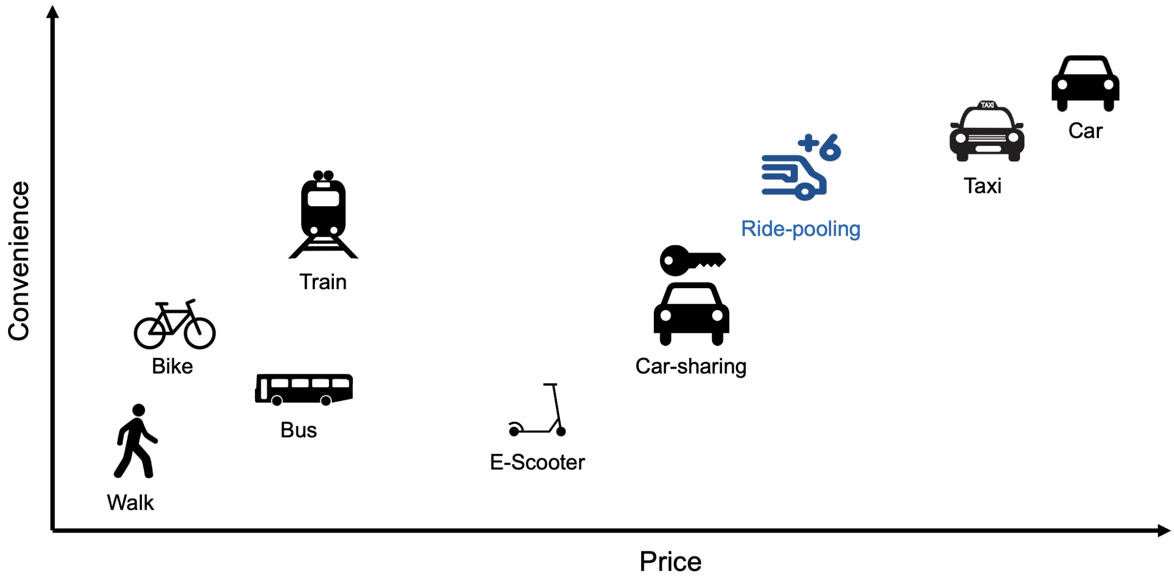

Review on theoretical assessments and practical implementations of ride-pooling

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Abstract

Digitized on-demand ride-pooling services emerged world-wide in recent years. They promise to provide a comfortable mobility alternative that is more efficient than conventional private transportation. While such services have already existed for decades in non-digitized form in emerging countries, digitized ride-pooling service were recently introduced in many cities to complement the existing public transport system. At the same time, numerous research studies investigated the implications of the newly introduced services.

After an introduction into the functionality of ride-pooling and its importance for different mobility systems, we provide a comprehensive review on research about its impact on the mobility system and the potential of current and future on-demand ride-pooling services. The review includes research on simulations and mathematical models of potential future ride-pooling services and research on current studies. The role of automated vehicles is analyzed and discussed. Additionally, we provide an overview of currently existing ride-pooling services and their characteristics, which is related to the scientific findings.

The findings reveal a large gap between research findings and real-world implementations as the large potential of ride-pooling systems is not yet reflected in public policies and urban mobility systems. The results suggest that automated vehicles and/or additional public policies are required to allow attractive cost structures for customers and operators of large-scale ride-pooling services.

Keywords

ride-sharing, ride-splitting, public transport, new mobility, on-demand mobility

1 Introduction

Pooling multiple trips into one vehicle is not a new idea and is the fundamental concept of public transportation. While public transportation usually operates with large vehicles such as trains or busses, ride-pooling is here defined as a service with smaller vehicles with up to 10 seats. The service is located between public and private transportation when it comes to privacy, comfort, travel times or service quality.

Self-organized non-digitized ride-pooling systems exist in many developing countries. The systems have in common that they are mostly self-organized by one or multiple local operators. Vehicles and customers are not digitally connected but customers hail a vehicle on the street or at a central terminal. Information about departure times, delays or cancellations are not transparent and often require in-person communication.

In contrast, digitized on-demand services that emerged in the past decade are fully connected and controlled by a central operator that brings customers and drivers together. The services considered here can only be booked via smartphone application and are characterized by a central dispatching system coordinating efficient fleet operations.

