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TOPICAL REVIEW

Shared pooled mobility: expert review from nine disciplines and implications for an emerging transdisciplinary research agenda

Felix Creutzig[1,2,10,*], Alexander Schmaus[2,3,10,*], Eva Ayaragarnchanakul[1,2], Sophia Becker[2,9], Giacomo Falchetta[7,8], Jiawei Hu[1,2], Mirko Goletz[5], Adeline Guéret[4], Kai Nagel[2], Jonas Schild[6], Wolf-Peter Schill[4], Tilmann Schlenther[2] and Nora Molkenthin[3]

1 Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany
2 Technical University Berlin, Berlin, Germany
3 Potsdam Institute for Climate Impact Research, Potsdam, Germany
4 German Institute for Economic Research (DIW Berlin), Berlin, Germany
5 Institute of Transport Research, German Aerospace Center, Berlin, Germany
6 Technische Hochschule Köln, Cologne, Germany
7 Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Venice, Italy
8 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
9 Research Institute for Sustainability—Helmholtz Centre Potsdam, Potsdam, Germany
10 Equal contributions as first authors.
* Authors to whom any correspondence should be addressed.

E-mail: creutzig@mcc-berlin.net and alexander.schmaus@pik-potsdam.de

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Abstract

Shared pooled mobility has been hailed as a sustainable mobility solution that uses digital innovation to efficiently bundle rides. Multiple disciplines have started investigating and analyzing shared pooled mobility systems. However, there is a lack of cross-community communication making it hard to build upon knowledge from other fields or know which open questions may be of interest to other fields. Here, we identify and review 9 perspectives: transdisciplinary social sciences, social physics, transport simulations, urban and energy economics, psychology, climate change solutions, and the Global South research and provide a common terminology. We identify more than 25 000 papers, with more than 100 fold variation in terms of literature count between research perspectives. Our review demonstrates the intellectual attractivity of this as a novel perceived mode of transportation, but also highlights that real world economics may limit its viability, if not supported with concordant incentives and regulation. We then sketch out cross-disciplinary open questions centered around (1) optimal configuration of ride-pooling systems, (2) empirical studies, and (3) market drivers and implications for the economics of ride-pooling. We call for researchers of different disciplines to actively exchange results and views to advance a transdisciplinary research agenda.

1. Introduction

Low-energy demand has been suggested as a key strategy to achieve climate change mitigation while avoiding risking high risk technologies such as BECCS (Grubler *et al* 2018). A central thought of this approach is to reduce primary energy while maintaining or improving service levels. This requires redesigning systems to increase the maximum useful energy that is extracted from the system (exergy). This is particularly relevant for land transport, where low motor efficiencies (of the internal combustion engine) meet low exergy (less than 100 kg human transported by often more than 2 t of steel). Increasing the occupancy of cars and encouraging individuals to transition from their private vehicles to shared mobility options are hence central tenets of low-energy demand worlds.

In this sense, shared pooled mobility, which refers to the sharing of vehicles among multiple passengers, has the potential to significantly contribute to low-carbon and sustainable mobility (Wilson *et al* 2020, Creutzig *et al* 2022). It can also help make transportation more affordable, accessible, and convenient for people who do not own a car or prefer not to drive (Cohen and Shaheen 2021). However, despite all promises, there is no sign of relevant take up of pooled mobility. The question is why so? And: are there ways to overcome barriers and lock-ins? We argue that these questions can be best answered by a transdisciplinary research agenda from different disciplines that study pooled shared mobility.

Currently, despite the multi-disciplinary interest in shared pooled mobility, there is a lack of collaboration and communication between these different disciplines. This can lead to fragmented research agendas and missed opportunities to address the complex challenges of sustainable mobility. There is hence a need for a more transdisciplinary approach to shared pooled mobility research to combine the results of these different disciplines.

Here, we bring together recent research progress from very different fields on shared pooled mobility to gain insights into which approaches and answers already exist and which open questions remain. We see the main purpose of this research agenda as a road map for academic researchers interested in transdisciplinary advances on shared pooled mobility, thus advancing a new epistemic community that generates policy-relevant insights. Our contribution further serves as an overview of the current state-of-the-art for businesses and municipal planners wishing to implement an efficient, sustainable and convenient service. The paper also helps to aggregate the assessment of ride-pooling as a socio-technical innovation, e.g. for IPCC reports.

2. Background

Shared pooled mobility gains substantial interest and has already been evaluated in several reviews from different perspectives. Shared pooled mobility is distinct from other smart mobility concepts (see box 1 for definitions).

Box 1. Definition.

Ride bundling can be implemented in a wide range of ways and different terms exist to distinguish between the specific modalities of the implementation.

Mobility-as-a-Service (MaaS): an approach that integrates different mobility services into a single platform. Users book an entire trip across transport modes.

Ride-hailing/Ride-sourcing: mostly unregulated taxi services. The trips are usually booked with an app.

Ride-pooling: ride-pooling describes systems of centrally operated, flexibly planned, on-demand trip bundling. It aims to transport more than one person at the same time.

Ride-sharing: ride-sharing includes ride-pooling but also personal vehicle sharing, where individuals offer to take an additional person with them, for example to share fuel costs.

Paratransit: ad-hoc on-sight ride-sharing without central planning. Often informal systems.

Shared pooled mobility: shared pooled mobility describes ride-sharing in cars and vans, generally intended to increase the occupancy of vehicles.

Shared mobility: shared mobility is the most general term including all ways of sharing vehicles, bikes or trips. It includes merely sharing the means of transport as, for example, car-sharing or bikesharing. Thus, shared pooled mobility is a subset of shared mobility.

In the literature, these differences are not consistently distinguished. Especially ride-sharing, ride-pooling,and ridesourcing are often used synonymously.

Shared pooled mobility is often seen as one part of mobility-as-a-Service (MaaS). The general concept of MaaS is that different mobility services are pooled into one platform. Customers then buy mobility packages instead of trips with a single transport mode. A literature review, divided into two parts reviewing research about travel patterns with and without considering MaaS, is found in (Durand *et al* 2018). Notably, the authors propose a research agenda, including also a paragraph about shared pooled mobility, and thus, align with our review. Another examination of MaaS is presented by (Maas 2022), wherein the author compares and connects the findings from 127 publications. This review specifically highlights research gaps, such as the exploration of traffic flow dynamics in the context of widespread MaaS adoption.

A review about the possibilities of MaaS in developing countries can be found in (Dzisi *et al* 2022). Additionally, the authors propose a specific business model for MaaS service in combination with paratransit. In (Victory and Ahmed 2023), the authors reviewed specifically paratransit and mode choice decisions. A review on politics regarding paratransit is given in (Klopp 2021). The author shows that paratransit was ignored by transportation planners until just recently, but, as this is changing, a shift from paratransit to transit can be observed.

In (Mitropoulos *et al* 2021) an extensive review about ride-sharing can be found. The authors combined a literature review with an exploration of websites of popular ride-sharing operators. A specific review about the development of the shared pooled mobility market in China, the corresponding changes in travel patterns and its influence on the reachability of environmental goals can be found in (Hu and Creutzig 2022). In (Berbeglia *et al* 2010) the authors present a technical review, highlighting especially the dynamic routing problem, which is the underlying problem when matching similar trips.

3. Methods

We advanced this paper in four methodological steps. We started with a workshop on shared pooled mobility, which was followed by the development of a transdisciplinary research agenda based on the research area of all contributors. Thirdly, we created an extensive literature review based on the perspectives derived in the second step. In the fourth step we combined the results of the three steps before. The four steps will be explained in more detail in the following paragraphs.

In the first part, we organized a workshop presenting different academic perspectives on shared pooled mobility. As a result of this workshop, we developed a core text summarizing the key findings of the different perspectives.

