DIT4TraM

Distributed Intelligence & Technology
for Traffic & Mobility Management

Tradable mobility credits and permits: state of the art and concepts

– Deliverable D4.1 –

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Contents

1. Introduction

Urban mobility faces challenges in terms of congestion, pollution, and sustainability. Transportation networks are not optimally used, as the transportation modes, routes, and departure times of travelers are chosen according to their individual needs and desires, which currently lacks coordination. This leads to a user equilibrium, which typically deviates from the system optimum and, thereby, creates a price of anarchy that yields to a suboptimal use of transportation infrastructure. Consequently, users are suffering from sub-optimal travel conditions, resulting in longer travel times and higher fuel consumption. The user equilibrium state is different from the social (system) optimum, defined as the optimal state for the users collectively. To improve social welfare and reach the social optimum, suitable institutions can require or help to redistribute (or reduce) travel demand in space or time. This process is called 'demand management.'

The objective of WP4 is to develop, simulate and compare demand management strategies that are based on the novel concepts of tradable credit and tradable permit schemes (TCS and TPS). By rationing and increasing or decreasing the cost of some travel behaviors, demand management schemes foster the re-distribution of the travel demand. The latter is designed to achieve a reduction of the negative externalities (e.g., delays, small passenger occupancy, pollution, or costs) of multi-modal transportation networks.

In this report, we provide an overview of the state-of-the-art literature on tradable credit and permit schemes. We compile, characterize and synthesize scientific contributions related to TCS and TPS. Both aspects of proposed policies of the travel supply and demand are investigated. Other demand management policies are succinctly introduced to put TCS and TPS into perspective. The literature review explicitly Identifies some gaps, both in terms of policies and traffic and demand representations. In conclusion, we derive some promising research directions for the remaining of WP4.

2. Concept

In this section, we define the concept of demand management schemes. We also make the difference between credits and permits explicit to provide a precise and consistent terminology for WP4.

2.1. Demand management scheme

When using economic measures to effectuate changes in the usage of road networks, two alternatives exist. The first one is **price-based management,** in which case payments are required to access infrastructure. The authority determines the price (i.e., toll) of specific segments. The extent of infrastructure usage is not restricted, but as the travel cost of some alternatives will increase, travelers will shift to other options in time, space, or mode.

The second option concerns **quantity-based measures.** With this form of demand management, the usage levels on the network(s) are fixed using mobility rights (Verhoef et al. (1997)). The users are given an initial allocation of those rights and trade them amongst themselves. The price of those rights results from the trading between the users rather than being set by the authority, as is the case for congestion pricing. By letting the users trade the mobility rights, this form of demand management is mainly decentralized. There is no money flow from the users to the authority, as the travelers are exclusively buying and selling mobility rights from and to other travelers. The regulation of those mobility rights can help the system reach states with a smaller price of anarchy.

At the time of writing, quantity-based schemes have not been implemented yet for traffic management purposes. However, they are currently used to reduce the carbon emissions of some industries. The EU Emissions Trading System (ETS) (Bayer and Aklin (2020)) is a framework in which large polluting companies spend a credit for each ton of carbon dioxide released into the atmosphere.

Generally, the quantity-based measures that have been proposed in the literature can be categorized as permit or credit-based schemes. However, the concepts of tradable credits and permits are not used consistently in the existing literature. In the following sections, we propose definitions for credit and permit schemes that correspond as much as possible to the available state-of-the-art contributions regarding quantity-based demand management.

2.2. Tradable credits

In the TCS, credits are a commodity needed to access the transportation network. The credits are indifferentiable (e.g., like currency units): we cannot distinguish one credit from another as they have the same value and are used similarly. However, the number of credits needed to access the transportation network may depend on the chosen route, departure time, and transportation mode. An initial number of credits is equally distributed among eligible travelers. These credits can be sold and bought amongst the travelers through a trading mechanism without the interference of a central authority. The distribution scheme can account for the travelers' heterogeneity and ability to buy credits or flexibility (like low-income travelers or workers not able to telework).

