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ABSTRACT

The interest in tradable mobility credits (TMC) is growing steadily. Compared to existing instruments, its cap-and-trade design for the demand side ensures that a limited quantity, e.g., traffic and related emissions, can by design not be exceeded. However, most TMC schemes are market-based financial instruments that can only be successful, if the market ensures the most efficient allocation of resources and if one can rely on the price. Hence, TMC schemes require trading activity and a liquid market that only emerges when participants are able and willing to trade. In this paper, we systematically review the TMC literature for aspects of trading activity and market liquidity, summarize the literature streams, and discuss determinants of participants' ability and willingness to trade TMCs. During the literature review we separate those into demand-side, supply-side, and market regulation factors. This first coherent discussion of creating liquid TMC markets with substantial trading activity challenges the instrument and allows us to draw valuable conceptual implications for the TMC scheme design, but also implications for stakeholders beyond concept. Generating trading activity and liquid markets is thoroughly possible, but robustly achieving it can be challenging.

1. Introduction

When means to internalize the external costs of carbon emissions have been discussed, two market-based alternatives were put forward: a Pigouvian tax and cap-and-trade scheme ("price" vs. "quantity"). Both alternatives have been implemented in various different formats around to world (Goulder and Schein, 2013). Contrary, to manage externalities in transport, the preferential approach has been to use fuel excise taxes and congestion charging, which can be related to pricing or the Pigouvian approach (Parry et al., 2007). Contrary, cap-and-trade schemes have only received little attention so far. Arguably, vehicle quota systems are among the closest schemes as of yet (Chin and Smith, 1997). However, it has been recently concluded that the promotion of economic instruments to address transportation externalities has had only limited success so far compared to carbon emissions (Lindsey and Santos, 2020), with only a few road pricing schemes having been implemented in practice (Anas and Lindsey, 2011).

In transportation, the cap-and-trade scheme is commonly known under the term tradable mobility credits (TMC) on the consumer side, rather than on the producer side as it happens for other cap-and-trade schemes like carbon emissions. They have been initially proposed by Verhoef et al. (1997) and they are considered a "promising alternative" to congestion pricing (Grant-Muller and Xu, 2014; Krabbenborg et al., 2021b). The primary behavioral mechanism in terms of mobility outcomes has been formulated by Yang and Wang (2011): travelers obtain credits, which they can trade or redeem for mobility; the resulting credit market price multiplied by the respective credit charge (per link or trip) is added to the generalized costs of travel for a mode or route. The market volume and charging scheme can follow various objectives and applications, as seen in the most recent literature overview provided by Balzer et al. (2021) and Provoost et al. (2023). Kockelman and Kalmanje (2005) stated that these schemes have the potential to gain higher acceptance, especially if users receive a sufficient share of the credits for free (De Borger et al., 2022).

However, there are challenges to a successful implementation of a TMC scheme. Notably, there is the question of public acceptance (e.g., Kockelman and Kalmanje, 2005; Krabbenborg et al., 2021a), but in a TMC scheme, there is also the challenge to ensure trading activity and liquid markets. Here, Nie (2012) was among the first to discuss this issue. For example, he emphasized that it could be that individuals wish to avoid the market or that individuals have too high transaction costs

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for finding trading partners that could lead to the market becoming "inactive". In the financial market literature, this and similar issues are subsumed under trading activity and market liquidity (Foucault et al., 2013). For similar artificial environmental markets, Stavins (1995) already noted "transaction costs, which may be significant in these markets, reduce trading levels and increase abatement costs". Consequently, the dimension of trading activity and market liquidity, or in other words, participants' ability and willingness to trade, is critical to consider in the design of TMC schemes.

A market is seen as "liquid" when it is easy, i.e., at little or no transaction costs, to find trade partners for large trade volumes without affecting the market price (Muranaga and Shimizu, 1999). While the discussion on trading activity and market liquidity is fairly abstract in nature, consider the following situation in a TMC scheme, where the market price of TMCs is the critical behavioral signal: if no one is able, willing, or forced to trade TMCs, there will be no market price (it is effectively zero), resulting in no or only minor influence on travel behavior. In addition, if there is no reliable market price, no one is arguably willing to make economic decisions. A more practice-oriented example is when a transportation system faces unplanned disruptions, e.g., subway strike, or larger deviations from the planned or desired state. If the market is not liquid enough to absorb larger trading demands than expected, prices will become volatile or the market dries up. Likewise, a low market price indicates an excess of credits on the market, which in return can imply a weak debt ratio towards the emission achievement rate. These situations must be avoided to harness the full economic potential of a cap-and-trade scheme on the demand side. Thus, the guiding research question of this paper is: what is the state-of-the-art understanding in TMC literature of the ability and willingness to trade TMC to ensure market liquidity and activity? We structure the findings across three domains: (i) basic design parameters, (ii) temporal dimension, and (iii) market actors.

In this paper, we contribute with the first holistic discussion on trading activity and market liquidity in TMC markets to understand when people are able and willing to trade their TMCs. We perform a systematic literature review, summarize the literature streams, and discuss the determinants of the ability and willingness to trade on the demand and supply side as well as the role of regulation. We summarize the most relevant hypotheses on factors that support or obstruct trading activity and market liquidity and finally conclude the findings.

This paper is organized as follows. Section 2 provides a literature review on tradable mobility credits, trading activity, and market liquidity, then derives conjectures for trading activity and market liquidity in TMC schemes. Section 3 extends the literature review and presents a current state-of-the-art regarding trading in TMC schemes. In Section 4 we discuss the determinants for participants' ability and willingness to trade. Then, we derive conceptual implications and hypotheses for trading activity and market liquidity in TMC schemes, implications for stakeholders in practice and future research directions resulting from the literature review in Section 5, before making concluding remarks in Section 6.

2. Context analysis

2.1. Tradable mobility credits

Tradable mobility credits (TMCs) are an economic instrument to correct market externalities. They belong to the family of cap-and-trade schemes. Comprehensive reviews of the relevant literature have been provided by Provoost et al. (2023), Fan and Jiang (2013), Grant-Muller and Xu (2014), and Blum et al. (2022). The basic principle is that credits are introduced as a mobility currency. Their face value is usually linked to travel performance or infrastructure capacity usage measures, e.g., kilometers traveled or the cost of using a link. Following a set objective a total budget of TMCs is defined. This budget is distributed to users, who can usually redeem TMCs for mobility and trade them in a dedicated market to generate a financial income. Blum et al. (2022) proposed to use credits, called MobilityCoins, also as additional incentives, e.g., for cyclists that cycle during peak hours, to promote a shift to sustainable transport modes. Although the prime objective of TMCs is congestion management, their objective can also include the reduction of other externalities like carbon emissions (Abdul Aziz and Ukkusuri, 2013; Miralinaghi and Peeta, 2019; Blum et al., 2022). As of 2022, no TMC scheme has been implemented so far. Nevertheless, next to understanding the primary mechanisms (e.g., Yang and Wang (2011)), public opinion and public acceptance have already been studied (e.g., Krabbenborg et al. (2021b)).