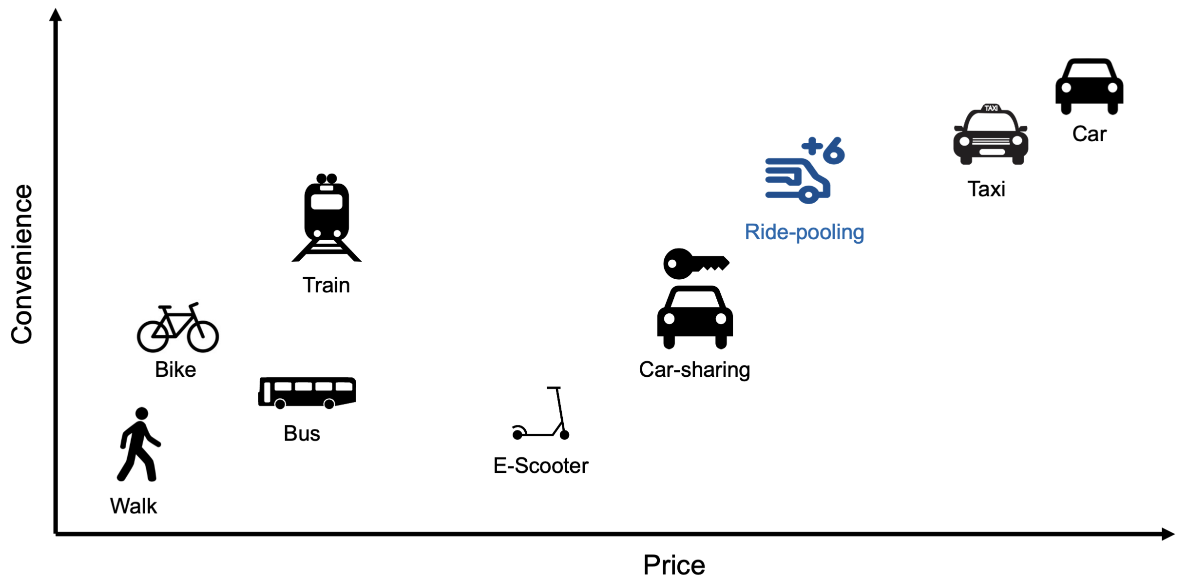
1.1 Ride-pooling definition and classification

Theoretically, ride-pooling is a form of the Dial-a-ride problem (Cordeau and Laporte, 2007), which describes n users traveling from origin to destination within a defined transport network. The goal is to deliver all users to their destination with minimal travel costs. The external conditions (e.g., static vs. dynamic requests, pick-up time windows) define the specific problem to be solved.

The idea of ride-pooling is to bundle multiple customer requests in the same vehicle with fully flexible schedules and routes. This way, vehicle occupancy and fleet efficiency is increased compared to private transportation via car, taxi, or ride-hailing. Customers often face detours due to pooling and have to accept additional travel parties during their trip, for which they are compensated by a lower trip fare compared to taxi or ride-hailing services.

Figure 1 shows an exemplary classification of multiple mobility modes including ride-pooling in a 6-seater vehicle with regards to pricing and convenience for an average urban trip. The perception differs from person to person or city to city and highly depends on the actual trip. While walking does not cost anything, it is the least convenient transport mode if a certain maximum walkable distance is exceeded. The established public transport modes bus and train are relatively cheap and in the case of the train also perceived as comfortable. In contrast, car and taxi (or ride-hailing) are more expensive private transport modes that offer the highest convenience with door-to-door transportation. The figure shows that the recently established transport modes e-scooter, car-sharing and ride-pooling promise to fill a gap between the private and public transport modes with higher convenience than established public transportation and lower prices than established private transportation.

Figure 1: Exemplary classification of mobility modes with regards to pricing and convenience.