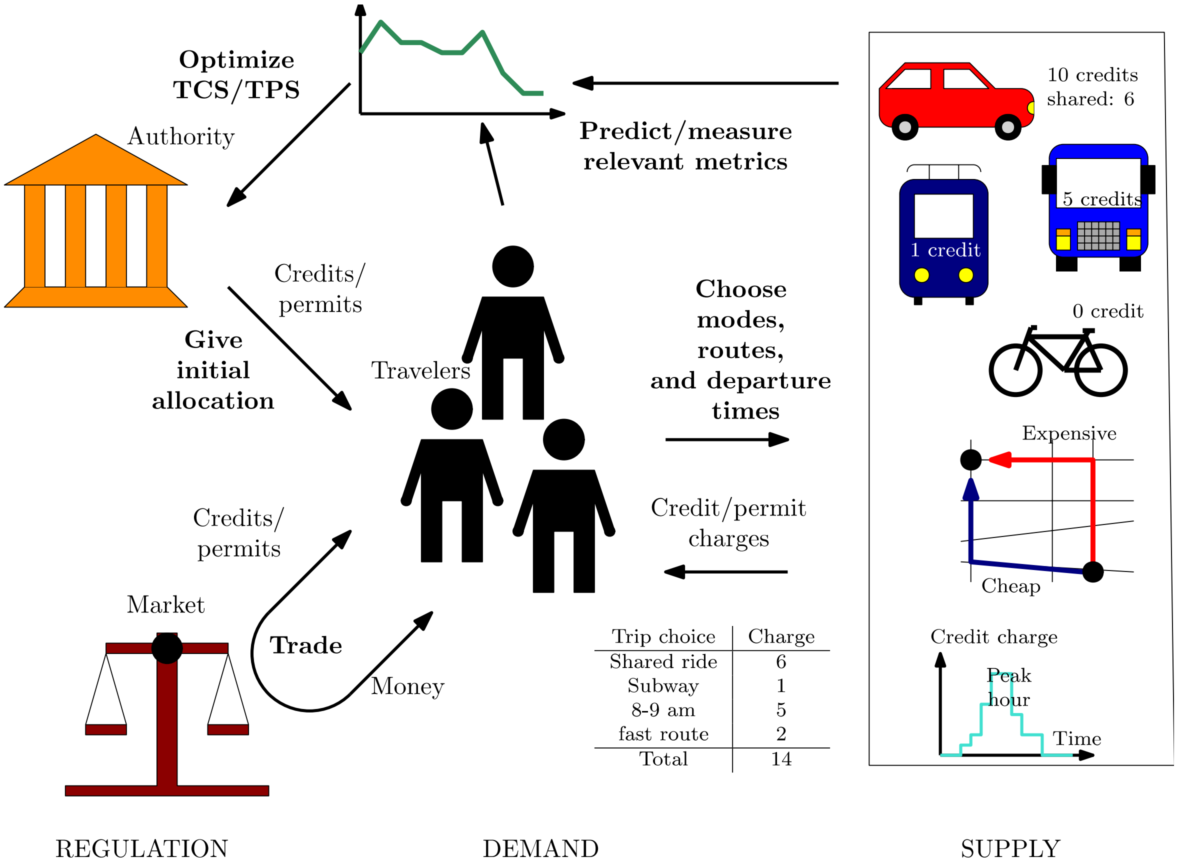
Yang and Wang (2011) formalized an early mathematical framework for TCS. Now, in most available works, the interval of credit assignment is a day, while only a few authors investigate the possibility of credits being transferred to the next day. In Ye and Yang (2013), the credits are allocated for a span of several days, and the price is updated each day based on the number of credits still available. Tian and Chiu (2015) define consumption periods for the TCS, at the end of which the users need to balance their credit account by using the credit market. If they fail, they need to fill the gap by buying credits at a high price from the authority. In Guo et al. (2019), the charges and the allocation are updated between each period. The contributions of Miralinaghi and Peeta (2020), (2019), (2018), (2016) consider the transfer of credits to a different period. The different frameworks presented in the works of Miralinaghi & Peeta account for interest rate (inflation), switch to greener personal cars via advantageous credit charges, and future price perception.

2.3. Tradable permits

The TPS is similar to a credit scheme in the sense that it allows access to the transportation network. However, in contrast to credits, permits are specific to a link and a timeslot. After an initial allocation, the users can trade the individual permits. As the permits do not provide the same access to the network, there is one price and one market for each individual permit. In this report, we also consider some schemes where no trading of permits takes place between users. Instead, the permits are auctioned by the authority. In comparison to TCS, there are fewer contributions regarding TPS in the literature.

TPS has been formalized by Akamatsu (2007) for a single Origin-Destination (OD) pair and by Akamatsu and Wada (2017) for several OD pairs in a network of links. For using a given link at a particular time, the user needs to buy a corresponding permit. To avoid queuing at bottlenecks, the number of issued permits per time unit equals the link capacity. Liu et al. (2014a) regulate a bottleneck with expirable parking permits to encourage users to arrive earlier and reduce queuing. P. Wang et al. (2018) propose a TPS for a network of links represented by flow-dependent travel time (BPR) functions, while accounting for a transit alternative. The permits are OD-based, while their quantity is selected to minimize the overall system cost.

We summarize the global framework of TCS and TPS in Figure 1. The regulating authority gives the initial allocations of credits and permits. Travelers trade credits and permits between themselves. Depending on their travel choices, they spend credits or permits, some alternatives being more expensive than others. Some relevant metrics are used to quantify the effect of TCS or TPS and optimize them.



Trip choice	Charge
Shared ride	6
Subway	1
8-9 am	5
fast route	2
Total	14

Figure 1: Traffic demand management with TCS and TPS.

3. Specifications

This section summarizes the different settings and parameters proposed by the various contributions regarding TCS and TPS.