TMCs are an alternative to road pricing and road user charging in transportation demand and traffic management to reduce congestion and emissions (Verhoef et al., 1997; Brands et al., 2020). Compared to road pricing, TMCs are considered promising and have important advantages, e.g., as credits, which have been allocated free of charge, can be seen by users as avoiding a tax, and unused credits turn into an 'immediate and tangible monetary' benefit (Raux, 2004). Further, credits do not require financial flows between users and the agency, only between users, making it a 'politically more feasible policy measure' (Brands et al., 2020). A credit-based scheme can outperform in terms of social welfare a toll scheme when the tolling system is not day-to-day adaptive, but the supply of credits is, but their welfare outcomes are identical when both schemes are day-to-day adaptive (de Palma et al., 2018). Only a few notable cases exist where congestion charges have been implemented, e.g., London, Milan, Stockholm, and Singapore (Santos, 2005; Anas and Lindsey, 2011). Nevertheless, it should be mentioned that under certain circumstances, the combination of carbon taxes and congestion charges could reduce social welfare when fuel-related externalities are overpriced (high fuel excise taxes) and a congestion charge (Anas and Lindsey, 2011).

Setting the parameters of the TMC scheme right is key to making a TMC scheme an economic success. These parameters are the charging scheme, the initial distribution to travelers, and the market mechanism (Provoost et al., 2023). For the latter, as aforementioned, price limits and transaction costs factor into market efficiency. In Balzer and Leclercq (2022b), the credit distribution is uniform among the travelers, and the Market Clearing Condition (MCC) represents the market mechanism. The network equilibrium is computed with a macroscopic approach for different credit charges (required to drive a car). Total travel time and carbon emissions are estimated to draw a Pareto front. This framework is extended in Balzer et al. (2023) to account for a time-varying credit charge. Blum et al. (2023) formulated credit charges based upon average mode-specific emissions. Various scenarios were explored, demonstrating the evolution of pricing changes and periodic credit allocations as well as selective use of credit for crowdfunding measures. This, in turn, culminated in a diverse stimulation of market prices and credit consumption patterns.

2.2. Trading activity and market liquidity

Trading activity refers to the exchange of the underlying asset – here TMCs – in terms of buying and selling. Trading activity is commonly measured in the total number of traded assets (per time period), the monetary value of all traded assets (per time period), and the number of trades (per time period) (Chordia et al., 2001), which describes the market performance. A market is considered liquid when large volumes of trades can be made at any time with little impact on the market prices. Liquidity can also be seen as an indicator of uncertainty: when liquidity is high, the market price uncertainty can be considered low, thus helping individuals and companies to make decisions that rely on the price (Muranaga and Shimizu, 1999). Liquidity is typically measured in the bid–ask spread, an indicator of transaction costs, that is the difference between the quoted bid and ask prices, either in absolute or relative terms (divided by the mid-point of the quote). The market depth is measured in the average of the quoted bid and ask depths,

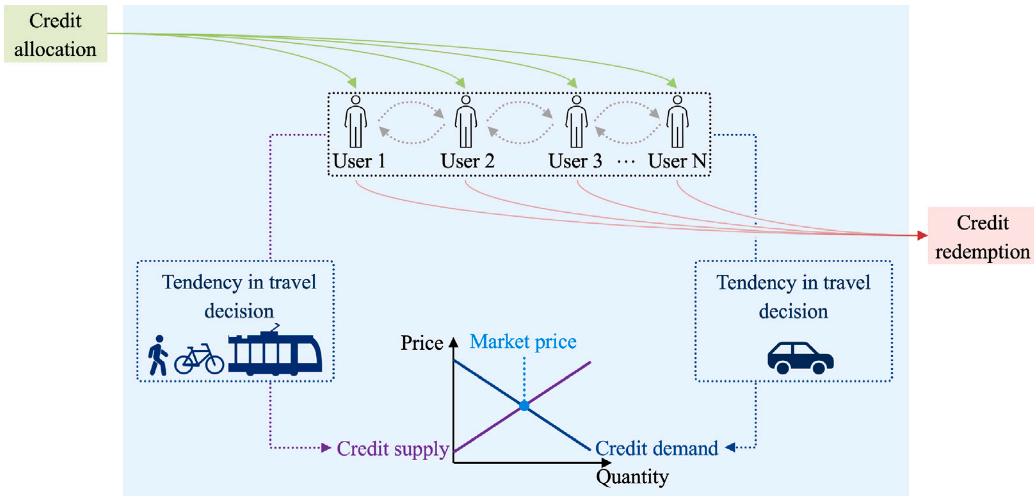

Fig. 1. Credit flow and challenge to trading activity in the TMC scheme and market.

i.e., the depth of the order book, either in absolute terms or weighted by the bid and ask prices (Chordia et al., 2001). Importantly, market liquidity cannot be expressed by simple arithmetic (Hicks, 1989), not even can all dimensions be captured with a single measure (Amihud, 2002).

TMCs can be considered part of the so-called environmental markets. Arguably as their primary discussed intention is to internalize the external costs of transport (emissions and/or congestion). These markets are artificial markets. Existing environmental markets cover a wide range of applications, e.g., carbon emissions (Perdan and Azapagic, 2011), green power (Frei et al., 2018), fishing quota (Newell et al., 2005), ecosystem services (Palmer and Filoso, 2009), and water quality (Shortle, 2013). However, the successful design of these markets leading to an effective allocation of resources is challenging and involves trial and error as stated by Bayon (2004) "*if we are going to use markets to protect the environment, we need to create more environmental markets with an eye for good design and then make adjustments as we go along. In short, we need to keep trying*". Probably the most notable environmental market is the carbon market, where the interactions of market design, trading activity, and liquidity with respect to the system efficiency have been of concern and received attention in literature, e.g., Pearse and Böhm (2014), Schmalensee and Stavins (2017), Zhao et al. (2016) and Ibikunle et al. (2016). Nevertheless, it has been noted already in literature that creating trading activity and liquid markets in these environmental markets is challenging (e.g., Stavins, 1995; Frei et al., 2018).

While trading activity and market liquidity are concepts for which some measures exist (see above), it is not trivial to argue when a market is liquid. For example, NASDAQ provides only a qualitative definition (similar to the definition above).[1] As a reference, when considering the foreign exchange market a liquid market, the relative bid–ask-spread in exchanging Euros for Dollars is at the time of writing 0.0082%. In addition, for the natural gas market, the International Energy Agency (IEA) considers that a turnover ratio or churn rate >10 corresponds to a liquid market.[2] Such high turnover ratios suggests that speculation is present in the market.