Second we brainstormed on different perspectives on shared pooled mobility and invited experts to join this writing group where not covered by preexisting expertise. This step was iterated after feedback from reviewers in a first round of reviews. As a result we obtained nine different perspectives on shared pooled mobility, delineated and motivated as follows:

A transdisciplinary approach enables research to establish the knowledge based on targets, transformation, and systems required to innovate shared pooled mobility. Transport studies analyze the impact of shared pooled mobility on traffic congestion, travel behavior, and emissions. Interestingly, many studies find a mismatch between the theoretically expected decrease of traffic through trip bundling and the observed increase of traffic in many practical implementations such as Uber or Lyft. Social physics can provide insights into the social dynamics of shared mobility, including how people interact with each other and the impact of social networks on ride-pooling behavior. Economics can provide insights into the financial incentives and barriers that may influence people's decisions to use shared mobility. For example, research has shown that offering incentives such as discounts or rewards can encourage people to use shared mobility services. Psychology can provide insights into the cognitive and behavioral factors that may influence people's decisions to use shared mobility, such as attitudes towards sharing, trust, and social norms. Research in human–computer interaction (HCI) can help systematically understand the user experience with digital shared mobility services. One goal is to identify potential in influencing interaction with decisions and reception of outcome when experiencing shared pooled mobility as a user. Energy system research can analyze the interactions of shared mobility with variable renewable electricity generation, and its impacts on energy consumption and greenhouse gas emissions. For example, research has shown that electric vehicles used for shared mobility can significantly reduce emissions compared to traditional gasoline-powered vehicles. Climate change solution science can provide insights into the potential of shared mobility to mitigate the impacts of climate change by reducing emissions. From paratransit systems in the Global South it is possible to draw valuable conclusions about shared pooled mobility, as these systems are very similar to shared pooled mobility but evolved already decades ago.

Third, we developed a search query covering each of the 9 perspectives and implemented the search in google scholar (table 1). A wide array of literature was only peripherally relevant for this review. We extracted relevant papers and combined them with the literature knowledge of domain experts in our review. Exclusion criteria were: (i) papers with title not concerned with transport and mobility; (ii) papers that are predominantly concerned with MaaS, carsharing, or micro mobility, and only peripherally with shared pooled mobility; (iii) papers with predominant focus on autonomous mobility. Inclusion criteria were: (i) specific consideration of ride sharing, ride pooling, shared pooled mobility, or paratransit in title or abstract; (ii) modeling studies, case studies, and overview studies were all considered.

Results demonstrate that some perspectives are widely covered, such as modeling and transportation network companies (>20 000 papers), while others, such as sector coupling and urban economic analysis have only investigated scarcely (<100 papers).

Fourth, we combined the original documented results of our workshop, our transdisciplinary approach to summarize knowledge from different research perspectives with the results of the systematic search queries from step 3. By this we came up with an extensive review on past and ongoing research on shared pooled mobility and a concept for future research to answer remaining research questions.

Table 1. Search queries as implemented in google scholar as of 30 November 2023. Search time includes papers and gray literature, as identified by google scholar, between 2016 and 2023.

Content	Query	Number of results
All queries included the term connected with specific terms via AND, as listed for all 9 domains below	'shared pooled mobility' OR 'mobility-as-a-service' OR 'paratransit' OR 'ride-sharing'	25 400
Transdisciplinary approaches to shared pooled mobility	Transdisciplinar*	937
Transport modeling: Exploring user behavior gauged with empirical data	Modeling AND behavior	22 600
Statistical physics: Exploring the collective dynamics of shared pooled mobility	Statistical physic* OR scaling law	184
Human–computer-interaction: understanding and optimizing the user experience of shared pooled mobility	Human–computer-interaction	1840
Market development: networked mobility and its interaction with public transport	'transportation network companies' OR Didi OR Uber OR Lyft OR GRAB)	20 200
Urban economics	'urban economic*' OR 'spatial economic*' or 'regional economic*'	68
Climate change solutions	Climate change	633
Impacts of shared mobility on the power sector	'power sector' or 'electricity' or 'sector coupling'	32
Global South perspective	'Global South' OR 'developing countr*'	1890

4. Research perspectives on shared pooled mobility

We provide a summary on nine research areas or perspectives, including a transdisciplinary social science approach, transport modeling, statistical physics, user experience research, market development, urban economics, climate change solution modeling, power sector, and global south perspective, relevant for the comprehensive understanding of shared pooled mobility. Figure 1 provides an overview on research areas and perspectives. In Box 1, we define crucial terms.

4.1. Social science: the relevance of different knowledge systems

For a successful governance of shared pooled mobility innovations, urban planners and political decision-makers need multiple forms of knowledge that can be generated through transdisciplinary processes. A general distinction is made here between three forms of knowledge: systems knowledge about the initial situation and the expected effects of a measure such as shared pooled mobility, target knowledge about the desired future state and transformation knowledge about the process required to transition from the current to the desired future state (Pohl and Hadorn 2007).

Political actors on the ground must develop **target knowledge** about shared pooled mobility: what are the most important goals that shared pooled mobility should achieve? In principle, shared pooled mobility has the potential to enable cities to achieve several of their goals at once, but a distinction can be made between three directions: (1) the reduction of car journeys and thus a reduction in traffic, climate-relevant emissions, local air pollution, noise and accidents; (2) social benefits, for example in the form of higher social capital and quality of life: when encounters and social interactions occur between strangers, this promotes social capital (Putnam 1993). Short conversations between people who live in the same region occur during the journey and anonymity is reduced. Trust in other people and in the community grows. Meanwhile, individual quality of life increases when car dependency decreases, including the dimensions of financial expenditure and perceived freedom (Stocker *et al* 2016). Finally, better spatial and temporal accessibility can also be achieved by shared pooled mobility. However, the direct and indirect social benefits of shared pooled mobility are difficult to measure and little empirical research has been conducted to date (Marsden 2022); (3) freeing up space previously used for parking private cars so that it can be unsealed and climate adaptation measures such as greening can be implemented.

Any effective governance of shared pooled mobility will require **transformational knowledge**, considering actor-specific perspectives, user behavior and regulation (Kostiainen and Tuominen 2019). Whether the positive potential of shared pooled mobility is actually achieved will then depend on the specific governance measures. Here, cities and other political actors generally have three fields of action: (1) infrastructure: e.g. high-occupancy vehicle lanes; (2) pricing: e.g. increase parking fees for residents,

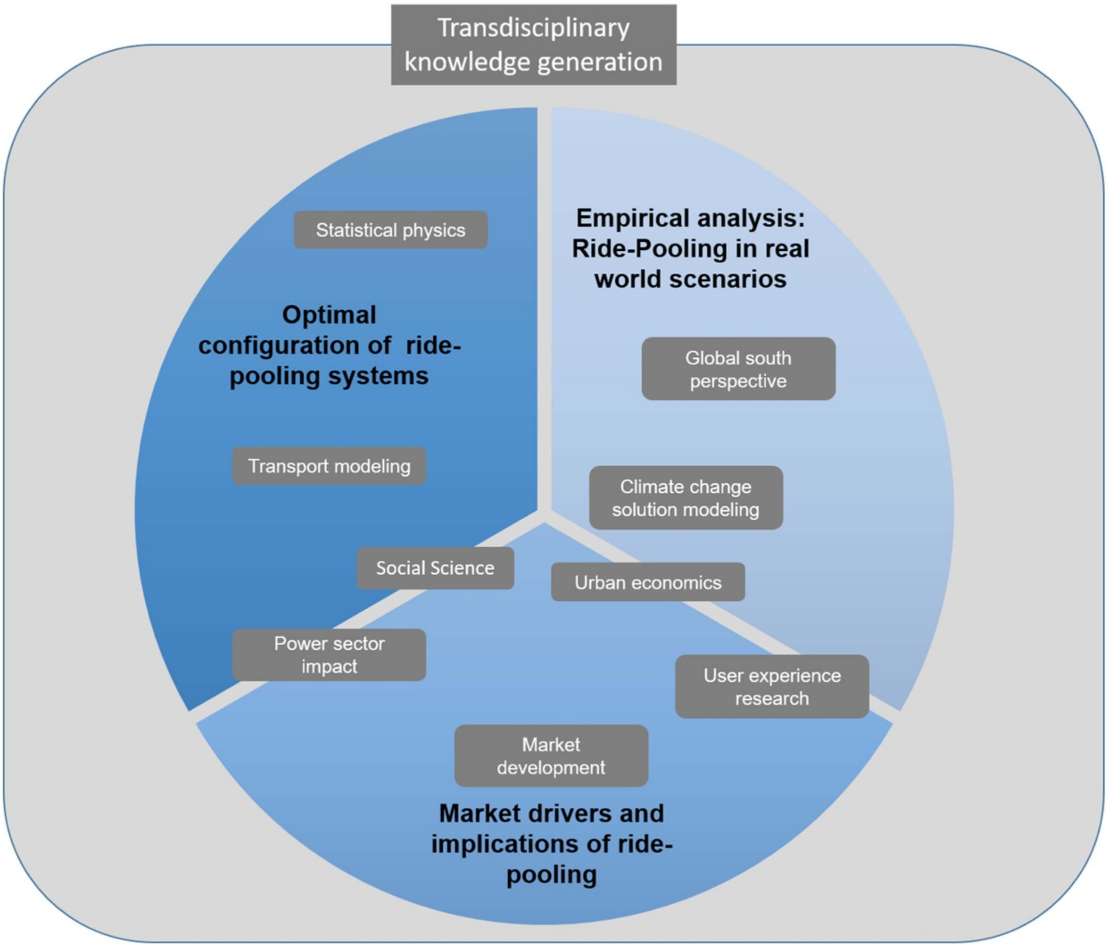

Figure 1. Connection of research areas introduced in section 4 and research question clusters derived from the research areas, as discussed in section 5.

especially the annual fee, so that it becomes quite expensive to own a car but hardly use it; increase taxes on buying and owning cars to reduce the private car ownership rate; city tolls as an incentive for pooled trips and a higher occupancy rate of cars. Examples are London, Stockholm; (3) regulation and financial support: e.g. co-financing of providers (with specifications as to which areas must be served complementary to public transport), zero regulation of providers or delimiting regulation of the cab industry, and simplifications in passenger transport legislation.