3.1. Objectives/KPI

When introducing TCS, the main objective is to **reduce externalities generated by transport, particularly those induced by congestion**. The total travel time, i.e., the sum of travel times of all travelers acts as a metric for the social cost of congestion. When considering the departure time problem and the fact that users need to be at their destination at a given time, the "total schedule delay" is used. This is typical for the morning commute case: on top of the travel time, the users experience a disutility if they arrive earlier, and a usually higher one if they arrive later (Arnott et al. (1990)). The measure of total travel time or total schedule delay is related to Key Performance Indicator (KPI) 3.1 (total travel time), 3.3 (congestion reduction), and 5.2 (change network efficiency) of the project DIT4TraM.

The **environmental externalities** of congestion are addressed by accounting for the emission of greenhouse gases and toxic emissions or by quantifying the change in the total fuel consumption. It corresponds to KPI 3.4 (change in total private cars tailpipe emissions [CO, NO_x, CO_2]), 3.5 (change in total heavy vehicles tailpipe emissions), 3.6 (change in energy consumption [kWh]), 3.7 (change in fuel consumption [mpg]), and 5.3 (change in network sustainability).

The social and political aspect is considered by defining and measuring the **equity** of the TCS. Already without any demand management policies, the travelers have different travel costs. On top of that, the TCS or TPS might profit some travelers at the expense of others. One needs to choose between equity in the sense of results, i.e., the absolute travel costs are similar for all travelers, or in the sense of opportunities, i.e., the improvement of travel costs is the same for everybody. The challenge is to account for the different OD pairs and revenue levels. Related KPIs are 7.7 (users' satisfaction), 7.8 (operators' satisfaction), 7.9 (authorities' satisfaction), and 7.10 (industry satisfaction).

3.2. Behavioral responses

Different behavioral responses are used to drive the user equilibrium closer to the social equilibrium and attain the political goals regarding congestion, pollution, and equity. This leverage can be achieved among various travel modes, such as private cars, public transportation, and shared mobility forms. The common denominator between these modes is that congestion, pollution, and equity issues can persist, and that capacity is limited, whereby the same principle of leveraging behavioral response (by means of TCS and TPS) can be applied.

Travelers will be stimulated to change their **departure times** by introducing a time-varying credit charge or permits with a specific time window as it becomes more expensive to drive or use public transportation during peak hours. This corresponds to KPI 4.4 (time of departure shift).

The road network is spatially heterogeneous: some links are overused, while others are underused. The same phenomenon occurs for public transportation, as vehicles on certain lines can become overcrowded, and the capacity of the service network can be exceeded. By charging the links or the areas differently, the users change their **routes**, and the demand can be better distributed over the network. This corresponds to KPI 4.3 (route shift).

Public transportation and shared mobility are often underutilized because travel time is longer and may involve walking and waiting as compared to a private car with a single occupant. Furthermore, passenger comfort is generally lower. By charging the user of privately owned cars, some users may **shift to public transportation** or share travel costs by ride-pooling/ridesharing. Differentiated charging schemes are introduced to **foster the usage of different types of private cars**, such as zero- or low-emission, or autonomous vehicles. This corresponds to KPI 4.1 (daily mode shift) and 4.5 (change in ridesharing percentage).

As the travel costs of some trips change with the introduction of a demand management scheme, the demand might vary with the travel costs. Thus, some contributions consider the travel demand as elastic. If the travel cost decreases, additional travelers will switch to a given mode, and if it increases, some users will cancel their trips or use alternative travel modes.

3.3. Charging scheme

The charging scheme is usually variable, i.e., non-constant and dependent on several parameters. It provides freedom to the authority to stimulate road users to change their choices in a direction suitable to the respective goals. Previous work has considered different parameters, on which the credit charges are based, including:

- **Link**: the charge is the sum of the charges of the links used during the trip (Yang and Wang (2011)).
- **Time**: the credit charge is dynamic in the temporal domain (Nie and Yin (2013)).

- **Distance**: the charge is proportional to the traveled distance (Shirmohammadi et al. (2013)).
- **Area**: the charge is fixed for all users in a given area Shirmohammadi et al. (2013).
- **Class**: the credit charge or allocation depends on the class of the user, usually its value of time (VoT) as a proxy for its wealth. In Xiao et al. (2013), the poorer users get more credits to compensate for their travel time increase.
- **Vehicle**: the charge depends on the type of vehicle. In Miralinaghi and Peeta (2019), low emission vehicles require a lesser charge to foster them against conventional (ICE) vehicles.
- **Negative charge**: the charge can be negative, to work as an incentive. In Xiao et al. (2019), negative credits charges on some links replace the initial allocation.

All of the abovementioned studies have been limited to car traffic.

3.4. Mobility-on-Demand

With the advancements of information and communication technologies in the last decades, the concept of Mobility-on-Demand (MOD) has emerged. This concept allows travelers to access more of the available forms of mobility. Travel modes that are facilitated through MOD include:

- **ride-hailing** (services like Uber where a designated vehicle is dispatched upon customer request),
- **ride-pooling** (where multiple ride-hailing trips are consolidated),
- **ridesharing** (where drivers are incentivized to share their trip with others in their private vehicle, a.k.a. **carpooling**),
- **car-sharing** (a form of car rental for short periods of time), and
- **bike-sharing** (a form of bicycle rental for short periods of time).