2.3. Conjectures

Considering Fig. 1 it becomes clear why trading activity matters: the flow of credits in most TMC schemes is from the agency's initial allocation to users redeeming credits for mobility. If all users have a sufficient number of credits for their mobility, they must not trade at all and the TMC market is empty with zero behavioral effects. Only if users have a balanced TMC trading supply and demand, a reliable market price emerges that acts on travel behavior. Note that this is only relevant when the TMC scheme requires a user-generated market price (see, e.g., Nie and Yin (2013) for a system proposal without trading requirement). Combining Fig. 1 and this paper's guiding research question translates into the TMC scheme design challenge of interrupting the general flow of credits in such a way to initialize the trading cycle with a reliable market price. This challenge can be broken down into at least two dimensions based on Section 2.2:

- the market should be *deep* by always having enough credit supply and demand, to allow for large trading volumes with low uncertainty in the system.
- the generalized transaction costs should be *low* to incentivize market participation and market price discovery (i.e., looking for a trade partner and negotiation) and prohibit hoarding of TMCs.

If this challenge is not appropriately addressed, the resulting oversupply or undersupply of TMCs would lead to market prices that are not adequately giving market signals. Importantly, another challenge is included: reliable market prices only emerge when users trade larger volumes, while users trade larger volumes only when they can rely on the market price. Hence, one can conclude that it is of utmost importance to understand how trading ability and willingness are enabled in a TMC scheme to make the system a success. So far, TMC scheme literature already discussed some aspects market design, price formation, and user behavior, but a coherent perspective is missing. Thus, to fill this gap, we perform a systematic literature review in Section 3 and discuss determinants of the ability and willingness to trade in Section 4.

3. Literature review — trading in TMC schemes

Some studies already investigated trading activity and market liquidity aspects of TMC schemes. To get an understanding of these aspects in literature, we performed a systematic literature review using the Web of Science database. We conducted the literature search in April 2023 using the following query:

```
ALL=(("travel" OR "transport" OR "mobility")
AND ("mobility credit*"
```

[1] https://www.nasdaq.com/glossary/l/liquid-market.
[2] https://www.iea.org/commentaries/fast-tracking-gas-market-reforms.

```
    OR "mobility permit*"
    OR "tradable credit*"
    OR "tradable permit*"
    OR "parking credit*"
    OR "parking permit*")
AND ("trading" OR "transaction" OR "market"))
```

We applied this query to the fields of transportation and economics and to all fields in the database. Note that this does not include the main text. The search resulted in 58 papers out of which 45 are relevant for this review as the others do not cover road transport or are conference papers that have been subsequently published in academic journals. Note we also tested “trading behavior” and “trading activity” instead of “trading” as well as “market liquidity” instead of “market”. In neither case, we find any additional papers, while rather substantially reducing the list of papers.

To get an overview of the prevalence of trading activity and market liquidity in the TMC literature, we search the main text of the 45 publications for the terms “trading activity” and “market liquidity” as well as terms that are typically used to describe the two mentioned aspects as explained in Section 2.2: “Trading volume”, “Market performance”, “Transaction costs”, “Volatility”, and “Speculation”. Generally, none of these publications mentions trading activity and market liquidity directly.

Noteworthy, Tian et al. (2019) mentions the requirement of having a liquid market “The TMC market should be capable of handling large volume of trades, without leading to noticeable price fluctuation”., but without explicitly stating the term market liquidity. However, a few publications mention, analyze or discuss the mentioned related terms. Here, “Transaction costs” is most frequently covered (in total 14 publications: Yang and Wang, 2011; Nie, 2012; Wu et al., 2012; Fan and Jiang, 2013; He et al., 2013; Bao et al., 2014; Grant-Muller and Xu, 2014; Wang and Zhang, 2016; de Palma et al., 2018; Gao et al., 2019; Lian et al., 2019; Brands et al., 2020; Zhang et al., 2021c,b), where a few discuss exactly their role in the success of this system, e.g., Nie (2012) and Zhang et al. (2021c). “Trading volume” is covered by in total 7 publications (Gao et al., 2019; Nie, 2017; Bao et al., 2014; He et al., 2013; Zhang et al., 2020, 2021c,b). “Volatility” is also mentioned by 7 publications (Shirmohammadi et al., 2013; Miralinaghi and Peeta, 2016; Brands et al., 2020; de Palma and Lindsey, 2020; Krabbenborg et al., 2020; Han and Cheng, 2016; Xiao et al., 2013), where Xiao et al. (2013) and Han and Cheng (2016) make clear statements about that volatility is undesired or a burden. “Speculation” is mentioned in six publications (Nie, 2012; Wu et al., 2012; Nie, 2015; Gao et al., 2019; Brands et al., 2020; Krabbenborg et al., 2020), where only (Brands et al., 2020) as a dedicated section on this matter while the others just mention it. Last, “Market performance” is mentioned by two publications (Miralinaghi and Peeta, 2016; Tian et al., 2019). From this analysis, we can already conclude that awareness of trading activity and market liquidity in TMC schemes is already present in literature.

3.1. Summary of literature streams

We group the reviewed literature into four streams with respect to market activity: “perfect market”, “transaction costs”, “uncertainty and volatility”, and “user trading activity”, where the streams are not mutually exclusive. Among the 45 reviewed publications, there are 7 without explicit consideration of market activity, rather than stating it as part of a TMC scheme (Zhang et al., 2011; Ramazzotti et al., 2012; Xiao et al., 2015; Mamun et al., 2016; Lahlou and Wynter, 2017; Wang et al., 2019; Liu et al., 2023). In the following, we present for each of the four literature streams a concise summary.

3.1.1. Perfect market

Undoubtedly, the focus in literature so far has been on mathematical modeling of the core mechanism of TMC schemes, arguably to understand the scheme’s impact on transport outcomes. Thus, originating from the seminal paper by Yang and Wang (2011) key assumptions frequently made are that trading occurs when it is mutually beneficial, the market is competitive and large leading to a uniform and constant price, and low transaction costs exist (e.g., Wu et al., 2012; Wang et al., 2012; Tian et al., 2013; Xiao et al., 2013; Wang et al., 2014; Zhu et al., 2015; Wang and Zhang, 2016; Han and Cheng, 2016; Bao et al., 2017; Wang et al., 2018a; de Palma et al., 2018; Zhang et al., 2020). In these primarily mathematical modeling works, trading is described through a simple macroscopic market clearing constraint where all consumed credits must be equal or less than the total market volume.

Recently, however, the first studies emerged who focused more on price discovery (Lessan et al., 2020; Brands et al., 2020).

3.1.2. Transaction costs

Transaction costs refer to all costs associated with transferring permits or credits from one party to another. The transaction costs comprise, e.g., a transaction fee imposed by the system operator to limit speculation (e.g., Miralinaghi and Peeta, 2016), transaction fees imposed by the trading platform or other intermediaries for their services, e.g., for providing information or finding partners (e.g., Grant-Muller and Xu, 2014), search time for finding trade partners (e.g., Fan and Jiang, 2013), which as argued by Nie (2015) could be substantial when compared to the travel time savings, as well as the “inconvenience” of using the system (Wang et al., 2014).