Transformation knowledge is a complex process of knowledge that is developed interactively by several groups of actors. Real-world laboratories can produce socially robust bodies of knowledge that integrate the findings of both scientific and practical actors (Pohl and Hadorn 2007). Real-world labs encourage experimentation, but also innovation adaptation, and have become increasingly popular in recent years (McCrory *et al* 2020, Bergmann *et al* 2021).

In this section we have outlined why target and transformation knowledge is still missing. The following sections focus on the current state of **systems knowledge** about shared pooled mobility.

4.2. Transport modeling: exploring user behavior gauged with empirical data

For a system understanding of shared pooled mobility, high resolution modeling—in terms of users and their spatial interactions—is necessary. In contrast to conventional 4-step transport models, agent-based transport models allow for dynamic high-detail transport simulations and thus for modeling shared pooled mobility. There exist various tools for (autonomous) fleet simulation, such as *FleetPy* or *AMoDeus*, that enable users to investigate operational aspects like fleet sizing or vehicle repositioning under arbitrary demand loads in realistic scenarios (Ruch *et al* 2018, Engelhardt *et al* 2022). However, these tools lack the interaction with other transport modes and are operated with static demands. Other holistic transport simulation frameworks like MATSim or POLARIS combine methods from discrete choice theory with behavioral models derived from empirical data, traffic flow models and data-driven methods for impact assessment such as GHG or noise emission quantification (Auld *et al* 2016, Axhausen 2016, Dias *et al* 2017). Examples for (empirical) data that are fed into these simulations range from case-specific stated-preference surveys, over large mobility surveys like Mobilität in Deutschland or Mobilität in Städten and census data to traffic counts (Nobis and Kuhnimhof 2018, Gerike *et al* 2020). Overall, shared pooled mobility simulations have been applied to regions from all over the world with diverse results (Hörl 2020, Liu *et al* 2017, Kaddoura *et al* 2021, Schlenther *et al* 2022; Schlenther *et al* 2023b).

Existing studies reveal relevant insights on the viability and potential of shared pooled mobility. Specifically, simulations that account for mode choice as well as real-world investigations indicate that most users of shared pooled mobility services are attracted from eco-friendly modes including public transport (Narayanan *et al* 2020, Shaheen and Cohen 2020). Variables such as the network topology, demand distribution and numerous service configuration parameters and strategies influence the (empty) mileage of these services that are commonly compared against private motorized transport (Bischoff *et al* 2018, Hörl 2020, Kaddoura *et al* 2020, Schlenther *et al* 2023b). While several studies suggest that one shared (pooled) vehicle could replace around 10 private vehicles (Bischoff and Maciejewski 2016, Bischoff *et al* 2018, Kagho *et al* 2021), recent investigations raise doubts that pooling will occur outside of peak hours, highlighting the role of individual preferences (Haferkamp and Ehmke 2020, De Ruijter *et al* 2023). Whenever pooling does not happen, the taxi-like service induces higher mileage than private motorized transport because of (empty) pickup trips. For relations that are found to be highly suitable for pooling, it remains unclear whether those could or should rather be served with small fixed-route buses. Simulations as well as real-world applications show that profit-oriented service operators are mainly interested in areas of high demand density (Bischoff *et al* 2018, Schlenther *et al* 2023a). In urban contexts, these areas are commonly well served by conventional public transport, which leads to undesirable competition and the aforementioned cannibalisation effects. However, especially in areas of coarse public transport networks, shared pooled mobility services could provide a meaningful addition to public transport, for example for school traffic, and/or as an option for the first and last mile (Lu *et al* 2023, Schlenther *et al* 2022). Concluding, there is a substantial need for more detailed research on the best-suited application contexts of shared pooled mobility as well as for well-informed regulation.

4.3. Statistical physics: exploring the collective dynamics of shared pooled mobility

While direct agent-based simulation as described above is the most realistic way of modeling shared pooled mobility, it is easily overwhelmed by computational demand. A statistical physics perspective investigates a simplified system, which preserves the full travel demand but omits dynamical mode choice and traffic density. This approach allows for analytical approximations and the derivation of mathematical mean-field descriptions. From a statistical physics perspective, the shared pooled mobility system is a complex dynamical process on a network. The street network and request distribution are given as properties of the service area. The fleet size, vehicle size and dispatching algorithm are chosen as fixed parameters of the service implementation. For the approximation of the dynamics, several approaches have been taken.

One approach, introduced in (Santi *et al* 2014) defines shareability networks, in which the requested trips are the nodes and connections indicate that they could be shared given the chosen constraints, namely acceptable maximum waiting time for the passengers and capacity of the vehicles. This was found to give rise in a universal scaling law of sharable trips in (Tachet *et al* 2017) and forms the basis of the widely used pooling algorithm defined in (Alonso-Mora *et al* 2017).

In most other approaches, the dynamics are directly stimulated as a poisson process with requests generated from the request distribution of the region and inserted into pooled routes according to heuristics (for example using the open source python package *ridepy* (Jung and Manik 2023)). Using timed origin-destination data is also possible, when available. The resulting pooled routes are analyzed for varying values of all parameters and system specifications to unravel their impact on the system's behavior. Such analyses are helpful in understanding under which conditions and in which regions ride-pooling constitutes a suitable sustainable transport option. Recently, (Lotze *et al* 2023) identified an easy to calculate system load (defined as the cumulative time required by direct trips, divided by the total driving time available to the system) as the sustainability threshold (load at which individual driven distance and shared pooled driven distance are equal) and found that such loads are achieved in small scale pilots at peak hours.

Another recent study finds that there are two viable solutions for shared pooled systems: The first one are niche markets, where current implementations of on-demand ride-pooling operate; a second cover most individualized transport, if fleet sizes can be made large enough (Herminghaus 2019, Navidi *et al* 2020). Partially based upon the aforementioned dispatching algorithm, (Mühle 2023) introduces an analytical framework to approximate the minimal fleet problem. However, these analyses were done in a Euclidean 2D plane using a uniformly random request distribution.

Other research demonstrates universal scaling of the efficiency (relative travel time) with the fleet size deployed, at a fixed relative request rate and also accounting for street network topology (Molkenthin et al 2020, Zech et al 2022). In the other extreme, the influence of network topology on ride-pooling efficiency was analyzed for a single vehicle in (Manik and Molkenthin 2020). Here it was found that the mesh-like structure of rural areas is better suited for pooling rides than the grid-like structures of cities or the hub-and-periphery structure of smaller cities together with the surrounding area. However, in most realistic scenarios this effect is eliminated by the lower request rates in rural areas, which has a negative effect on pooling.

Another notion of efficiency is presented in (Ruch et al 2021), in which it is defined as a trade-off between individual travel time and global distance traveled. The analysis in this paper compares mean total travel time and vehicle miles traveled across different fleet sizes as well as pooling algorithms.

A collaboration with the agent based transport modeling community will help to identify the favorable fixed point in traffic models with dynamic modal demand patterns. Such an understanding is crucial in order to find system parameters that encourage customers to switch from private vehicles to shared mobility. However, dynamical modeling can only estimate the effects of time efficiency and perhaps pricing, while in reality many more factors may influence such a decision, as detailed in the next section.