Integration of such modes into tradable credit and permit schemes provides opportunities for intelligent demand management, either by shifting demand to other modes, where there is a residual capacity, or by consolidating demands such that they can be served with fewer resources.

There have been relatively few works that consider integrating MOD concepts into tradable credit or permit schemes. Until 2017, there were no works that explicitly combined shared TCS and TPS concepts with on-demand transportation. However, as early as 1995, roadway allocation methods were proposed to reduce congestion and encourage carpooling and transit use Johnston et al. (1995). The method that the authors proposed allocates permits for specific lanes only to high-occupancy vehicles (HOVs), including carpooling vehicles. Arguably, the method has some similarities with permit schemes, even though its rigidity does not match the flexibility of TCS and TPS, which involve digital trading mechanisms.

Hara and Hato (2019), (2018); Roca-Riu and Menendez (2019) introduce an auction mechanism for shared mobility services. The main objective of these works is to provide incentives for users of car- and bike-sharing systems to change their origin-destination choices, such that vehicles are positioned better with respect to the demand. Tradable permits are used to assign travelers the right to travel between specific origin-destination pairs. This work employs TPS as a method to increase efficiency in MOD services. In particular, the scope of the study is limited to the operations of mobility sharing services instead of a comprehensive higher-level framework that includes a wider spectrum of travel modes.

In Zang et al. (2020), a TCS is used to manage the usage of HOV lanes on highways. Similar to the work of Johnston et al. (1995), the authors consider that HOV lanes exist next to general-purpose lanes and that the HOV lanes can be exclusively used for carpooling. This provides a travel cost incentive to travelers who choose to share their trips. The proposed method does not include the GP lanes as part of the credit scheme, as the authors specifically aim to limit the access of HOV lanes. Xiao et al. (2021b) introduce a similar approach, but implement a TPS with time-limited carpooling lanes instead of permanent HOV lanes. In this concept, the carpooling lanes are designated to operate within a reserved time window during rush hour periods. During other hours, the lanes are open to all travelers.

The authors of the previously mentioned work extend their methodology in Xiao et al. (2021a), where they incorporate parking constraints into a TPS with carpooling. Besides adding parking at the destination as a constraint for the model, the authors present two alternative tradable parking permit schemes: one where differentiation occurs between parking permit prices of solo drivers and carpoolers, and another where prices are uniform between modes. The authors conclude that the scheme with uniform, undifferentiated pricing is most efficient. Additionally, they suggest that further research could focus more on combined traffic management schemes, in which different modes as well as mobility sharing options are integrated.

In Zong et al. (2021), a different approach is taken to investigate the synergy between TCS and carpooling. This approach arguably yields a more comprehensive scheme that encompasses a broader spectrum of modes and options for sharing. The authors introduce a credit discount coefficient corresponding to different numbers of passengers, such that prices are lower when car trips are shared with other travelers. They demonstrate that travel volume, travel cost, and carbon emissions can be reduced by implementing the TCS with carpooling enabled. It should be mentioned, however, that the authors only considered carpooling as a form of MOD. Therefore, an interesting future research direction would be to include further forms of MOD like ride-pooling, bike-sharing (shared modes) and ride-hailing (non-shared modes).

3.5. Experiments

No full-scale TCS has been implemented yet. However, several aspects have been independently studied using field experiments, serious games, or surveys.

A field experiment took place in The Netherlands. Ettema et al. (2010); Knockaert et al. (2012) present the results of this peak avoidance experiment: car drivers receive money when they do not drive during the peak hour. During the experiment, car usage decreased, even though most car drivers returned to the old habits when the incentives stopped. The incentives need to be continued to maintain the peak hours avoidance. It poses an issue about the sustainability of such a scheme, since one would constantly need funds to finance the incentives.

The MOBIS experiment in Switzerland introduced a "Pigovian" pricing scheme (Axhausen et al. (2021)). Each participant pays a tax corresponding to the external cost of its travel. It represents the damage it induces to others in terms of congestion, pollution, and health. The "Pigovian" tax increased the private costs by about 16% and reduced the external cost by 5%.

Different serious games have been proposed. The participants react to a fictive TCS via a computer-based interface. In the experimental game of Aziz et al. (2015), the participants choose routes subject to "personal mobility carbon allowances". They can trade those allowances on a multi-unit double-auction market. The participants are learning from the system and improving their usage of the carbon allowances. In Dogterom et al. (2018), a distance-based TCS is set up. Here, the participants have an initial quota of kilometers per car allowed. They can reschedule their activities or change mode to decrease the usage of their credit. Additionally, they can sell the remaining credits or buy additional ones at a fixed price. The results of the experiments show that about two-thirds of the participants change their car use. In Tian et al. (2019), another experimental game is proposed, where participants have credits and money budgets. They choose their routes and trade with a multi-unit double-auction market. From the experiments, it emerges that participants are spending more credits in the beginning, after which they start saving some credits for later use. The authors also noticed a learning behavior as the number of satisfied bids and asks increased over time. The authors of Brands et al. (2020) conducted an experiment with participants regarding parking permits. The scenario that the authors selected is the following: participants need to park their car downtown. To do so, they have to secure parking permits that they can buy and sell daily. Permit prices fluctuate on a daily basis as well. If they fail, they will face a monetary penalty. The outcomes showed that most of the decisions were rational, while participants with higher levels of education tend to earn more money from the trade than others. This implies concerns about the equity of such a scheme.