Once transaction costs become too large, participants may become inactive (Nie, 2012) and trading volumes decline and the market price diverts from its equilibrium (He et al., 2013; Zhang et al., 2021b,c), where the latter authors show that in such situations travelers with higher values-of-time benefit substantially more from a reduction in travel costs compared to travelers with lower values-of time. In any case, in such cases with too high transaction costs the market-based instrument becomes inefficient (Nie, 2012; He et al., 2013). Importantly, Nie (2012) notes that the initial allocation and marginal transaction costs “may affect the final equilibrium”.

As emphasized by Lian et al. (2019) for setting the transaction fee “tradability of credits is a dilemma” as system operators and intermediaries seek to cover their costs, while users only trade if it is beneficial for them, depending on their value of time. Here, it is argued that innovation in technologies of mobile platforms may facilitate trading and reduce transaction costs (Lian et al., 2019). Also intermediaries, e.g., financial institutions can act as brokers in the market to reduce transaction costs (e.g., Fan and Jiang, 2013; Grant-Muller and Xu, 2014).

3.1.3. Uncertainty and volatility

The literature is well aware of the fact that “price and quantity regulation are not equivalent under uncertainty” (de Palma and Lindsey, 2020) and that in “presence of uncertainty and strongly convex congestion costs” quantity control instruments such as TMCs should be favored (de Palma et al., 2018). Despite this advantage, uncertainty in the market has to be addressed in terms of trading activity. Uncertainty here refers to uncertainty in supply and demand (e.g., Shirmohammadi et al., 2013) and in the market price (e.g., Miralinaghi and Peeta, 2020), eventually leading to price volatility and in some situations not at all to equilibrium situations (Gao et al., 2019). As with too high transaction costs, increasing uncertainty decreases the effectiveness of TMC schemes.

The reviewed literature presents at least two approaches to reduce uncertainty and associated price volatility. First, Zhang et al. (2021a) propose to define a recommended market price in the beginning. Second, multi-period schemes where TMC can be used in several periods, i.e., users can save some for later or hedge against price fluctuations, are proposed to dampen price volatility (Ye and Yang, 2013). In such situations, multi-period schemes can achieve more efficient resource allocation (Miralinaghi and Peeta, 2016; Wang et al., 2018b). Given the natural uncertainty in transportation systems, e.g., due to weekday or weather, the obvious implication for the system design to addresses uncertainty and volatility is to use multi-period schemes according to the presented literature.

3.1.4. User trading activity

Obviously, TMC users only trade with each other when it is mutually beneficial (Yang and Wang, 2011). However, literature presents various behavioral aspects that impact trading activity too. Here, the focus groups in Krabbenborg et al. (2020) provide first-hand perceptions of the public. In these focus groups and in the reviewed literature, the following four dimensions appeared: "valuation of time", "loss aversion", "speculation", and "skills".

First, as aforementioned, the valuation of time determines when trading is beneficial (Nie, 2017). Given the population's heterogeneity in this valuation, it is clear that users with higher valuation are likely to participate in trading at higher market prices and transaction costs, probability giving them more congestion relief benefits (Zhang et al., 2021b,c).

Second, it is well known in behavioral economics that individuals assess or value losses greater than gains of the same magnitude. Such situations also occur in TMC schemes and research has shown that increasing "loss aversion", decreases system efficiency (e.g., Bao et al., 2014; Miralinaghi et al., 2019). Here, Grant-Muller and Xu (2014) propose to consider models of "individual behavior and choice" in the model building for understanding and designing TMC schemes.

Third, as phrased by Nie (2015) "markets always create speculators". Speculation means hoarding credits and taking advantage of price differentials. Here, the reviewed literature discusses speculation primarily as undesired (e.g., Grant-Muller and Xu, 2014; Nie, 2015; Krabbenborg et al., 2020), but there is desired speculation too (Brands et al., 2020). The latter authors argue that buying and selling at multiple times always when one is better off one could lead to a faster convergence the equilibrium price. The authors also define undesired speculation as market price manipulation and eventually large speculation profits. To prevent this, the authors propose to use transaction fees, trading by the piece, having a maximum number of credits one can own, and if the user has already made multiple trades on the same day, the price should not be changed after a transaction.

Fourth, it is argued many times that such a trading system is "complex" and requires skills (e.g., Tian et al., 2019; Krabbenborg et al., 2020), in turn, that for such a scheme in order to stay functional, an upper limit to the system's complexity exists (Brands et al., 2020). When considering that depending on the type of TMC scheme design one to five trades per trip are necessary (Fan and Jiang, 2013), the efforts and time required could be substantial (Nie, 2015). As a consequence, Nie and Yin (2013) use the argument of not relying on active trading for motivating their proposed TMC design alternation, which implicitly summarizes the concern in literature over making such complex schemes functional.

3.2. Summary and gap

A first interesting observation from this systematic literature review is that all publications are from 2011 onwards, also underlying the impact by Yang and Wang (2011) on the methodological development of TMC research. Literature before that date (e.g., Kockelman and Kalmanje, 2005) and Kalmanje and Kockelman (2004) may have had a different focus, which is also reflected in the fact that the keywords "trading" and "transaction" are not present in the main text. Nevertheless, as the work by Raux (2004) emphasizes that concern about high transaction costs for permits was already present. Considering the time period from 2011 onwards, the systematic search did not reveal all publications that address trading in TMC schemes. For example, the agent-based market activity modeling by Tian and Chiu (2015), the TMC scheme design analysis by Provoost et al. (2023) calling for liquid markets, and the conclusions by Krabbenborg et al. (2021a) that trading requires cognitive effort and that "people generally prefer schemes that require less *trading hassle*".

Nevertheless, the review reveals that aspects of trading activity and market liquidity are already present in literature and that research is aware of the challenges associated with it. While the methodological focus has been so far on understanding the basic principles of TMC schemes assuming a "perfect market", we can make the conclusion from this systematic review that the behavioral dimensions of trading and additional transactions costs have to be considered in the assessment of TMC schemes as it has the potential to make an in-theory economically efficient instrument inefficient (e.g., Nie, 2012; He et al., 2013; Bao et al., 2014; Miralinaghi et al., 2019). The TMC literature already presents starting points for analyzing market liquidity and trading activity. Still, it is clear that first an understanding of factors contributing to trading activity and market liquidity is required.

4. Discussing determinants of participants' ability and willingness to trade

Arguably, the determinants of participants' ability and willingness to trade depend on demand-and supply-side factors as well as on the regulation of the system. Therefore, we discuss determinants in the following in these three dimensions.: The demand-side in Section 4.1 discusses travel behavior and user preferences, the supply-side in Section 4.2 discusses transportation systems as well as network structure and land use, while regulation in Section 4.3 discusses the scheme's objectives, credit distribution, and speculation.

4.1. Demand side

4.1.1. Travel behavior

Much of the variation of the observed travel behavior is predictable (Ewing and Cervero, 2010; González et al., 2008). This predictability allows to discuss factors that contribute to trading activity and market liquidity.