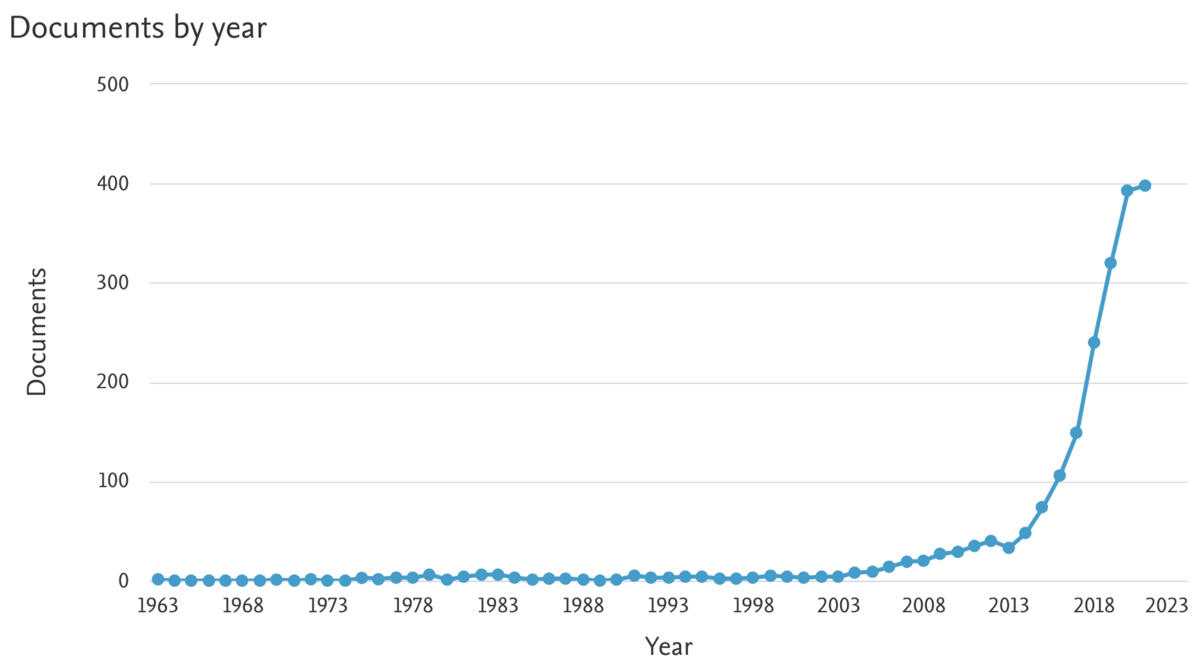
The more prominent and established on-demand service type is ride-hailing, which was offered worldwide for more than a decade by companies such as Uber, Lyft, Didi Chuxing or Ola. Research showed that despite some positive impacts, such as reduced parking requirements or service in previously underserved areas, ride-hailing causes additional vehicle kilometers traveled (VKT) and hardly strengthens public transit (Tirachini, 2020;

Tirachini and Gomez-Lobo, 2020; Henao and Marshall, 2019; Cats *et al.*, 2022). In order to avoid such negative impacts and to reduce the VKT, ride-pooling systems aim to transport as many customers as possible in the same vehicle at the same time. Here, we focus on studies on ride-pooling and only list ride-hailing studies if they can be generalized and add to the knowledge about ride-pooling.

1.2 Ride-pooling research history and directions

Research on ride-pooling, often also called ride-sharing, ride-splitting or shared autonomous vehicle (SAV) services, has been growing over the past years. Figure 2 shows the number of documents published in the field of ride-pooling and ride-sharing. The topic caught first attention in the decade after 2000 before the numbers of publication grew exponentially in the past decade. The number of studies dealing explicitly with pooling is smaller as the term *ride-sharing* is often used for peer-to-peer ride-sharing or ride-hailing services.

Figure 2: Number of documents published per year according to a Scopus search for the keywords *ride-pooling*, *ride-sharing*, *shared rides* and *pooled rides*.