Other contributions are based on surveys to assess the public reaction to a TCS and the population's preferences between TCS and the more common congestion pricing. In Krabbenborg et al. (2021), (2020), the acceptability of TCS is investigated. A survey is used to understand the reasons behind the acceptability, and a case study with a fictive city is introduced to compare pricing and TCS. In the survey, public support varies from 30% to 50%, depending on how the credits are initially distributed. The highest level of support occurs when the credits are uniformly distributed among car users. The majority of the participants of the case study rejected the TCS: only 20% accepted the TCS, while 56% agreed with the congestion pricing. One essential argument is that congestion pricing has already been successfully implemented in the real world. Hence, it is argued that there is no need for the complexity of another scheme such as TCS. The results of this study highlight the importance of the user experience and the communication of the advantages of TCS and TPS, especially compared to congestion pricing.

4. Models and solutions methods

TCS and TPS contributions from the literature mainly focus on finding the system equilibrium, i.e., the traffic assignment under the TCS or TPS, and comparing it with the status quo case. The majority of past works, such as Yang and Wang (2011), are then developing methods to find the TCS and TPS parameters that minimize the sum of the costs for all users. Different assumptions are made for the analytical formulations and numerical simulations. The conditions under which the credits and permits are traded as well as the representations of the traffic supply and demand are categorized In the following sub-sections, underlining the common features and differences of the contributions on TCS and TPS.

4.1. Market settings

Most of the literature does not make explicit that the trade mechanism and the credit price are determined by a **market-clearing condition** (MCC): the price is non-zero if and only if all the credits are consumed, like in Yang and Wang (2011). It is assumed that the users trade between themselves, but the exact mechanism is not specified.

In Ye and Yang (2013), the **authority updates the credit price over the days,** depending on the difference between credits consumption and allocation.

In Liu et al. (2015); Su and Park (2015), the permits for using the highway are **auctioned**. The travelers bidding the highest amount of money are buying the permits.

The contribution of Tian and Chiu (2015) focuses on the trade of credits using a **double-auction market** and how the marginal value of the credits depends on the travelers. In a double-auction market, each player (here, the potential traveler) enters the market to buy or sell credits with a chosen quantity and price, after which the market mechanism maximizes the number of credits traded.

Several contributions account for **transaction costs**. They represent either a tax or a valuation of the effort (time and energy) spent to trade credits in order to prevent speculation and market abuse. Nie (2012) introduced transaction costs proportional to the traded quantity. In Bao et al. (2014), the transaction costs are linearly proportional to both price and traded quantity. The transaction costs in Zhang et al. (2021c) are a constant, multiplied by the traded quantity to a power that is equal to or greater than one. It represents the fact that, by increasing the traded quantity, the difficulty to find trading partners increases.

4.2. Supply representation

Most of the literature about TCS (including the preliminary work of Yang and Wang (2011)) represents the congestion using the **BPR function** (Bureau of Public Roads (1964)), where the travel time on a link is a static function of the flow. The TCS methods using the BPR framework aim at re-routing the travelers.

A significant number of contributions on TCS and most of the papers on TPS use **Vickrey's bottleneck** (Vickrey (1969)). With this model, the capacity of the link is fixed and stays constant. When the demand exceeds the capacity, the vehicle waits in a vertical queue. The contributions on TCS based on Vickrey's bottleneck aim to spread the demand over time to make the queue disappear.

Bao et al. (2019) uses **Chu's model** (Chu (1995)), which is an extension of the BPR model, accounting for the departure time distribution.

Liu et al. (2020), not yet published, is the only contribution about a TCS using a **trip-based Macroscopic Fundamental Diagram** (MFD), also known as the generalized bathtub (Jin (2020); Lamotte and Geroliminis (2018); Mariotte et al. (2017)). With the MFD, the speed on the network depends on the current number of vehicles on the network.

A small part of the works uses **traffic simulators**: DynusT in Tian and Chiu (2015) and MATSim in Su and Park (2015). It allows for a realistic and complex representation of congestion and assignment, even though analytical discussions are limited. As there is no mathematical description of the congestion, properties such as optimal parameters, existence, uniqueness, or stability of the equilibrium under TCS or TPS cannot be analytically proven.

4.3. Demand representation

The equilibrium is usually defined by the **Deterministic User Equilibrium** (DUE): no user can unilaterally improve its travel cost by changing mode, departure time, or route. In Yang and Wang (2011), TCS is implemented, while assuming DUE.