4.4. HCI: understanding and optimizing the user experience of shared pooled mobility

While the sections above see traffic demand as given (4.3) or subject to purely rational preferences (4.2), studies show that there is a discrepancy between the theoretically expected user preferences and those observed in practical implementations. Users of car pooling systems have to choose to enter uncertain social situations, when being matched with other people on shared rides. This section investigates the user perspective through the lens of the domain of HCI. We explore how 'smart' systems may support user decisions, how gamification can make these decisions more interesting, focusing on the emotional enjoyment of using car pooling services as a promising factor for actually using them.

While the reasons and motivators for carpooling have been studied since the 1970s, the actual human factors for using so-called 'smart' systems that support shared pooled mobility services have only recently been under investigation (Millonig and Haustein 2020). Novel apps are accordingly designed to optimize user decisions during the matchmaking process in carpooling in a 'smart' way by analyzing user data for behavior and preferences, driven by innovation in mobile applications and services that incorporate machine learning. Recent studies show how computer systems for sustainable solutions could be designed (Raghavan and Pargman 2017). A first glimpse of an analysis combining research on HCI and mobility as a service can be found in (Johansson and Lund 2022).

Studies on shared pooled mobility experiences find that users perceive carpooling as a good solution and a positive human experience when the matching is accurate, but many uncomfortable situations often prevent user retention (Adelé and Dionisio 2020). They identified shortcomings related to uncertainty regarding information search and co-using systems with others caused by the 'smartness' of the services, e.g. intransparent pooling suggestions where the user does not understand why the system proposes a particular match of users to a pooling, effectively losing sense of agency and control. These findings reflect known challenges in several subdomains of HCI, namely in context-aware computing (Schilit and Theimer 1994) where uncertainty in context recognition should be matched with an appropriate level of user control or automation (Dey and Häkkilä 2008). While a high level of user control seems helpful, users often are overwhelmed by 'information glut', i.e. too much information with unpredictable impact on selecting an optimal ride, making practical solutions challenging. In the subfield of digital game design, game makers use information balancing to create motivating challenges where the concept of partial predictability is seen positively as a catalyst for making decision-making interesting and more emotional (Sylvester 2013).

Gamification hence appears as a way forward to make shared pooled mobility more attractive (Deterding et al 2011). Gamification proposes to generate a higher impact on user motivation and behavior change, e.g. by choosing appropriate mechanics, dynamics, and components (Werbach and Hunter 2012, Klock et al 2019). Specifically, this potential is being discussed concerning transportation services where motivational factors and marketing are already shown to impact behavior change without explicitly using gamification (Yen et al 2019). This potential is also underlined by a recent analysis of user experience factors of carpooling services, which proposed emotional enjoyment as a main level besides easy-using and functional availability (Xie et al 2020). Another relevant HCI subdomain is user-centered design focussing on the identification of potential user groups (Winter et al 2020) and the adaptation of systems to their particular needs in development processes (Holtzblatt and Beyer 2017). The domain of game user research proposes interesting concepts of player personalization and adaptation of system behavior in real-time (Bakkes et al 2012, Göbel and Wendel 2016).

In summary, this perspective through a lens of HCI shows that we can design systems that effectively provide interesting experiences with optimal matches of users through usable systems that are tailored specifically for or adapt to relevant contexts and situations in a reliable manner.

4.5. Market development: networked mobility and its interaction with public transport

While the previous sections have discussed the theory on how to design networks of pooled vehicles, this section addresses the application of shared pooled mobility in the transport system. We look mainly at two aspects: (a) the private market of transportation network companies (TNCs) and (b) the interaction with public transport.

From a perspective of the private market, shared pooled mobility has advanced in the course of the global expansion of TNCs such as Uber, Grab, DiDi or Lyft. Today, TNCs are active in many countries, with studies estimating that services are available in 80 or more countries (Goletz and Bahamonde-Birke 2021, Hasselwander *et al* 2022). TNCs have experimented with offering pooling options as extension of their core business of ride sourcing (under product names such as uberX Share, GrabShare or Lyft Shared Rides) since 2014 (Hemel 2017). However, they faced headwinds from regulators or mini-bus operators that felt threatened by such activities (Goletz and Bahamonde-Birke 2021) and during the COVID-19-Pandemic, TNCs generally stopped offering ride-pooling options. Today, pooling by TNCs remains a niche market. UberX Share (formerly uberPool), for instance, is available only in about 40 cities (Tsay 2023), while UberX (non-pooled ride-sourcing) is available in more than 1000 cities (Uber 2023). Meanwhile, Lyft, Uber's main competitor in North America, ceased its pooling service in the second half of 2023, explaining that with too many detours were taking 'people out of their way' (Davalos 2023). In some cases ride-sharing operators work together with transit agencies, in order to reduce costs for a public transportation system (Minot 2018). An extensive overview of the growing sharing economy can be found in (Shaheen *et al* 2020a).

At least when looking at the billion dollar business of TNCs, pooling does not (yet?) seem to be an important part of it. If and how this could be overcome is subject to ongoing scientific discussions: (Zhang and Nie 2021) analyzes the economic trade-off to offer non-pooled and/or pooled services that TNCs face, which is influenced by fleet size and drivers, price per trip, profit per trip and other factors. She finds that a mixed strategy offering pooled and non-pooled rides can maximize profits for TNCs, and that in order to increase pooling a (congestion) tax policy that penalizes solo rides can be effective. Such policies have already been applied in practice: The city of Chicago, for instance, has imposed taxes on TNC rides that differ depending whether the ride is single-occupancy or pooled, with pooled rides having lower taxes. For this case, (Abkarian *et al* 2023) found an increased count of pooled rides by 27%. Another aspect that is considered to have high potential is the complementary integration of ride-pooling with public transport (PT). Here, the main idea is that ride-pooling could solve the challenge of first-last-mile access towards PT, thereby increasing the overall use of PT and reducing car use. (Mohamed 2022) studied the interaction of uberpool and PT from the governance perspective, finding that authorities lacked competencies in relation to ride-pooling. He also finds that about 60% of the trips that have been made by ride-pooling would have been made by public transport. Further research relates to the planning of the interaction of ride-pooling with (line and schedule based) public transport (Lorente *et al* 2022), so that the scheduled and non-scheduled on-demand services can be connected in an efficient way. (Hou *et al* 2020) have studied factors that affect 'willingness-to-pool', findings that distance and duration (both factors that increase the trip fare) had a positive effect on the willingness to use ride-pooling, while trips to or from the airport, that likely were undertaken under time pressure and with luggage, had a negative impact.

For the future, it will be important to research how ride-pooling offered by TNCs can be used in a way that supports the transition to sustainable mobility. In its current form, TNC mainly sells non-pooled ride-sourcing, a product that has equal or higher emissions to car rides, while ride-pooling remains a niche. Research is needed to understand how to incentivize the use of ride-pooling for users, and how to regulate it so that TNCs (or any other private company) will offer it wherever they operate. This seems to be also very relevant against the backdrop of the expansion of TNCs: as these companies have shown an enormous pace in global expansion, going from zero to 80 countries in 10 years, they could become one of the forerunners to make ride-pooling available globally. Especially as they already have the technical capabilities to offer such a service on their platform, which likely is just a feature to be activated. Apart from TNCs, the role of companies that only offer pooling services such as MOIA in Germany or Via in the US should be studied by academia, thereby contributing to closing the research gap between theoretical effects and the practical application of shared pooled mobility.

A stated choice experiment in Switzerland supports the assumption that in future, autonomous vehicles are likely to be used in a shared, pooled mode, with 61% of respondents in the control condition preferring pooled (autonomous) vehicles over private ones (Stoiber *et al* 2019). Combining instruments influencing comfort, cost, and time could potentially increase the proportion of pooled uses of autonomous vehicles (Stoiber *et al* 2019).

4.6. Urban economics: business case limited to dense urban centers?

As transport modeling focuses on how the mobility system simulates, statistical physics explores how the dynamics of the process of the mobility system work, user experiences explain how the effective designs that influence shared pooled mobility usage are shaped, and market development discusses how the market share of shared pooled mobility is at its current state, this section draws attention to how viable and functional shared pooled mobility is in different urban forms and city sizes in terms of population density.

User density matters for car sharing and also for shared pooled mobility to make joint routing time efficient. Currently, this translates into financially viable business models only for dense agglomerations. One consulting study suggests that free-floating car sharing remains limited to cities with populations above 500 000 inhabitants (Kearney AT 2019). In contrast, other sorts of car sharing, e.g. station-based car sharing, are more flexible and are often present in smaller municipalities (Bundesverband CarSharing e. V 2019).