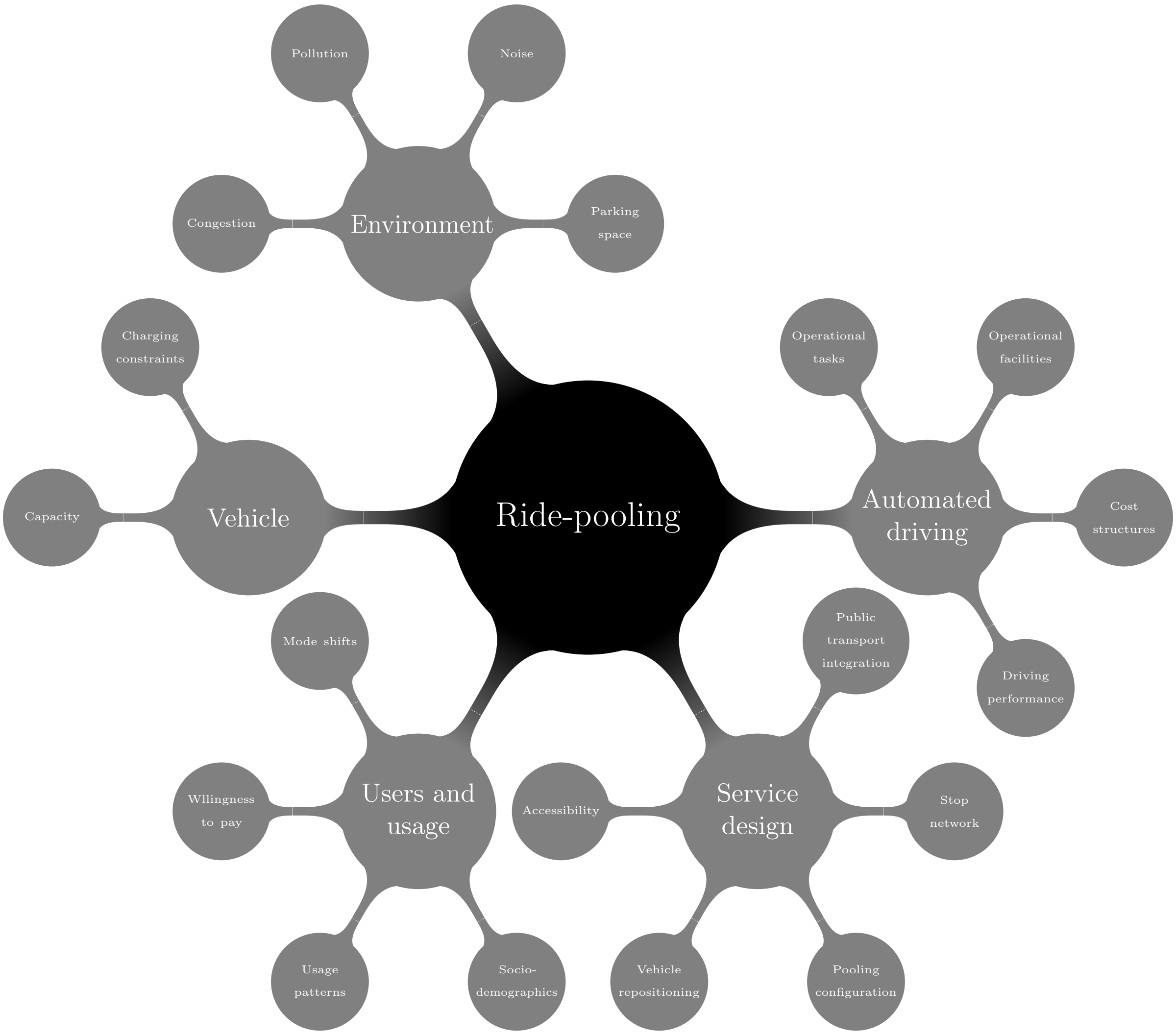


This exponential growth of research in the field of ride-pooling and ride-sharing also called for meta studies on the topic. Multiple review paper were published that summarize research in the field of on-demand ride-pooling. The mentioned study by Tirachini (2020) for instance summarizes findings on ride-hailing and its implications for the transport system. He only touches on the relevance of shared rides. Agatz *et al.* (2012) provided a first review paper on the challenges of optimizing carpooling at a time when on-demand digital mobility services were not as prevalent as they are today. Tafreshian *et al.* (2020) study peer-to-peer ride-sharing that may be integrated into existing on-demand services.

