Liu, W., Yang, H., Yin, Y., 2015. Efficiency of a highway use reservation system for morning commute. Transp. Res. C 56.
Brands, D.K., Verhoef, E.T., Knockaert, J., Koster, P.R., 2020. Tradable permits to manage urban mobility: Market design and experimental implementation. Transp. Res. A 137, 34–46.
Yao, Q., 2017. A systematic framework to understand central bank digital currency. Sci. China Inf. Sci. 61, 1–8.
Parra-Moyano, J., Macherel, A., Treccani, A., 2018. A 9-dimension grid for the evaluation of Central Bank digital currencies. SSRN Electron. J.
Agur, I., Ari, A., Dell'Ariccia, G., 2022. Designing central bank digital currencies. J. Monetary Econ. 125, 62–79.
Schubert, N., Obermeier, D., Kohlbrenner, F., Sandner, P., 2021. Development of a token design framework. In: 2021 IEEE International Conference on Decentralized Applications and Infrastructures. DAPPS, pp. 30–38.
Freni, P., Ferro, E., Moncada, R., 2022. Tokenomics and blockchain tokens: A design-oriented morphological framework. Blockchain Res. Appl. 3 (1).
Nie, Y.M., Yin, Y., 2013. Managing rush hour travel choices with tradable credit scheme. Transp. Res. B 50, 1–19.
Balzer, L., Leclercq, L., 2022. Modal equilibrium of a tradable credit scheme with a trip-based MFD and logit-based decision-making. Transp. Res. C 139, 103642.
Han, F., Cheng, L., 2016. The role of initial credit distribution scheme in managing network mobility and maximizing reserve capacity: Considering traveler's cognitive illusion. Discrete Dyn. Nat. Soc. 2016, 1–12.
Zhu, W., Ma, S., Tian, J., 2017. Optimizing congestion and emissions via tradable credit charge and reward scheme without initial credit allocations. Physica A 465, 438–448.
Xiao, F., Qian, Z.S., Zhang, H.M., 2013. Managing bottleneck congestion with tradable credits. Transp. Res. B 56, 1–14.