Some contributions account for **Cournot-Nash** players (CN) to represent transportation companies: a CN player (here a potential traveler) cooperates with other players from the same entity (usually a company) to minimize the entity's costs and not its individual costs, for instance in He et al. (2013).

The **Stochastic User Equilibrium** (SUE) accounts for perception errors. It is reached when the decisions of the users match their current affectation. The decision model is often the logit. The probability of choosing an alternative depends on the travel cost of this alternative compared to the costs of the other options. In Ye and Yang (2013), TCS is implemented while assuming SUE.

Under a TCS or TPS, the users are selling or buying credits or permits to reduce their travel time. The parameter named **Value of Time** (VoT) is defined to quantify the amount of money a user is ready to pay to reduce its travel time. Some contributions account for different VoT to represent different types of users and especially travelers with different revenues, to differentiate the impact of the TCS on low-income and high-income travelers. In Wang and Yang (2012), the TCS accounts for VoT heterogeneity, as the credit charge depends on the class of the traveler.

Human behavior is often suboptimal. The following **biases** are known:

- **Loss aversion**: travelers selling credits are earning money, and those buying credits are losing money. Under loss aversion, the users value the money they lose more than the money they earn (Bao et al. (2014)).
- **Cognitive illusion**: the travelers do not consider the cost of spending credits as long as the number of spent credits does not exceed the allocation (Han and Cheng (2016)).
- **Perception error**: As both, the supply and demand affect the credit price, its value is uncertain. Therefore, travelers are prone to random errors when predicting the credit price (Zhang et al. (2021a)).
- **Framing and labelling**: users are more eager to spend the credits from the allocation (which are provided for free) than additional ones they need to buy on the market (Bao et al. (2016)). The difference to cognitive illusion is that, even if they do not need to buy additional credits, they still consider the cost of spending the credits they got for free.

The effect of biases on the system is complex, as the travelers interact through the market or transportation network. It can lead to complex patterns (Helbing (2004)).

4.4. Comparison of TPS contributions

The different contributions about TPS for traffic management are summarized in Table 1. For each contribution, we check which behavioral response is considered along with the supply representation.

Table 1: Comparison of TPS-related works.

Reference	Congestion model	Mode[1]	Route	Dept. time
Akamatsu (2007)	Vickrey	E	X	X

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[1] The letter 'E' means the model accounts for elastic demand without explicitly considering different transportation modes.

Akamatsu and Wada (2017)	Vickrey		X	X
Lessan et al. (2020)	Vickrey			X
Liu et al. (2015)	Vickrey			X
Liu et al. (2014b)	Vickrey	X		X
Sakai et al. (2015)	Vickrey		X	X
Shirmohammadi and Yin (2016)	Vickrey			X
Su and Park (2015)	MATSim		X	X
Wada and Akamatsu (2013)	Vickrey		X	X
J. P. Wang et al. (2018)	BPR	X	X	
P. Wang et al. (2018)	Vickrey			X
Xiao et al. (2021a)	Vickrey	X		X
Sakai et al. (2017)	Vickrey			X

Most TPS frameworks use a fixed-capacity bottleneck to represent the congestion. The leverage of the TPS is then changing the departure time distribution. The number of emitted permits per bottleneck is equal to the capacity for time periods, which prevents the formation of queues. One paper deals with the BPR functions. In this paper, the authors optimize the number of emitted permits to minimize the total travel time. The representation and investigation of the route and mode choices are under-represented.

4.5. Comparison of TCS contributions

Relevant contributions on TCS are compared in Table 2. It compares the behavioral responses taken into account and considers emissions of pollutants, transactions costs, and human biases.

Table 2: Comparison of TCS-related works.

Reference	Mode	Route	Dept. time	Emission	Transaction cost	Human biases
Bao et al. (2016)	E	X				Framing and labeling

Bao et al. (2014)		X			X	Loss aversion
Bao et al. (2017)	E	X				
Bao et al. (2019)			X			
Chen et al. (2016)		X				
de Palma et al. (2018)	X	X				
Gao and Hu (2015)	X					
Gao et al. (2019b)		X				
Gao et al. (2019a)		X				
Gao and Sun (2014)		X		X		
Gao et al. (2018)	X					
Gao et al. (2016)	X					
Guo et al. (2019)	E	X				
Han and Cheng (2016)		X				Cognitive illusion
Han and Cheng (2017)		X				
He et al. (2013)		X			X	
Jia et al. (2016)			X			
Jiang et al. (2017)		X				
Li and Gao (2014)		X				
Lian et al. (2019)		X			X	
Miralinaghi and Peeta (2018)	E	X		X		
Miralinaghi and Peeta (2016)	E	X				
Miralinaghi and Peeta (2019)	X	X		X		