Becker and Axhausen (2017) and Gkartzonikas and Gkritza (2019) reviewed studies on stated preferences of the acceptance of automated vehicles, which is a prerequisite for the introduction of automated on-demand services. Duarte and Ratti (2018) reviewed the impact of autonomous vehicles on cities and their transport systems and outline their potential negative (more VKT and pollution) and positive (higher vehicle utilization, reduced parking space) effects. On-demand mobility platforms aim to commercialize the positive effects for cities and also customers. Mitropoulos *et al.* (2021) reviewed existing peer-to-peer ride-sharing platforms that connect users offering and users requesting a ride. They find and discuss economic, behavioral, regulatory and technological barriers. Narayanan *et al.* (2020) provides a review on studies about shared autonomous vehicle (pooled and un-pooled) services that are not yet operating but promise to attract many customers in future. They structure service types, modeling methods and research directions, providing a comprehensive overview on current research and future research directions. Pernestål and Kristoffersson (2019) and Jing *et al.* (2020) review simulation studies on the implications of driverless vehicles that we also highlight in this study. Shaheen and Cohen (2018) reviewed ride-pooling service models and research studies in North America and found that practitioners and researchers predict higher efficiency, lower costs, and lower emissions of pooled fleets.

Figure 3 shows a mindmap of ride-pooling research directions that were covered in previous studies. The map is not complete and can be extended in many directions. Ride-pooling systems can be analyzed theoretically by surveys or model-based assessments of hypothetical services. More practical insights are gained by analyzing real-world services. Again, common research methods are surveys or model-based evaluations and a combination of both.

Figure 3: Ride-pooling research directions.



1.3 Contributions

Although all of the previously presented meta studies touch the area of ride-pooling, their focus is different and does not connect research with existing practical implementations. This study closes this gap by providing an overview of the main findings of theoretical assessments of ride-pooling and research from existing ride-pooling services. We additionally provide an overview of existing ride-pooling services and discuss the gap between theoretical assessments and practical implementation.

This study is structured as follows: Section 2 provides an overview of theoretical studies on ride-pooling and the potential implications on transportation systems. Section 3 shows learnings from existing ride-pooling services through surveys and statistical (spatial) models. Section 4 gives an overview of ride-pooling services world-wide and their characteristics. Finally, we discuss the insights in Section 5 and draw conclusions on the future development of ride-pooling.

2 Theoretical assessments of ride-pooling systems

In order to evaluate potential implications of ride-pooling on future mobility behavior and the transport system, theoretical findings are generated based on hypothetical surveys, models and simulations. The given mobility system or toy scenarios are usually the basis of the assessments.

The following section presents a selection theoretical studies on ride-pooling, distinguishing between studies based on hypothetical surveys and studies based on model-based evaluations

2.1 Survey-based theoretical assessments

The most suitable method to investigate potential users, their socio-demographics, and their usage preferences of a hypothetical ride-pooling service is the execution of stated preference surveys. Countless such surveys in the field of automated and connected vehicles, ride-hailing, and new mobility modes were made world-wide in recent years (see Becker and Axhausen (2017) and Gkartzonikas and Gkritza (2019)). We provide a glimpse on survey studies investigating the preferences to use a hypothetical ride-pooling service.

Krueger *et al.* (2016) were one the first to investigate the preferences for pooled rides and asked 435 Australian respondent to choose if they would change their usual mode by ride-hailing or ride-pooling. Ride-pooling was more attractive for younger individuals and active car-sharing users. Interestingly, the pooled option was chosen less for leisure trips.

Bansal and Kockelman (2018) asked 1,088 individuals in Texas, US, on their opinions and potential usage of automated vehicles. The survey mainly focused on the willingness to pay for technological vehicle features and levels of automation. Additionally, it was asked if respondents would be willing to share a ride with a complete stranger, which only 16.4% of the respondents accepted.

Two comprehensive survey studies on ride-pooling were reported by Lavieri and Bhat (2019) in the US and Alonso-González *et al.* (2021) in the Netherlands.
Lavieri and Bhat (2019) asked 1,607 commuters in the Dallas-Fort-Worth Metropolitan Area in the US about their willingness to share trips with strangers. They found a lower willingness to share for respondents with higher incomes and experience with existing ride-hailing systems. The presence of strangers was perceived more negative for leisure trips than commute trips, which seconds the findings of Krueger *et al.* (2016). Overall, the additional travel time due to pooling was perceived worse than the presence of strangers.

Alonso-González *et al.* (2021) asked 1,006 individuals about the factors for or against sharing a ride with strangers in a system that offers pooled and unpooled rides. Most current on-demand rides are booked for unpooled rides although simulation studies show strong benefits of pooling. The authors found that less than one third of the respondents have strong preferences against pooling. However, they identify the low cost benefit compared to the time loss due to pooling as a main reason for the low selection rate for pooled rides. The discomfort due to other passengers is found to be less disturbing for customers, which seconds the findings of Lavieri and Bhat (2019).