Nonetheless, congested megacities will be most attractive for shared pooled services. According to the United Nations, as of 2018, there are 33 megacities in the world—21 are located in Asia (United Nations 2019). A study in Bangkok (Ayaragarnchanakul *et al* 2022), one of the Asian megacities, confirms the probable viability of (door-to-door) shared pooled mobility by indicating that as long as the 5-seater shared pooled vehicle is fully occupied and the detour time is no more than 10 min, commuters will opt for it because the travel time and travel cost trade-off is worth it for them. Shared pooled mobility is especially attractive to commuters living in gated communities (62% of car owners and 48% of total car trips), where choices of modes are more limited.

Shared pooled mobility could also be a viable option in a populated subset of area in a city. By developing a similarity index between two trips, it was possible to cluster over 85% of taxi trips during the morning peak (8–11 a.m.) in the Midtown and Upper East Side of New York City. Taxi trips constitute almost one-third of total trips in New York and 94% of these trips recur daily on weekdays. Furthermore, this exact method was applied to Chengdu, which is less dense than Midtown and the Upper East Side of New York City. The results are almost as good as New York's, but only 73% of clusters are recurrent (Veve and Chiabaut 2020).

Apart from urban density, urban form plays an important role in the outcome of shared pooled services. The spatial structure of a polycentric city suggests ridesharing services could reduce road traffic in the inner core city of the Beijing Metropolitan Area, a polycentric city with a strong core and seven sub-centers (Liu *et al* 2021). Resulting from scenarios of car-sharing and transit promotion in 288 prefectural Chinese cities, polycentric megacities show reduced gasoline-fueled private car usage when compared to monocentric megacities. This finding is however not transferred to cites of other sizes smaller than 5 million citizens (Li *et al* 2018). Future simulation of integrated land use-transportation models are recommended to draw general conclusions (Hawkins and Nurul Habib 2019).

Unfortunately, shared pooled mobility cannot reach the desired modal share without pushing for private-vehicle associated costs of tollway and parking charges too. Further, pricing private vehicles with the true social cost, a correction of market failure, results in fewer externalities related to road traffic (Ayaragarnchanakul and Creutzig 2022). This essentially minimizes the endowment effect, a thought that people sometimes value ownership over their willingness to pay (Hawkins and Nurul Habib 2019).

Although the concept of shared pooled mobility has prospered in densely populated and diverse urban areas, it is also gradually extending its reach to less densely populated and suburban areas such as small and medium-sized college towns of 50–500 thousand citizens (Cohen and Shaheen 2021). The purpose is to improve accessibility and social inclusion rather than reducing traffic externalities. For example, ridepooling is used either as the first-and-last-mile connections to public transit or as public transit replacement in the suburbs of Northern Virginia (Shaheen *et al* 2020b). Government agencies are also partnering with ridesharing services as a feeder to train stations (Hawkins and Nurul Habib 2019).

Balancing the trade-off of important transport-related factors that commuters emphasize is crucial for shared pooled mobility to become successful. These factors vary depending on users and markets in different cities as discussed earlier in the previous subsection. For instance, travel time, convenience (in terms of accessibility and availability), travel cost, and privacy are the most valuable factors of commuting (in that order) in Bangkok (Ayaragarnchanakul *et al* 2022). The pricing gap between public and private transport modes also plays an important role in mode-shifting potential. Integrating demand estimation that balances user utility with transport systems planning models is crucial to minimize detour time and shared travel costs, but sufficient user density in residential clusters like gated communities is a prerequisite for economic feasibility.

4.7. Climate change solutions: pool rides, not hail

Research from the perspective of urban economics, by examining the economic drivers and market incentives of shared mobility systems, can play a key role in shaping affordable and convenient shared mobility systems. Turning to research on climate change solutions, these insights can inform the development of strategies and policies aimed at addressing climate change effectively.

Shared mobility is seen as an important component to reduce transport related climate emissions, due to its ability to reduce private car use and ownership. In urban areas, it can help to reduce traffic congestion, noise, and accidents, while also reducing energy consumption and emissions by decreasing the fleet size and increasing vehicle utilization (Hu and Creutzig 2022, Zhong *et al* 2023). In rural areas, it can help to reduce the dependency from cars, increase the efficiency of public transport by increasing seat occupancy (Hult *et al* 2021, Schlüter *et al* 2021). Limiting global warming to 1.5 °C will require rapid decarbonisation of the world's transport systems, while urban transport is currently dominated by petrol and diesel-powered vehicles (Glazebrook and Newman 2018, Monaco 2023). Combining the potential of shared mobility with vehicle electrification and other strategies to reduce vehicle carbon emissions may be a viable solution of decarbonizing land transport (Sustainable Mobility for All 2022). However, the emission reduction potential of this comprehensive strategy is currently unclear. For example, a detailed investigation of shared motorcycle use in Jakarta, Indonesia, demonstrated that customers benefited from the flexible new services, but that overall sustainability benefits, such as GHG emissions, were canceled out by deadheading and limited mode shift from private vehicles (Suatmadi *et al* 2019).

In the climate solution literature, two perspectives are of relevance: life-cycle accounting and scenario modeling.

First, life-cycle accounting. In the literature on shared mobility, life-cycle accounting has been used to evaluate the carbon emissions associated with various transportation modes, such as bike-sharing, car-sharing, and ride-pooling. These studies typically compare the emissions from shared mobility options to those from traditional transportation modes, such as private car ownership, and assess the potential environmental benefits of a shift towards shared mobility (Yi and Yan 2020, Sun and Ertz 2021). A previous work evaluated marginal CO2 emissions for each kilometer a person travels in shared mobility modes (Creutzig 2021). Findings reveal that two wheelers are more climate friendly than four wheelers. A private bicycle is 15 times more CO2-efficient than an average car with an internal combustion engine. More importantly, occupancy makes all the difference for car use. With four passengers, the car will perform similar to bike sharing and e-scooters.

Ride hailing (or ride-sourcing) is particularly problematic, as illustrated in figure 2, because ride hailing services, if not having a fossil-free drivetrain, can have higher carbon footprints than private vehicle trips due to deadheading (empty mileage en route to the pick-up) (Bischoff and Maciejewski 2016, Tirachini and Gomez-Lobo 2020, Creutzig 2021). Including larger systemic effects, such as reduced life-cycle footprint due to higher utilization of vehicles may have positive effects on the carbon footprint (Morfeldt and Johansson 2022) or even further worsening effects as people shift from public transit (Schaller 2021).

Second, scenario-based assessments enable extensive analysis of how high-quality shared pooled mobility can contribute to deep decarbonization in the passenger transport sector. *A series of studies based on simulation on different regions (such) lead by ITF-OECD shows CO2 emission can by −31%∼−62% in five cities (Dublin, Auckland, Helsinki, Lisboa and Lyon) with all private cars in cities were replaced by shared vehicles, while the only 10% or less of the number of vehicles were needed for citizens* (International Transport Forum 2017a, 2017b, 2018, 2020). *There is a general lack of understanding of shared mobility patterns and potential for climate change in developing countries, leading to an inconsistent local policy structure aimed at incorporating shared mobility into the wider set of mobility choices.* In a recent *proceeding* study, some of this paper's authors found that deep decarbonization to net-zero in the passenger transport sector would rely on a comprehensive climate policy (including electrification, sharing mobility, and rapid replacement of coal and gas power plants with renewables) that maximizes the benefits of emission reduction (Hu *et al* 2024). To achieve the same emission reduction, the total number of vehicles in the shared mobility scenario is less than 1/2 of that in the EV scenario, which will greatly reduce vehicles' material demand. Importantly, because of reduced demand for transport sector electrification, additional energy demand can be more easily covered by renewable energy sources.

In future studies, we hope to extend the assessment framework with a high-frequency vehicles database, more accurate emissions accounting methods, and reasonable scenario design. More valuably, not only carbon emissions benefit but also decarbonize cost, material demand, and land use need to be considered in an integrated climate change solution model.