First, car ownership is expected to influence trading behavior, where the resulting hypothesis for trading activity is (assuming that car travel is charged higher than alternative modes): those who like driving or have to drive have higher demand and willingness to pay for TMCs, while those who do not need a car might be more susceptible to a behavioral change. Consequently, the latter group is willing to sell more, which is quantitatively illustrated in Fig. 2. Δ_s shows the shortage of credits in relation to a uniform allocation of the agency for a car-focused user group. In contrast, Δ_e shows an excess of PT users. Thus, the implication for trading activity is the system design must be aware of and consider the composition of these groups in the general population. It also becomes apparent that if the population consists only of people who need or do not need the car, trading supply and demand will be imbalanced with negative consequences for trading activity.

Second, travel behavior aspects like trip distance, the location of home and workplaces, the accessibility to public transport (PT) services are affecting trading activity. Here, it could be expected that persons with a high regularity of their (car) trips (e.g., commuters) – even stronger for longer trip distances – will have a hedging-oriented or buy-and-hold trading behavior. They will be active on the market, but require larger TMC volumes, i.e., a deep and liquid market, as they can plan better how long the credits will suffice and aim to benefit from better prices when trading larger volumes. This trading behavior could be partially offset by a higher initial allocation of TMCs. Nevertheless, in the latter case, these volumes would again bypass the TMC market (see Fig. 1) and thus not contribute to creating a liquid market. Contrary, persons who have rather varying and flexible travel behavior

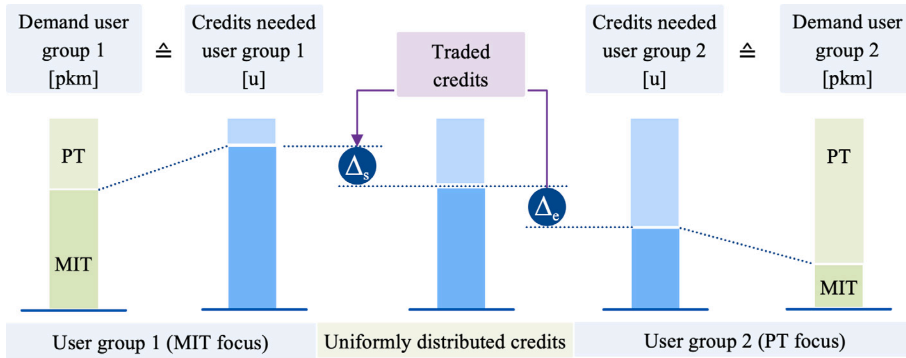

Fig. 2. Cause of credits to be traded: user groups.

(e.g., students) could be more sensitive to the incentives provided by TMCs. Regarding public transport accessibility, the higher its levels the more likely people are to respond to the TMC market signals and generate TMC trading supply and demand, while their volumes per person could be expected to be smaller compared to long-distance commuters.

Generally, following the D's (density, destination accessibility, diversity, distance to transit) of travel demand (Ewing and Cervero, 2010), we expect that the ability and willingness to trade is likely to increase with the *D*'s. The higher they are the more likely people are to have alternatives and have lower car travel and car costs, making them less likely to face high financial risks and start hedging, while being willing to be active on both sides of the TMC market.

4.1.2. Human preferences

Personality traits, socio-demographic and socio-economic factors are likely to impact the willingness to sell and the willingness to buy credits. Here, Section 3.1.4 presents a discussion focusing on trading in TMC schemes, while Dogterom et al. (2017) present an overview of behavioral responses in TMC schemes in general. Building on this, regarding the validity period of credits, risk-averse people might save more credits until the end of the period. This behavior could be influenced by the *endowment effect*, meaning overvaluing what is in one's own possession. Dogterom et al. (2017) argue that this effect might lead to over-conserving credits and a suboptimal trading level. Especially for TMC schemes with a market-driven, rather than fixed-price levels, the authors expect this effect to be significant. If risk-averse people, on the other hand, use large amounts of credits, they might buy credits earlier than others, and have a larger remaining budget at the point of purchase than risk seeking people. This is closely related to the *immediacy effect* (Keren and Roelofsma, 1995), as having credits now is worth more than having them in the future. Rewards can also play a role in the general willingness-to-sell credits in a TMC scheme. If, for example, cycling is rewarded with positive amount of credits, as in the MobilityCoin system (Blum et al., 2022), this can additionally influence the time of sale, and both affect the trading behavior of risk averse and risk-seeking people.

4.2. Supply side

4.2.1. Transport systems

The supply side of an urban transportation system consists of road networks, dedicated public transport infrastructure like subway and tram lines as well as the associated public transport services. The road network is usually shared among modes, while dedicated infrastructure for some modes may exist, e.g., HOV, bus, and bike lanes. The TMC schemes proposed in literature mainly aim at reducing car usage. As some travelers may give up driving their car due to the additional credit costs, it is necessary to account for the shift to other transportation modes. Especially since those travelers may sell their unused credits on the market and thus increase the market supply. In addition, as proposed by Blum et al. (2022) and Balzer and Leclercq (2022b), TMC charging scheme must not be limited to car and can include other transportation modes as well. Table 1 summarizes the most relevant urban transportation modes with their associated TMC scheme rationale.

The rationales of TMCs for the presented modes in Table 1 act together with the overall system objective, e.g., reducing congestion, carbon emissions or space consumption. Therefore, different targets such as pollution and total travel time might lead to different target modal share outcomes. Reducing carbon emissions from vehicles with internal combustion engines would eliminate almost all existing cars and promote active modes (bicycle and walking). Such a measure would, however, greatly increase the total travel time and decrease accessibility for the elderly.

The individual passenger car currently sees several transformations that can impact trading activity. First, vehicle automation could make cars driving closer together (Seilabi et al., 2020), thus the same road network can accommodate more vehicles. Second, the share of *greener* vehicles (electrical and hybrid) is increasing, reducing the emissions of pollutants linked to car travel (Miralinaghi and Peeta, 2019). Third, car-pooling and ride-hailing services can increase average vehicle occupancy (Xiao et al., 2021), likely to increase the usage efficiency of cars. The TMC agency can set incentives by charging according to vehicle type and occupancy, but it becomes apparent that trading activity will differ substantially depending on whether the vehicle kilometers or individual mobility (and goods) is charged. Higher trading volumes can be expected for individual mobility.

4.2.2. Network structure and land use

The urban center is presumably always part of a TMC scheme. First, it is usually an area where *congestion problems* exist, namely overcrowding and high emission levels. Second, TMC incentives could lead to behavioral shifts because a good public transport service level usually exists, making it a viable alternative. Approaching the suburbs, this may change as congestion problems might be less severe and fewer mode alternatives exist. Thus, TMC makes sense where car externalities can be limited or mitigated.

Network structure and land use (urban form), housing costs and the travel costs interact in the long term (Glaeser, 2007). For example, high costs for car travel caused by TMC may increase the housing demand in the (transit oriented) city center; or at low congestion levels and low costs for car travel, many would favor to move into larger housing in the suburbs (Gubins and Verhoef, 2014). The well-off are expected to relocate to their desired locations and thereby either aim to sell (living in the city center) or buy (living in the suburbs) credits, while the less well-off have to locate elsewhere. With respect to trading activity, demand or supply then could become imbalanced and governed by market power if the interactions of urban form, income and travel behavior is not properly considered in the system design.