Miralinaghi and Peeta (2020)		X		X		Loss aversion
Miralinaghi et al. (2019)			X			Loss aversion
Nie (2015)			X			
Nie (2012)	E	X			X	
Nie (2017a)	X					
Nie and Yin (2013)	X	X	X			
Seilabi et al. (2020)	X	X				
Shirmohammadi et al. (2013)	E	X				
Tian et al. (2013)	X		X			
Wang et al. (2019)		X				
G. Wang et al. (2014a)		X				
G. Wang et al. (2014b)		X				
Wang et al. (2020a)	E	X				
Wang et al. (2020b)	E	X		X		
Wang and Yang (2012)	E					
X. Wang et al. (2014)	E	X				
Wang et al. (2012)	E	X				
Wang and Zhang (2016)		X				
Wu et al. (2020)	X	X			X	Loss aversion
Wu et al. (2012)	X	X				
Xiao et al. (2015)	X		X			
Xiao et al. (2019)		X				

Xiao et al. (2013)	X					
Xu and Grant-Muller (2016)	X					
Yang and Wang (2011)	E	X				
Ye and Yang (2013)		X				
Zang et al. (2020)	X	X				
Zang et al. (2018)	X	X				
Zhang et al. (2021b)	E	X			X	
Zhang et al. (2020)	X	X				
Zhang et al. (2021a)	E	X				Perception error
Zhang et al. (2021c)		X			X	
Zhou et al. (2020)	X					
Zhu et al. (2017)		X		X		

Most of the proposed TCS methods in the scientific literature leverage the route choice and represent the congestion with a network of BPR functions. The mode choice is often only indirectly considered via elastic demand, and the departure time problem is under-represented. Only a few papers account for the vehicles' emissions, as most of them only focus on minimizing the total travel time or its monetary equivalent. Human biases in transactions are sometimes considered, but the majority of publications assumes that trade induces no costs and that users are perfectly rational.

In Nie (2012); Shirmohammadi et al. (2013), the authority sells additional credits at a fixed and relatively high price on top of the distribution the initial allocation for free. In case the demand for car travel is huge, the credit price rises until it reaches the authority price. At this point, the travelers directly buy credits from the authority. In this framework, a traveler can always travel with any mode anytime on any route, even if it can be expensive and the credit price is bounded. This framework can be interpreted as a hybrid between TCS and congestion pricing: the credit cap can be violated when there is a relatively large need to drive personal cars or prevent the credit prices from becoming too high.

In a more decentralized framework, the credits are not given by the authority, but earned by car drivers traveling off-peak (Nie (2015)) or by using alternative routes (Xiao et al. (2019); Zhu et al. (2017)). The authority does not determine the number of credits, but only chooses which behaviors lead to a loss or gain of credits.

5. Position compared to other demand management schemes

TCS and TPS are not the only policies relative to demand management. To provide some context and references, we now compare some relevant contributions in terms of demand management for traffic regulation: urban tolls, license plate rationing (LPR), and peak-avoidance incentives.

5.1. Urban tolls

Congestion pricing was proposed for several cities and implemented in some (Bhatt et al. (2008); Croci and Douvan (2016); Eliasson (2014); Gu et al. (2018)). In the following, we list some examples of implementations:

- Singapore is the earliest city in 1975 with the Area License Scheme: a paper to show on the windshield. In 1998, it was replaced by the Electronic Road Pricing replaced. The toll is time- and space-specific: the charging rate changes every 30 minutes, and an embedded device records when tolling gates are crossed.
- In London, a Congestion Charge was introduced in 2003 with a fixed price per day. CCTV reads the plate numbers, which are automatically processed.
- In Stockholm, an urban toll was implemented in 2007 after a previous experiment in 2006. The cordon-based toll is active during peak hours and changes every 30 minutes. Plate numbers are read and processed automatically as well.

Other major cities had projects for the implementation of urban tolls, which were discarded, for instance, in New York City and Hong Kong (Gu et al. (2018)).

The advantages of congestion pricing are that the approach is relatively simple to apply and its implementation in different cities proves the pertinence of this policy. The urban tolls generate additional revenue for the city council to fund the infrastructure and administration necessary for applying and enforcing the policy.

Its drawbacks are that it is perceived as another tax for car drivers on top on fuel tax and license registration, and it penalizes low-income inhabitants more than high-income ones. TCS and TPS address both aspects, since the money flow stays between the citizens, and part of the credit/permit consumption is already covered by the initial allocation.

5.2. License plate rationing

Different cities implement license plate rationing (LPR) occasionally to curb traffic emissions during pollution peaks. With LPR, cars are allowed to drive on a given day according to their plate number. In the typical implementation of the LPR, cars with odd plate numbers can drive every second day and cars with even plates every other day only. Some vehicles are exempt from the policy, usually low-emissions ones. In Nie (2017b), (2017a), the author argues that LPR is ineffective because it fosters purchasing a second car to circumvent the policy. He presents TCS as a good alternative.

Goddard (1997) takes the case of Mexico City as an example to underline the perverse effect of the LPR (named Non-Driving Day in the paper). As it encourages inhabitants to buy a second car in the long term, more cars than before and higher exhaust gas levels were observed in the streets.

Though the method is fast and simple to implement, it is the least flexible policy and does not account for the real utility of driving a car. In a TCS or TPS, a traveler who needs to drive a car on a specific day is likely to secure enough credits/permits by bidding a high enough price. With a policy based on LPR, this traveler would be forced to find an alternative or face a fine.