Overall, we find a clear preference for pooling by younger individuals with lower incomes. Pooling is not perceived negatively per se and sharing a ride with others is often not problematic. However, the potential time loss and low cost savings make pooling less attractive compared to ride-hailing. Different perceptions of pooling are also observed in different parts of the world. While only 16.4% of respondents in Texas, US, were willing to share a ride (Bansal and Kockelman, 2018), more than two thirds of the respondents in the Netherlands stated that they have no strong preferences against pooling (Alonso-González *et al.*, 2021).

2.2 Model-based theoretical assessments

While the survey-based theoretical assessments require stated preferences of potential users, model-based theoretical assessments assume a certain user behavior and model the system functionality, its impact on the transport system, or the benefits for the transport system and the environment.

A major topic when it comes to on-demand services is the development of automated vehicles and the expected change in the cost structures. As observed in the previous Section, the costs are crucial for the usage of a ride-pooling system. The most comprehensive breakdown of cost structures with conventional and automated on-demand vehicles was provided by Bösch *et al.* (2018), who found that salaries account for 88% of current taxi costs. They modeled future cost structures and reported that future costs for ride-pooling with automated vehicles are less than a fifth of current costs for a manually driven ride-pooling service. An investigation of ride-hailing cost structures in Munich, Germany, was made by Negro *et al.* (2021). They similarly found a substantial decrease of costs of over 50% with automated vehicles.

The reduced costs with automated vehicles can be considered in discrete mode choice models that predict a certain mode share for given mode prices, travel times, and estimated modal preferences. When combined with transport models, the use of new mobility services can be estimated for an entire population. Hörl *et al.* (2021) combined a mode-choice model for Zurich, Switzerland, with a transport model of the same city and simulated the interdependences of price, customer behavior and service level for a future automated taxi system. Considering these complex interactions they identified a fleet of 4,000 robotaxis to serve 150,000 daily requests with cost-covering operations. However, they did not consider pooled rides. The following studies are a selection of relevant simulation studies assessing the implications of ride-pooling.

Agatz *et al.* (2010) and Ma *et al.* (2013) developed two of the first heuristic-based algorithms for dynamic ride-pooling and found efficiency gains in the transportation system through pooling. They already noted that a critical mass is required to allow efficient pooling. Martinez and Viegas (2017), Alonso-Mora *et al.* (2017), Bischoff *et al.* (2017), and Gurumurthy and Kockelman (2018) were among the first ones to simulate large-scale ride-pooling systems. Martinez and Viegas (2017) focused on the interaction with other mobility modes and modal shift effects in Lisbon, Portugal. Alonso-Mora *et al.* (2017) developed an anytime optimal algorithm for a pooled fleet with up to 10 seats that replaces the entire taxi fleet of New York City in the US. Both studies show drastic efficiency gains through ride-pooling compared to private car or taxi and ride-hailing services. Less vehicles are required (e.g., only 15% of the existing New York City taxi fleet) and less VKT are caused if people are pooled along their trips. Bischoff *et al.* (2017) developed an open-source ride-pooling algorithm in the simulation environment MATSim (Horni *et al.*, 2016) that has been used extensively since then.

Zwick *et al.* (2021b), Kagho *et al.* (2022) and Kaddoura and Schlenther (2021) used that algorithm to investigate the relationship of demand size and pooling efficiency and found higher pooling rates with larger demand density. Zwick *et al.* (2021b) show that ride-pooling is most efficient in large and densely populated cities. Engelhardt *et al.* (2019) used another algorithm and found that at least 5% of all private car trips need to be replaced by ride-pooling to observe a VKT decrease. Lower adoption rates can even lead to higher VKT due to empty operational rides.

A comparison of multiple developed ride-pooling algorithms was made by Ruch *et al.* (2020), finding that the algorithm of Alonso-Mora *et al.* (2017) leads to the highest pooling rates. The importance for intelligent dispatching and routing systems is shown, which also incorporates efficient repositioning systems de Souza *et al.* (2020); Bischoff and Maciejewski (2020). Lu *et al.* (2021) compared multiple repositioning algorithms and found substantial differences for the services with regard to overall wait times, wait time distributions, and overall system efficiency. They show that the pooling configuration highly depends on the aims of the system, e.g., if it should operate as efficient as possible or if it should provide the same service level throughout the service area.