Table 1
The basic set of transportation modes considered in a TMC scheme.

Mode	TMC related features
Car	It is the most flexible and usually fastest transportation mode. However, through its low vehicle occupancy in terms of passengers and super-linear volume-delay relationship, it is generally the main contributor of transport emissions and congestion levels. We can distinguish cars according to their level of passenger occupancy, propulsion technology, level of autonomy, and their service type (e.g., personal car, ride-hailing etc.). Arguably, the rationale of TMCs for cars is to minimize externalities.
Public transportation	This mode provides usually substantial passenger capacity and an alternative to the car in the (urban) transportation system. It is the least flexible as both routes and timetables are fixed. During peak hour this mode can also experience overcrowding and delays, but usually not of the same magnitude as cars. We can distinguish this mode according to vehicle type and associated service, e.g., tram, bus, subway etc. Arguably, the rationale of TMCs for public transport is to stimulate changes in congestion- and other externality-related travel behavior choices, e.g., mode, departure, and route choice.
Bicycle & micro-mobility	This mode is a flexible and the most eco-friendly mode, while seeing only little congestion effects. However, it may not be suitable for long trips or during bad weather. Furthermore, it is not an option for a part of the population (mobility impaired travelers). Arguably, the rationale of TMCs for bicycles is to incentive their use to realize their benefits (health, capacity, flexibility etc.) as a further alternative to car travel.

Practical problems with respect to the network structure can also influence trading activity. The geographic boundaries of a TMC scheme may depend on the jurisdiction of the regulating authority, e.g., county or municipality boundaries. In addition, in some countries not all streets in a city are managed by the same agency, e.g., motorways are managed by the state and local streets are managed by the city. Thus, excluding travelers or parts of their travel demand from the TMC scheme, could not only reduce the total market size, but also imbalance trading supply and demand in the TMC market, in particular when some roads are exempted from the charging scheme.

4.3. Regulation

4.3.1. Scheme objectives

One of the essential design decisions of relevance is the scheme's objective. The objective determines what the credit represents and how many credits are consumed upon specific usage of the transport system. For instance, the decision for increasingly refined credit charging methods (link-, area-, time-, and mode-based) might contribute to an increase of trading activity in the market. One might argue that a more refined charging method could increase the number of credits that are needed by users to afford their mobility needs. Hence, more trading would be necessary to satisfy these needs. It should also be noted that the credit charging method might induce fluctuations in trading activity. 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 TMC-wise) 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 some choosing the car again, 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. As discussed in the section of human preferences, users might not prefer this situation and start hoarding credits if the scheme is less comprehensible to them. However, this could also increase trading activity as they buy more often when their balance is insufficient, or sell when they have leftover credits when the market is liquid and they can rely on the market price.

4.3.2. Credit distribution

The initial distribution of credits can be done for free, through auctioning, or through selling at a fixed price (or a combination of those). However, in this paper, a predominately initial distribution of credits for free is assumed, as otherwise, the between-user TMC market would become less relevant. The amount and distribution among eligible users can arguably influence trading activity in the TMC 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, trading becomes unnecessary. Hence, it is likely that a rather uniform allocation will make it necessary for users to trade, whereas an allocation depending on other factors might yield very low trading activity market liquidity. As aforementioned, Nie (2012) notes that the initial allocation of credits and transaction costs are interacting and could negatively affect the final equilibrium, a fact which should not be omitted in the scheme design.

4.3.3. Speculation

Further regulative tools relate to combating speculation and hoarding on the market. As aforementioned, Brands et al. (2020) presents a discussion on desired and undesired trading. In addition to this discussion, means to spur speculation are, for example, expiry dates. They introduce another variable that determines the monetary value of credit: credits that will expire soon might be sold off at lower prices than those that are valid for a longer period. The use of credit expiry dates could spur speculation, thereby increasing trading activity and market liquidity. Also, depending on the expiry dates' granularity, the trading activity intensity might fluctuate more over time.

As prominently mentioned, e.g., by Nie (2012) and Brands et al. (2020), transaction fees can be used to reduce hoarding. If a progressive scheme (i.e., the wealthy are taxed at a higher rate) is applied, trading might be stimulated as an alternative to holding on to assets for a longer time. Hence, capital taxes could arguably increase trading activity. 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 from trading unless they need credits for their mobility needs. This might prevent speculators from entering the market and ensure that only those are trading who actually need them. Then, trading activity will be less frequent than among speculators who attempt to profit, but it could also discourage intermediaries as discussed in the reviewed literature in Section 2.1 who would support the market from participation.

5. Generating trading activity and market liquidity

The literature review in Section 2.1 and discussion on determinants in Section 4 lead to key implications and hypotheses for generating trading activity and market liquidity in TMC markets. Section 5.1 summarizes hypotheses and derives conceptual implications. Section 5.2 discusses implications for stakeholders beyond concept. Section 5.3 discusses future research based on the identified literature gap, which is primarily investigating the complex interactions to generate trading activity and market liquidity using simulators following Bayon's (2004) rationale of "trial and error" in the identification of the best design parameters for an environmental market.

Table 2
Hypotheses on supporting and obstructing the ability and willingness to trade or generating trading activity and market liquidity in TMC schemes.

	Supporting	Obstructing
Demand side	• Heterogeneous travel demand • Certainty (no hoarding)	• Loss aversion • Endowment effect • Immediacy effect
Supply side	• Mode alternatives • Land-use heterogeneity • Adopting technology changes	• No alternative modes • Car-dependent areas only
Regulation	• Refined charging scheme • Uniform initial allocation • Some degree of speculation • Limited validity periods	• Low comprehensibility • Specific initial allocation • High transaction costs

5.1. Hypotheses and conceptual implications

Table 2 summarizes the discussion on the dimensions of demand, supply, and regulation. It becomes apparent that it is not "*easy*" to define TMC scheme parameters that automatically lead to active market participation. Nevertheless, we conceptually see that generating trading activity and market liquidity is possible, e.g., by utilizing the following hypotheses.

First, we conclude that trading activity would benefit from using the existing heterogeneity in travel behavior and preferences within the population to generate trading demand and supply, i.e., excess and lack of credits in the system from user's perspective. For example, car-oriented users who need credits will buy credits from public transport-oriented users who may want to sell credits. This could be achieved by having a rather uniform than individual-specific initial allocation of credits. Second, the more car-dependent areas are included in the scheme's area, and the fewer economic choices are possible, credit demand may surpass credit supply as many users require credits, but few are willing to sell. Thus, the system must comprise mixed zones with high accessibility and high car dependency. Third, the initial credit distribution, available transportation modes, and system objective must be jointly considered, e.g., the agency must keep track of developments and adjust the system design if necessary; otherwise, disruptions may disproportionally impact trading supply and demand. Fourth, desired speculation and market making by third parties can support the generation of trading activity and market liquidity (Galariotis et al., 2019; Frei et al., 2018), while these activities should not disadvantage the primary users of a TMC scheme. Fifth, learning from other environmental markets (Bayon, 2004; Schmalensee and Stavins, 2017) and mature financial markets (Bank for International Settlements, 1999). Last, the understandability of the scheme could potentially impact trading activity as people may avoid the market and trading if the system is too complex or requires too much "trading hassle" (Krabbenborg et al., 2021a; Nie, 2012). Here, the system objective, e.g., limiting car externalities, should be meaningful and comprehensible in the context of the TMC scheme area.