4.8. Power sector: shared pooled BEVs have distinct impact

To take into account the potential contribution of shared mobility to the reduction of carbon emissions, it is also necessary to better understand how a significant shift from private car use to shared car use may affect the electricity sector, in the case where a

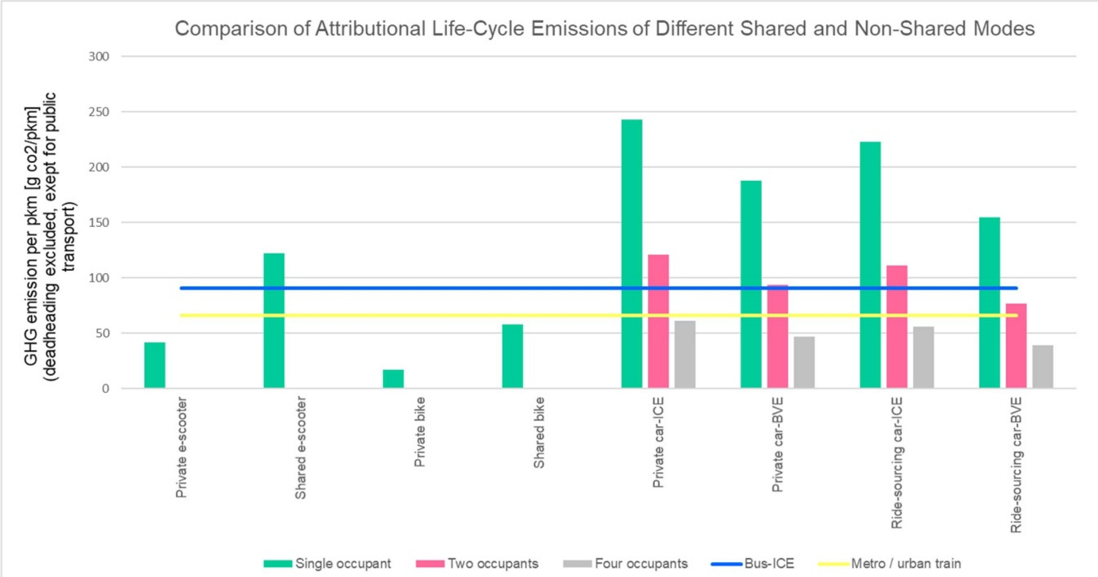

Figure 2. GHG emissions of different travel modes for different numbers of occupants. Ride-sourcing with car-ICE (ICE: Internal Combustion Engine) still has high emissions, while ride-sourcing with Battery electric vehicles (BEV) has comparatively low emissions (Creutzig 2021). Increasing the occupancy (ride pooling) is central to reduce per capita emissions. Reproduced with permissions from Creutzig (2021).

large part of the vehicle fleet is electrified. The interactions between private electric cars and the power sector, on the one hand, and shared electric cars and the power sector, on the other, may lead to different outcomes in terms of renewable energy integration. This, in turn, affects the carbon intensity of the power sector, which in turn affects the carbon intensity of the whole supply and operation vehicle chain. Such interactions can be investigated using power sector modeling techniques.

Battery electric vehicles (BEV) that are used for shared pooled mobility may have very different effects on the power system than privately-owned BEV, which constitute so far the main focus of research on the interactions between the transport and the power sectors. In future power systems with increasing shares of variable renewable energy sources, the ability of electric vehicles to make flexible use of variable electricity supply gains importance (Blumberg *et al* 2022, Strobel *et al* 2022). The power sector impacts of BEV depend on parameters such as the passenger road mobility demand, the battery capacity provided by electric vehicles, as well as charging availability and charging mode (Schill and Gerbaulet 2015, Taljegard *et al* 2019). The latter also depends on the type of charging systems, e.g. stationary vs. dynamic charging via electric road systems, on their geographical distribution and power rating, and on the availability of smart charging or vehicle-to-grid technologies (Lauvergne *et al* 2022). Investigating how these factors shape the interactions of shared pooled BEV with the power sector requires bringing together several fields of expertise, namely transport modeling, power sector modeling and behavioral sciences.

Travel demand plays an important role in determining the electric load effects of BEV, i.e. their absolute electricity demand and hourly load profiles (Xu *et al* 2018, Crozier *et al* 2021). Of particular importance in a power system dominated by variable renewable energy sources is the impact of BEV on the peak residual load, and their ability to make use of periods with high renewable electricity generation. To understand the impacts of shared pooled mobility, we must better understand how it modifies travel demand and substitutes other transport means—in particular private electric cars. Depending on how widespread smart charging and potentially even vehicle-to-grid technologies may become for shared pooled electric vehicles, they could help to integrate variable renewable energy sources. Their interaction with the system integration of variable renewables further relies on the substitution effect between electric shared pooled vehicles and other electric vehicles, in particular privately-owned ones.

The overall storage capacity supplied by the shared pooled vehicles also plays a determining role in the flexibility potential offered to the power system. From a power sector perspective, the storage capacity of electric shared pooled vehicles depends on both the fleet size and the battery capacity of individual vehicles. From the perspective of shared pooled fleet operators, the optimal battery capacity of vehicles is very much linked to the travel demand it has to supply and the charging availability. For instance, in order to undertake long trips with very little time to charge in between two trips, such vehicles might need to be equipped with batteries that are significantly larger than batteries of vehicles designed for private use only. Yet, if shared pooled BEV came with much better charging opportunities than privately owned BEV, this would limit their need for larger batteries. The bigger the overall storage capacity provided by shared pooled mobility, the larger their potential flexibility supply to the power sector. In contrast, shared pooled mobility may also come with smaller grid charging availability as vehicles are likely to be more often on the road and less often idle, which would rather attenuate the flexibility potential of shared pooled vehicles. The impacts on the power system flexibility depend on this trade-off between potentially larger batteries and smaller grid availability, which is quantitatively not understood so far.

4.9. Global south perspective: leapfrogging possible?

We discuss the market situation of shared pooled mobility in section 4.5. While these systems are rather new in the Global North, similar systems have long existed in the Global South. Analyzing them could provide us with valuable information necessary for implementing shared pooled mobility efficiently.

Previous research has sought to formally characterize paratransit, both through a conceptualization of its common characteristics across different contexts, and through an analysis of specific country or city-level studies. Key references include the work by (Behrens *et al* 2021) and (Behrens *et al* 2016), where paratransit's business models, regulatory regimes, and operating practices in relation to public policy and city-level planning are analyzed based on different regional realities, while also pinpointing the emerging role of potentially disruptive (digital) technologies. Additional general assessments of MaaS in the Global South include the systematic review by (Hasselwander and Bigotte 2023), who conclude that to untap its full potential, ad-hoc MaaS models are required to match context-specific regulatory frameworks, available infrastructures, institutional and financial constraints, and user preferences for existing paratransit systems. The most crucial barriers to a MaaS implementation in the Global South—with specific emphasis on the integration of paratransit in transportation planning and on multimodal transport planning—is offered in (Boutueil *et al* 2020, Ho and Tirachini 2024), respectively. Finally, a large number of studies has assessed paratransit experiences, challenges, emerging trends, and recommendations for sectoral regulation and development in specific countries: for instance, the interested reader can refer to (Lozano Paredes 2023) for South America; (Kasera *et al* 2016) for Namibia; (Klopp and Cavoli 2019) for Mozambique and Kenya; (Saddier *et al* 2017) for Ghana; and (Phun *et al* 2019) for Thailand.

Throughout the twentieth century—and largely until today—private vehicle ownership has been strongly and positively associated with economic growth across world countries (Pucher *et al* 2007). As seen from figure 3, high-income countries (the 'Global North') exhibit high motorization rates (vehicles per capita), leading to socio-infrastructural settings defined as '*car dependence*' (Mattioli *et al* 2020), e.g. the current 900+ vehicles per person in the United States, while Global South countries display considerably lower values (e.g. Botswana, the country with the highest PPP GDP in sub-Saharan Africa, stands at 260 vehicles per capita per 1000 people). This heterogeneous picture is mostly the result of income constraints to purchase and operate private vehicles by dwellers in the Global South.

Global South countries and cities are characterized by significant transport infrastructure gaps, with limited and infrequent public buses, low density of rail and light urban rail, and scarce active mobility infrastructure (e.g. bike lanes) (Pandey *et al* 2022, Zhou *et al* 2022). As a result of such infrastructure and income constraints, in the Global South the prevalent approaches for meeting mobility demand have largely been two: (i) the massive use of walking as a transport mode; and (ii) what is defined as 'paratransit'.

As extensively discussed in (Behrens *et al* 2016), paratransit describes the originally informal (but increasingly recognized and partially regulated by public authorities of several countries) system of ride sharing services that is widespread across countries of the Global South. Irrespective of existing differences among regions (including the local name for what is commonly called paratransit, ranging from *matatu* in Kenya, to *Dala Dala* in Tanzania, or *Colectivo* in Latin American countries), paratransit has several common characteristics. Paratransit vehicles are typically small, privately-owned and operated buses or vans that collect passengers on a loosely fixed route without timetables, combining multiple passengers with similar or overlapping destinations into a single shared vehicle which may stop anywhere to pick up or drop off their passengers and only departing when most or all seats are filled. This system ensures high occupancy rates, which in turn result in low per-fare, per-passenger environmental impacts ((Creutzig 2021); cf figure 2).