With the expected reduced VKT and fleet sizes due to ride-pooling also come environmental benefits. Zwick *et al.* (2021a) simulated a city-wide ride-pooling system in Munich, Germany and explicitly investigated the impact on traffic noise. Despite drastic VKT reductions of up to 54%, noise reductions are limited due to its logarithmic relationship with traffic volume. Their investigation showed the benefit of using a stop network on main streets to reduce detours and pick-up/drop-off rides in residential areas.

When it comes to the implementation of real-world urban ride-pooling systems, the consideration of operational constraints are highly relevant. Vosooghi *et al.* (2020) considers predictions that most future automated ride-pooling vehicles will be electric and studies its implications on the efficiency. They found a substantial impact of charging infrastructure and charger placement to avoid empty VKT and increase availability and efficiency.

Overall, we find positive implications of hypothetical ride-pooling services on the transport system, particularly with regards to reduced VKT and fleet sizes. Exceptions were found for small-scale services with low demand density and small vehicle fleets because the operationally necessary empty VKT exceed the savings of pooling. The following section sheds light on research about real-world ride-pooling services.

3 Practical assessments of existing ride-pooling services

The previous section showed many potential positive implications of ride-pooling found in studies on hypothetical services. Here, we analyze studies that focus on survey- and model-based assessments of real-world ride-pooling services.

3.1 Survey-based practical assessments

We first look at surveys with users of existing ride-pooling services. Lo and Morseman (2018) and Mohamed *et al.* (2020) asked Uber users in the US and London, respectively, about their preferences to use Uber and its pooled option UberPool. Lo and Morseman (2018) combined qualitative interviews and two quantitative surveys with up to 3,000 customers. They identified the travel time to be the most important factor for the willingness to use the pooled option, followed by availability. However, users expect a certain discount to prefer ride-pooling over ride-hailing. Mohamed *et al.* (2020) asked 907 Uber users during their ride, half of them UberPool users and directly compared the answers about socio-demographics, trip purposes, and trip characteristics. UberPool users were older and reported lower education levels than users of the hailing option. UberPool users were more likely to report driving for rides to/from social activities and to visit friends/family, but were less likely to report using the service for rides to work, which contradicts the findings of Krueger *et al.* (2016) and Lavieri and Bhat (2019) (see Section 2.1).

Kostorz *et al.* (2021) and Knie *et al.* (2020) conducted two large surveys in Germany with users and non-users of the ride-pooling services MOIA and CleverShuttle, respectively. They both found the services to be an attractive complement to the existing public transportation system, particularly at night times when demand is highest. Kostorz *et al.* (2021) asked 11,372 people in Hamburg, among them over 10,000 MOIA users in a comprehensive survey on socio-demographics and usage patterns. They found the MOIA users to be rather multimodal and wealthier than non-users. This indicates that the ride-pooling system is more attractive than in other countries, where ride-hailing is the predominant on-demand service. The 3,542 CleverShuttle users surveyed by Knie *et al.* (2020) that their portfolio of mobility options increased with the service and makes them less dependent of a private car.

3.2 Model-based practical assessments

While survey-based assessments are very helpful in understanding users' characteristics, perceptions, and expectations of future ride-pooling services, they do not provide detailed information about revealed preferences and the complex system interactions with the environment and other mobility modes. Models, whether statistical regressions or simulations, provide additional knowledge and are applied to revealed usage data, as well as survey responses.

A common tool to understand usage of ride-pooling services is the application of spatial regression models that allow the identification of spatial patterns that allow interpretation about usage schemes.

Multiple studies investigated service offering pooled and unpooled rides and identified spatial patterns where pooling is selected more often in China (Li *et al.*, 2019) and the US (Hou *et al.*, 2020; Brown, 2019; Malik *et al.*, 2021; Dean and Kockelman, 2021; Soria and Stathopoulos, 2021; Gehrke *et al.*, 2021).