5.2. Implications for stakeholders

In a TMC ecosystem, various stakeholders are present, e.g., government, policy-makers, industry, and users. Hence, it is essential to discuss the implications beyond the concept for each of these stakeholders if a TMC scheme is implemented and understand the effects on trading activity and market liquidity. In other words, a considerate and comprehensive evaluation of the matter is required from the perspective of each stakeholder, shown in Table 3. This ensures that all viewpoints are acknowledged and integrated into the decision-making during the design process.

From the perspective of agencies, the key task is to manage the credit allocation, as well as to determine the credit charges, following the (by policy makers) defined objective of the TMC scheme. This is pivotal in nurturing a thriving market. Essentially, the agency emerges as the linchpin in this system, shouldering the responsibility for market dynamics and regulatory oversight. By closely monitoring the number of credits in circulation, the agency can ensure that motorized individual transport (MIT) remains a limited commodity in terms of mileage, keeping it below actual demand, otherwise, there will be no credit market price, and close to the target value. Additionally, when implementing a transaction tax, the agency possesses the flexibility to calibrate parameters to optimize the system's revenue. This revenue stream is pivotal not only to offset operational costs but also to compensate for the anticipated decline in energy tax revenue. The key implication for agencies is that generating trading activity and market liquidity helps to obtain meaningful price signals and thus making a TMC scheme having impact, where agencies have the ability, but also the responsibility to define system parameters accordingly.

For policymakers, TMC schemes can serve as a tool to meet sustainability targets. Compared to other road user charging schemes, TMC schemes can be socially and politically more acceptable. Nevertheless, as it can be expected that policymakers set the system objective and define the rules of the system operations, their actions can substantially interfere with trading activity and market liquidity. There are two possible scenarios. First, if the agency and the government are one entity or have an overarching agreement, the system has a good chance of functioning as in the textbook, and the agency controls everything. Second, however, if the agency and the government act opposingly, trading activity and market liquidity may be at risk, e.g., when policymakers want to subsidize certain groups or respectively means of transport to get the voters favor. These subsidies can inadvertently alter market dynamics by reducing credit consumption or increasing credit generation of incentives. Thus, all interventions from policymakers must be tracked and reflected in the overall system parameters.

Regarding the transport industry, their primary objective is usually maximizing profits. It is, therefore, in their interest to reduce not only the transaction costs of credits but also to gain user demand. A simple principle operates here: the fewer externalities a user incurs by opting for a particular mode of transport, the more affordable the credit prices, thereby driving up demand for that mode. This provides a tangible incentive for the transport industry to minimize its externalities. Enhancing the efficiency of modes of transport, e.g., by technological advancements, results in a convergence of their respective greenhouse gas emissions profiles towards neutrality. This homogenization is narrowing the difference in credit demand across these transportation modalities. Consequently, a diminishing trading activity is anticipated.

For trading or exchange platform providers – entities operating as third parties – the primary objective is extracting profits from a previously non-existent market. The opportunity of these platforms is directly tied to market activity and liquidity, for which it can be expected that they design their services for. These providers have a degree of influence on credit demand by imposing additional costs possibly borne by users. Additionally, there is a potential for market speculation, which is primarily motivated by profit. To circumvent this, the agency might need to enforce regulations, such as capping credit ownership, restricting trade volumes, or limiting automated high-frequency trading systems, which, in return, has profound implications on the market dynamics.

Regarding market users, it is commonly assumed that they aim to maximize the utility of their decisions. In a TMC scheme, this utility maximization can be impacted in various ways, e.g., using the system so that no extra costs emerge, gaining additional revenue from trading credits, or making income from speculation. How the agency regulates this behavior impacts market dynamics, affecting user behavior. Hence, the implication for market users is the market design should be such that they deliberately want to act in such a way that promotes trading activity and market liquidity.

Nonetheless, it is important to acknowledge that the delineations between these stakeholder groups are not always clear. For instance,

Table 3
Stakeholder in a TMC scheme.

Stakeholder	Characteristics
Agencies (regulator)	• Managing credit allocation and setting credit charges • Central figure, responsible for market dynamics and regulatory oversight • Decision about transaction tax and adjust parameters to maximize system revenue
Policymaker	• Setting objective, operational rules and sustainability targets • Effective if agency and government have overarching goals • Interventions, such as subsidies for certain groups or transport modes can disrupt market dynamics
Transport industry	• Main goal is maximizing profits by increasing user demand • Lower externalities associated with a transport mode make credit prices more affordable • A decrease in trading activity is expected due to a convergence in emissions profiles of different transport modes
Third parties (platforms)	• Focus on profiting from a new market • Success is linked to market activity and liquidity • Risk of market speculation driven by profit motives
Users	• Typically aim to maximize the utility of their decisions • Strive to avoid extra costs, earn revenue from trading credits, or profit from speculation • Market should be designed to encourage users to engage in ways that enhance trading activity and liquidity

regular mobility users might simultaneously seek to maximize trading revenue. Though we have compartmentalized these groups for analytical clarity, the real-world implications beyond concept are more complex.

5.3. Directions for future research: testing for trading activity and market liquidity

The literature review in Section 3 has revealed that the aspect of trading activity and market liquidity, as well as their importance, is present in the literature, but that so far, the understanding of how to achieve this target in a more realistic application or even optimizing its parameters, e.g., introducing a TMC scheme in a metropolitan area, seems missing. This understanding covers the three domains of (i.) basic design parameters, (ii.) temporal dimension, and (iii.) actors active in the market. We can conclude that for achieving an understanding of the generation of trading activity and market liquidity in more realistic applications, a promising avenue is following the "trial-and-error" rationale of Bayon (2004) for the design, but using available simulators. In other words, the ability and willingness to trade under different scenarios and behavioral parameters — can be quantified using simulation. In transport, different approaches emerged. Here, suitable approaches are, e.g., macroscopic models, e.g., as used by Yang and Wang (2011), models based on the macroscopic fundamental diagram (MFD) as used by Balzer and Leclercq (2022b), and agent-based models, as used by Tian and Chiu (2015). Here, it is recommended to start building such models and optimizing the scheme design using a macroscopic perspective before ultimately investigating an assessment of behavior using agent-based models at the last stage.