Interestingly, even though several characteristics of paratransit mirror the features of shared pooled mobility described in this paper, paratransit has emerged decades before the rise of the sharing economy in the early 21st century. In the Global South, shared pooled mobility is indeed implicitly already one of the leading urban modes of transportation.

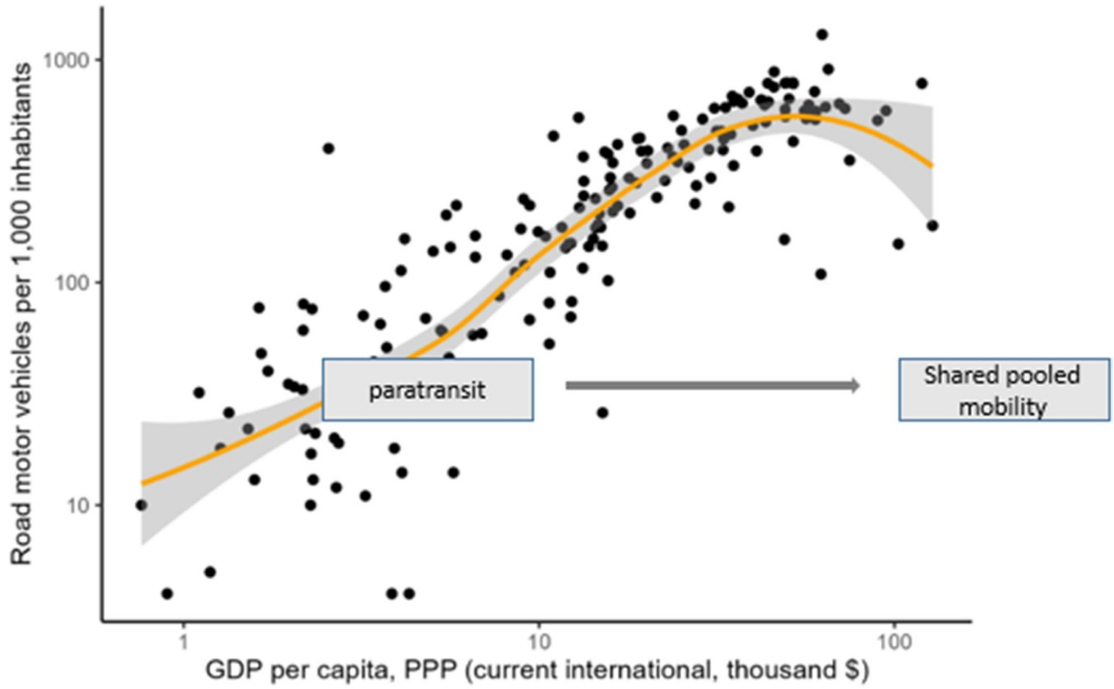

Figure 3. Scatter plot and locally estimated scatterplot smoothing (LOESS) fit of PPP per-capita GDP (World Bank 2023) against motorization rates (Imamaliev *et al* 2021). Each dot is a country between 2019–2022 (depending on source's year). Developing countries have the potential to leapfrog by maintaining and improving existing paratransit to shared pooled mobility and avoid car dependence and lock-in.

Paratransit has attractive characteristics for urban and peri-urban populations of developing countries due to its proximity, affordability, effectiveness. Statistics on the modal share for a broad range of cities in developing countries is offered by (Middleton 2018) who shows that paratransit accounts for very large shares of total public transport usage. For instance, in Accra, Ghana, it is above 90%; in Abidjan, Cote D'Ivoire, it meets half of the entire mobility demand; in Addis Ababa, Ethiopia, it stands at about 35%, in Dar Es Salaam, Tanzania, it is above 60%, and in Lagos, Nigeria, it reaches almost 40%.

The current and projected climbing urbanization rates and increasing affluence in the Global South are strongly boosting mobility demand (United Nations 2022). So far, motorization rates have remained relatively low, also due to the significant cost compared to average salaries and to limited and congested road networks (Olvera *et al* 2008). However, as demonstrated in the literature, the status symbol nature of private vehicle ownership still represents a reason for concern in relation to future mobility trends in the Global South (Luke 2018, Ramakrishnan and Creutzig 2021). In addition, besides socio-cultural reasons for car ownership aspiration, there also exists a set of issues related to paratransit that need to be solved if shared pooled mobility is to consolidate as a leading modal share in the Global South. Specifically, despite its qualities, the shared pooled mobility of the Global South is also characterized by several challenges that are common across countries, including (Sietchiping *et al* 2012, Venter *et al* 2020, Gupta 2022): (i) low vehicle standards (e.g. inefficient engines, high local pollutants emissions, limited vehicle maintenance); (ii) safety and regulation, such as limited safety standards inside for paratransit vehicles passengers and limited compliance to driving regulation by paratransit drivers; (iii) informality and taxation (i.e. limited revenue collection opportunities and challenges in regulating the service); (iv) informality and route planning to meet transport demand (limited room for policy intervention by public decision-makers, e.g. to implement mobility policies and coordinate existing transport services with public infrastructure investment) (Boutueil *et al* 2020).

Several studies have highlighted the importance of high-quality, granular transport data, as well, as of multi-stakeholder discussions (including public decision-makers and private paratransit service providers) for understanding needs and barriers and enhancing urban planning in rapidly evolving developing cities (Klopp and Cavoli 2019, Falchetta *et al* 2021). In future decades, planners and policymakers in the Global South concerned with meeting growing mobility demand with affordable, efficient, and sustainable systems should seek to consolidate paratransit as a sustainable mobility solution that uses digital innovation and low-carbon technologies to efficiently bundle and schedule rides (Pirie 2014). Already in recent years, private companies (e.g. SWVL, Careem, Ola) have sought to use technology and algorithms to improve the operational efficiency of paratransit in Global South contexts.

Countries of the Global North could draw inspiration from the paradigm of paratransit coupled with efficient, low-impact vehicles, sound regulation, and digital innovation (i.e. shared pooled mobility) as a virtuous concept. Countries from the Global South could leapfrog from paratransit to shared pooled mobility system avoiding car dependence and urban sprawl (figure 3). This would decrease private vehicle ownership and use and therefore improve efficiency, decrease congestion and reduce environmental pollution, including transport sector GHG emissions.

5. Towards a transdisciplinary research agenda

Several research questions arise from the synthesis of the variety of angles given above, which require knowledge from several areas to solve. The research questions are classified in three research question clusters: (1) optimal configuration of ride-pooling systems, (2) empirical studies, (3) market drivers and implications for the economics of ride-pooling. An overview of clusters and associated research areas is depicted in figure 1. In the following the three research question clusters are explained in more detail.

5.1. Optimal configuration of ride-pooling systems

As one strategic point for optimizing shared pooled mobility, we suggest analyzing ride-pooling from a systemic point of view and find optimal configurations for ride-pooling vehicles, fleets, operators, customers and systems.

5.1.1. Dynamical parameter analysis of shared pooled mobility setup

While some studies indicate that ride-pooling has the potential to drastically reduce the number of vehicles necessary for serving the demand, observations and agent-based simulations often find that pooling only occurs in a fraction of requests as outlined in 4.2 and 4.3. This necessitates a detailed analysis of the parameter space of all ride-pooling parameters from fleet size (Balac *et al* 2020) to dispatch algorithms for a wide range of request rates to gain a better understanding of the underlying dynamics and how the different approaches fit together. This would aim to answer the question whether a high-pooling scenario is possible and for which parameters it can be reached.

5.1.2. Regionally optimal ride-pooling parameters

Beyond the dynamical parameters there are also geographical characteristics impacting ride-pooling performance. For example, first studies have tried to answer the optimal fleet size for specific areas of ride-pooling services (International Transport Forum 2015), but different methods and improved empirical resolution is required. We suggest that the ride-pooling parameters should be systematically determined in dependence of the given street network, the expected or measured demand, social and economic factors and regional aspects (downtown or suburb).