5.3. Peak avoidance incentives

Incentives have been proposed in the literature as an effective method for demand management. In multiple countries and cities, platforms have been developed to provide such personalized incentives to trigger changes in travel behavior, aiming to shift demands away from car traffic peak hours (Ettema et al. (2010); Fahrioglu and Alvarado (2000); Hu et al. (2015); Knockaert et al. (2012); Zhu et al. (2015)) or encourage the use of other travel modes instead of non-shared cars (de Kruijf et al. (2018)).

Ettema et al. (2010); Knockaert et al. (2012) present the Spitsmijden case from The Netherlands, in which an extensive reward experiment was conducted under real-world conditions on a congested highway segment in the Netherlands. The experiment was considered to be successful, as the participants halved their trips during the morning rush hour. The authors argue that incentives may be a more popular policy instrument than traditional taxation methods. However, in comparison to taxation methods and permit/credit schemes, the costs to financially compensate drivers are expensive for authorities. Also, the approach arguably does not ensure an equitable pay-for-use policy, as people who already traveled outside the rush hour are not fairly compensated, even though they already showed the desired behavior before the system was implemented. In TPS and TCS, there is no money flow from the authority to the travelers, which results in lower costs for authorities and a fairer distribution of charges among all travelers.

6. Conclusions

In this literature review, two demand management schemes were compared: Tradable Permit Scheme (TPS) and Tradable Credit Scheme (TCS). The main difference is the flexibility of the mobility schemes. The literature mainly focuses on TCS. Most contributions do not make explicit the market mechanism as they only focus on the assignment at equilibrium.

The first gap identified in the literature is the representation of traffic. Congestion models are usually based on Vickrey's bottleneck or BPR function. They are relatively simple (with fixed capacity and static travel times). They allow to derive outcomes feeding analytical discussions. It is questionable, however, if such a representation is sufficient to prepare for real-life implementations.

The second gap concerns mode changes during a trip. In most publications, private car travel has been at the center of attention of the proposed schemes. Some works consider public transport or car-pooling as a potential mode shift, but research is lacking with regard to comprehensive, mode-agnostic schemes. A TCS or TPS would arguably be more interesting, if different transport modes could be combined, such that demand can be shifted to other modes, where capacity is not saturated. Some contributions account for different modes, but only a few allow the users to change modes during the trip. Thus, inter-modality is usually lacking: a traveler might drive its car to a park-and-ride facility, take a train and finish its trip with a shared bike.

Our review of the existing literature about TCS and TPS provides research directions for Task 4.2. The demand management should account for the pros and cons of both schemes. TCS is more flexible as there is only one market and one commodity. However, an authority is assumed to choose the credit charges and thus to decide, which alternative is more expensive than another. With a TPS, an authority only regulates the number of issued permits, while a market determines the price of the different choices. The credits and permits should not only be usable to drive a personal car to regulate the multi-modal network entirely, but also for on-demand and shared services such as ride-pooling. Attention should be paid to the trading mechanism as well as the market rules and costs. The complexity caused by the multi-modality and the consideration of different modes with different credit charges or permits can be managed automatically by an agent performing trades. As a travel journey planner determines the travel time and distance for each alternative, it can also compute the travel cost. This will remove the complexity burden from the traveler. Machine learning and self-organizing complex system approaches could be used to tackle this complexity.

The literature lacks simulation of TCS and TPS for a real city, even though it is necessary to get a more precise estimation of the effects of the TCS. Most of the contributions use relatively standardized or straightforward networks as use-cases (e.g. Sioux Falls or Nguyen-Dupuis). Evaluating a TCS or TPS based on an application for a real city like Amsterdam (Task 4.3) promises insights and comparison elements for different demand management schemes to prepare an experiment with the inhabitants (WP7). The simulation should be coupled with user decisions and the market settings.

Our review supports the plan of extending the numerical and analytical discussions at the equilibrium for different TCS and TPS, using large-scale dynamic congestion simulations and the Macroscopic Fundamental Diagram (MFD). It is a convenient way to optimize the TCS or TPS (Task 4.4). Especially, the different modes are usually represented on different networks in the TCS/TPS framework. Using MFD allows accounting for the interactions between the different modes (3D-MFD).

This review has also been instrumental in selecting two reference approaches for cross-comparison (T4.3). The first reference policy is the congestion pricing strategy, as it has been implemented for the city of Stockholm: car drivers pay a toll when crossing a cordon. Pricing is time-dependent, i.e., more expensive during peak hours. The second reference policy is license plate rationing, as it is already applied in different cities to reduce emissions during pollution peaks. Different degrees of LPR will be used, depending on the type and number of travelers and cars exempt from the LPR, such as low-emissions vehicles. Lastly, peak avoidance incentives might be considered as a third reference approach, but since it has only been tested in an experimental setting and has not been fully deployed in a real-world environment, it is not regarded as one of the main reference approaches for cross-comparison.

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