Macroscopic models have found widespread applications in large-scale, network-wide traffic management. The core feature of these models lies in their ability to capture the macro-characteristics of traffic flow, i.e., the collective behavior of vehicles, making them highly applicable when the overall flow patterns are of interest (Mohan and Ramadurai, 2013). In addition, macroscopic models are deterministic and have traditionally a focus on planning, while they naturally capture network-wide interactions as present in TMC schemes. Market activities can be directly integrated in the traffic assignment, by, e.g., using computable general equilibrium (CGE) models in Mixed Complementarity Problem (MCP) formulation (Blum et al., 2023) or Variational Inequality (VI) (Wang and Zhang, 2016). Here, a market clearing condition that states that supply minus demand for credits should be non-negative, is associated with a variable for credit market price. Such macroscopic models are perfectly suited to investigate the domain of basic design parameters as they simplify the complexity of traffic patterns over substantial geographic areas at reduced computational costs. Such models can assist in the identification of reasonable and effective TMC schemes, e.g., by adjusting credit quantities in the market, by exploring various pricing scenarios, and by examining the mechanism of achieving a system objective.

The MFD is a predictable and well-defined relationship between the accumulation of cars and their travel production/speed in an entire urban area (Daganzo, 2007; Loder et al., 2019). It, therefore, focuses on aspects that affect entire networks. The trip-based MFD, an assignment procedure based on the MFD (Mariotte et al., 2017), assumes the vehicle speed is spatially homogeneous and depends on the number of vehicles driving on the network. In contrast to the previously mentioned macroscopic models, it usually considers congestion dynamics, while being computationally less expensive than microscopic models. This computational advantage has been already proven in the case studies and analyses (e.g., Balzer and Leclercq, 2022b,a; Balzer et al., 2023). This simulation framework can be considered adequate for exploring the impacts of TMC scheme parameters over large ranges, but also where the time dimension is relevant, e.g., market or congestion dynamics within a single day, or when studying the behavior within a "fiscal" period, but also when studying the time evolution of TMC schemes over several "fiscal" periods in order to meet targets. Within this modeling approach, the potential benefits and challenges of cascaded credit allocation in batches can be investigated as well as the how the longevity of credits (expiration) impacts market dynamics and system outcomes.

In transport, agent-based models typically simulate activity sequences of agents (Axhausen et al., 2016). Thus, in such simulations, every agent is considered separately with its travel demands and abilities. This level of detail, however, leads to rather high computational demands when simulating vast geographic areas at a high resolution. As calibrated agent-based models usually describe populations with their inherent existing heterogeneity (e.g., Hörl and Balac, 2021), using agent-based models seems obvious when investigating, e.g., distributional effects of TMC schemes, impacts on specific activities, or the impact of different initial allocation strategies based on socio-economic attributes of a population. Nevertheless, such a tool is not suited for optimizing the parameters of TMC schemes. This simulation framework can investigate all three domains, where in particular the actor domain with its different preferences can be adequately simulated in an agent-based simulator. Also, such agent-based simulators allow to integrate a better representation of user behavior obtained from field experiments and pilots, as showcased by (e.g., Hamm et al., 2023).

Nevertheless, in the "trial-and-error" rationale (Bayon, 2004), the overall system design parameters and scheme properties cannot be arbitrarily set or optimized but must remain within politically and socially accepted bounds. Defining these will be the first step in any approach to identifying and optimizing system parameters that generate trading activity and market liquidity and, ultimately, efficient markets.

6. Conclusions

Trading activity and market liquidity are abstract concepts with many dimensions, being critical to the success of market-based instruments for many involved stakeholders. In this paper, we investigated and discussed market liquidity and trading activity in tradable mobility credit schemes, a cap-and-trade scheme on the demand side in the transportation sector, which is considered a promising alternative to conventional congestion charging. Based on a systematic literature review, we concluded that the TMC literature is already aware of the importance of trading activity and market liquidity, but that a gap exists with respect to a comprehensive and substantiated understanding of the interrelations between the basic design parameters, the temporal dimension, and the market actors. Regarding the latter, there is no clear overview of the players in a TMC scheme, their different intentions in the market, and how these affect market dynamics. The discussion presented in this paper emphasized that it is not trivial to ensure a robust market.

For clarity, we categorize the findings of this paper into three distinct domains: basic design parameters, temporal aspects, and market actors. Under the first domain of basic design parameters, it is imperative that motorized individual transport, and by extension credits, remain a scarce and desired commodity in the market at all times. Notably, while choosing public transport consumes fewer credits due to its lower specific externalities, the volume of credits should balance the mobility demands of both motorized individual transport and public transport. This equilibrium is pivotal for promoting a mode shift, yet without harming essential mobility needs. Supporting these requirements can be realized through strategic initial allocation processes and by recognizing the diversity inherent in users' mobility behaviors. Shifting focus to the temporal aspects, behavior such as hoarding or other unintended market actions can harm the desired market dynamics. The duration of a 'fiscal' period, defined from one allocation to the next, emerges as a critical factor influencing trading activity. A perceivable trend is observed where trading activity typically surges as the period progresses, especially as users' remaining credits diminish. Several of these temporal challenges can be mitigated through refined system design. For instance, implementing user group related, cascaded batches for credit allocations can redress the imbalances of credit abundance or shortage. Through this mechanism, credits are continually injected into the system and taken out of the system by consumption, effectively leveling out profound excess or shortage of circulating credits. Transitioning to the market actor domain, the distinct roles within the market are instrumental in fostering its dynamics. It is noteworthy that the objectives associated with these roles can sometimes be at odds. To ensure these conflicting objectives do not undermine overarching goals, rigorous regulation is indispensable. Consequently, this underscores the significance of a flawless system design.

In Section 5.3 we derived implications and recommendations for investigating the generation of trading activity and market liquidity. Nevertheless, it also became apparent that optimizing TMC scheme design is challenging: TMC schemes represent a confluence of intricate socio-technological parameters intersected by multiple stakeholders with often divergent interests. This complexity is difficult to parameterize and include in a simulator, yet to formulate an objective function for optimization of the design. Hence, future research should investigate how such confluence and interests can be considered in the design optimization. Nevertheless, considering the urgency to achieve climate goals, future research should also focus on collaborative pilot projects across countries or cities, which could generate invaluable experience and behavioral data. Such endeavors not only expedite the accumulation of insights but also foster a culture of shared learning, in analogy to the successes observed in carbon markets (Bayon, 2004; Narassimhan et al., 2018).

CRediT authorship contribution statement

Philipp Servatius: Data collection, Analysis and interpretation of results, Draft manuscript preparation, Reviewed the results. **Allister Loder:** Conception and design, Data collection, Analysis and interpretation of results, Draft manuscript preparation, Reviewed the results. **Jesper Provoost:** Data collection, Analysis and interpretation of results, Draft manuscript preparation, Reviewed the results. **Louis Balzer:** Data collection, Analysis and interpretation of results, Draft manuscript preparation, Reviewed the results. **Oded Cats:** Conception and design, Analysis and interpretation of results, Draft manuscript preparation, Reviewed the results. **Ludovic Leclercq:** Conception and design, Reviewed the results. **Serge Hoogendoorn:** Reviewed the results. **Klaus Bogenberger:** Conception and design, Reviewed the results.

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