5.1.3. Intercomparison of high and low income countries

Viewing ride-pooling from a global perspective, it becomes clear that it needs to be differentiated between low- and high income countries. In high income countries most people have a private vehicle, which should be replaced by ride-pooling. In low income countries, the initial situation differs, most people do not have a private vehicle, thus, ride-pooling should prevent private vehicles from becoming the most dominant mode of transport. Hence, the implementation strategy of ride-pooling differs between low and high income countries. Second, ride-pooling is relatively cheaper in low income countries compared to high income countries, as for example, informal paratransit forms of ride-pooling already exist. These differences need to be investigated in order to optimize the usage of ride-pooling in low and high income countries.

5.1.4. Relationship of ride-pooling and line services (public transit)

On-demand pooling and line services represent two ways of bundling trips. It would be interesting to better understand their interaction in a number of respects: Some early simulations suggest that for very small networks and very large request rates and fleet sizes, on-demand ride-pooling dispatchers produce cyclic routes. Do cyclic and non-cyclic routes co-exist? What is the nature of the transition between them? Do the cyclic routes correspond to line services in realistic scenarios?

5.1.5. Interactions between dispatch algorithms, rebalancing, service quality, and resource consumption

The efficiency of a ride-pooling system is fundamentally determined by its dispatching algorithm, which allocates requests to specific vehicles (Maciejewski *et al* 2016, Hörl *et al* 2018). Electric charging adds another aspect (Bischoff and Maciejewski 2014). Fleet rebalancing improves service quality, but consumes more resources (Winter *et al* 2017, Schlenther *et al* 2023a). In contrast, pre-booking allows significant savings (Lu *et al* 2023). Research is needed to identify different trade-offs between these aspects, and to possibly relate them to properties of the demand or the road network. To implement efficient fleets this research must be supported by empirical studies about real-world ride-pooling systems (see next section).

5.2. Empirical analysis: ride-pooling in real world scenarios

Analyzing ride-pooling applications in real-world scenarios is crucial if they are to be deployed on a large scale. It matters how shared mobility interacts with other public transport, how sustainable ride-pooling is compared to private vehicles and how urban form and density influences shared-mobility.

5.2.1. Real-World analysis of ride-pooling

A large share of papers that analyze ride-pooling are investigating ride-pooling with simulated data. The demand is often simulated as an uniform request distribution, meaning that from every stop the system gets the same amount of requests over time. We suggest on the one hand that ride-pooling simulations should focus on real-world scenarios with demand from real-world measures, after optimizing them from a theoretical point of view. On the other hand, results from real-world ride-pooling systems should be studied systematically. One of the main challenges here seems to be how to deal with incomplete or sparse data on one hand and limited computational capacity on the other hand.

5.2.2. Formal vs. informal ride pooling systems

While informal, decentrally operated flexible minibus systems have long been successfully operated in many regions in the global south effectively bundling trips at a low price, digital ride-pooling systems tend to operate as a taxi service with occasional pooling at much higher prices. Studying the differences of informal and digital shared pooled mobility offers a unique chance at revealing the causes of ride-pooling platforms failure to reach larger market shares.

5.2.3. Intermodal public transport using ride-pooling

How ride-pooling would interact with other public transportation systems is only rarely investigated. On the one hand, ride-pooling could function as a system along other public transportation systems, which offers users another, more comfortable, way of traveling from one place to another. On the other hand, ride-pooling could also be a system that serves only as a supplement for other systems, for example, in last-mile travel or during off-peak hours (Luo & Nie, 2019). Research is needed on how to identify when and where ride-pooling could be used and how to find the optimal configurations for such ride-pooling systems.

5.2.4. Influence of shape and density of a city on shared mobility usage

Which type of mobility, for example private vehicles or subways, is preferred by the inhabitants of a specific area of a city is strongly influenced by its density and shape (Wagner *et al* 2022). Here we suggest investigating what the requirements for a viable shared pooled mobility option in terms of the size (density) and shape of a city are. This would allow it to design specified ride-pooling or intermodal transport options for different cities and its boroughs.

5.2.5. Sustainability of ride-pooling

The overall goal of implementing ride-pooling is to increase sustainability of transportation by reducing the usage and ownership of private vehicles. Right now, studies about the comparative and overall material, environmental and climate footprint of shared pooled mobility for different shared-pooled mobility scenarios that also account for energy sector interactions are missing. We suggest using findings about optimal real-world shared-mobility scenarios to determine the sustainability of ride-pooling compared to the usage of private vehicles.

The insights gathered from real-world ride-pooling systems allow it to design optimal ride-pooling systems in the sense of operational efficiency. From the perspective of the operators this is often not enough, for them financial aspects often play an important role too. Thus, the following section 5.3. gives an overview of research studying financial aspects of ride-pooling.

5.3. Market drivers and implications of ride-pooling

Shared mobility offers the opportunity to provide services where public transit is financially less viable as user density is relatively low. This requires analyses of the market opportunities for shared mobility options.

5.3.1. Integration of variable renewable energy sources

The proliferation of shared mobility could significantly impact future power markets, particularly if these vehicles utilize renewable energy sources. Consequently, it is imperative to investigate whether shared pooled mobility facilitates or impedes the integration of variable renewable energy sources into future power systems and what impact the details of the pooling service's set-up have on it. Additionally, an exploration of the driving factors behind these outcomes is warranted.

5.3.2. Life-cycle assessment impacts of switching to shared pooled mobility

Ride-pooling can employ a diverse array of vehicles, from compact cars to small-scale buses. Like private cars, these vehicles necessitate a substantial variety of materials, thereby exerting an environmental impact. Notably, the construction of batteries for shared vehicles requires rare earth elements. We propose a focus on the differential life-cycle assessment impact of shared-pooled mobility, particularly in comparison to alternatives such as privately owned electric vehicles.

5.3.3. Market systems incentivize usage of shared pooled mobility

The efficacy of shared-pooled mobility as a transport alternative hinges on the design of an appropriate market model. Further research is required to discern the market systems that promote the use of shared pooled mobility, including the exploration of spatial settings—namely, the application of ride-pooling in suburban and rural contexts. Additional inquiries include identifying settings that enhance the multimodal use of shared mobility and other environmentally friendly modes, such as public transport and active modes. It is crucial to determine the conditions under which individuals relinquish car ownership and effectively curtail motorized transport.

5.3.4. User comfort and pleasant interactions with ride-pooling

Understanding how to build and improve matching systems that provide reliable and enjoyable services and effectively provide onboarding and user retention. How can digital systems and the interaction with them offer decision support and lead to reliably positive, e.g. meaningful and interesting social experiences? This research needs experimental setups with methods from user-centered, context-aware and maybe even game-based systems in the domain of HCI that yield powerful and daring interactive prototypes and their analyses.

6. Conclusion

In this paper we provide a novel transdisciplinary research agenda that aims to identify the social, economic, and technological conditions under which shared pooled mobility can contribute to low-energy demand climate solutions. We identify three main research areas: the optimal configuration of ride-pooling systems, empirical studies to analyze ride-pooling under real world conditions and, the analysis of market drivers and implications for the economics of ride-pooling as the. To thoroughly study these areas, we propose to combine the expertise in the respective research areas represented by the different contributors of this work, namely transport modeling, statistical physics, social science and urban economics. To determine how a ride-pooling system can be designed to be as convenient as possible for the passengers, it makes sense, for example, to consider both a technical perspective—how can passengers reach their destination as quickly as possible—and a social perspective—how must the vehicles be designed, so that users can get on board. To determine how ride-pooling could be used to explicitly replace private vehicles, considering an economical perspective—how much operating costs are required—and a social perspective—how expensive should the system be for users—is useful. This research could be improved by simulating ride-pooling systems or observing existing ride-pooling services. With this transdisciplinary approach, transformational and system knowledge about the optimal implementation strategy for shared pooled mobility will become increasingly useful. These knowledge gains are intended to support the development and implementation of ride-pooling systems in urban and rural areas, by businesses or public transit operators, as stand-alone systems or in combinations with other transportation systems. With this flexible public transportation system we hope to motivate people to switch to public transport and to limit the usage of their private vehicles, in order to reduce emissions of the transport sector.

Data availability statement

No new data were created or analysed in this study.

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ORCID iDs

Felix Creutzig https://orcid.org/0000-0002-5710-3348
Alexander Schmaus https://orcid.org/0009-0002-8470-4365
Jonas Schild https://orcid.org/0000-0002-1931-9359
Tilmann Schlenther https://orcid.org/0000-0001-6781-6918
Nora Molkenthin https://orcid.org/0000-0002-7190-0714

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