It is observed that the pooled option is more often selected in regions with lower income levels, and younger residents (Hou *et al.*, 2020; Brown, 2019; Malik *et al.*, 2021; Dean and Kockelman, 2021; Soria and Stathopoulos, 2021), which confirms the findings from multiple surveys. Pooled trips are booked more often in areas with high population densities Li *et al.* (2019); Brown (2019); Gehrke *et al.* (2021) and occur more often at later times of the day (Li *et al.*, 2019). The latter finding is a contrast to theoretical survey findings that indicated a lower attractiveness of ride-pooling for leisure trips.

Some studies also looked at the spatial patterns of ride-sharing systems, all of which operate in Germany, where ride-hailing faces high regulatory hurdles. Knie *et al.* (2020) had access to usage data of the ride-pooling service CleverShuttle in four German cities and found a concentration of trips in the highly populated areas in the city centers. A spatial regression study was conducted by Zwick and Axhausen (2022), who had access to trip data of the ride-pooling service MOIA in Hamburg and Hanover. They showed a significantly higher demand in areas with a high number of inhabitants, gastronomic facilities, workplaces, and rail stops. In contrast to ride-pooling services in the US or China, MOIA was used in areas with higher social welfare.

Another relevant research field of ride-pooling is the integration into the existing public transport system by providing first/last mile services. Zuniga-Garcia *et al.* (2022) analyzed a pilot program in Austin, Texas in the US, where on-demand services provided first/last mile solutions for public transportation. Their findings are humbling as the result indicated that the on-demand service was rather used for short door-to-door trips than to reach public transport stations. This seconds the findings of Reck and Axhausen (2020) that subsidized ridesourcing projects for first/last mile services often face low ridership. Potential reasons are high costs that do not justify the relatively little comfort benefit, and the discomfort of transferring from one mode to another one.

One of the most comprehensive studies of ride-pooling in Germany was done by Kagerbauer *et al.* (2021) who estimated a mode-choice model based on the survey of Kostorz *et al.* (2021), which was included in a simulation model to replicate the current MOIA service and evaluate the potential demand in future scenarios. They found that the current ride-pooling system already provides an attractive complement to the existing public transport system. Additionally, they investigated the impact of public policies and technological advancements regarding automated vehicles on the service usage, quality, and efficiency. It is found that the demand potential increases from a current 0.1% modal share to 3.0% if public policies against private car usage are introduced and the MOIA fares are halved due to automated vehicles.

4 Overview on ride-pooling services world-wide

After providing research on hypothetical or real-world ride-pooling services, this section provides an overview of ride-pooling services and their characteristics, no matter if researched or not. While we rely on scientific studies in the case of paratransit services in emerging countries, we mainly focus on a market overview of Foljanty (2022) in the case of the digitized on-demand ride-pooling services.

4.1 Paratransit services in emerging countries

A more informal way of ride-pooling exists in the form of paratransit and minibuses that mostly operate in developing and emerging countries. In an overview of such services in the southern hemisphere, Behrens *et al.* (2021) underline that these services usually fill gaps in formal public transport offers. Another review of informal paratransit services is presented by Cervero and Golub (2007). In Haiti, the local paratransit is called tap-tap (eng.: quick-quick) and covers up to 56% of passenger transport in the metropolitan area of Port-Au-Prince Oviedo *et al.* (2022). While routes are more or less fixed, tap-taps will only depart as soon as all seats are occupied. A similar concept is provided by the tro-tro services in Ghana (Finn, 2012; Saddier *et al.*, 2017), where 14-18 seaters provide fixed route services with flexible departures. In the Philippines, the Jeepney industry offers rides with colorful minibuses which are owned by individual operators (Chiu, 2008) and in Nairobi, the 'matatus' paratransit vehicles are operated with very different business structures and owner-operator forms (McCormick *et al.*, 2013). The Dolmuş system in Turkey is also operated by individual entrepreneurs and does not have fixed fares, stops or schedules (Özbilen, 2016). A last example is the minibus system in South Africa (Joubert, 2013) which is a self-organized system with a more complex structure including associations organizing segments of the market, vehicle owners who are responsible for maintenance and employed drivers.

While these examples offer some kind of demand-responsive transport, most of them have in common that the service is quite unstructured, informal, less regulated and usually not assisted by digital platforms and apps, which is in contrast to the modern ride-pooling services in stronger regulated markets.

4.2 Digitized on-demand ride-pooling services

Digitized ride-pooling services were implemented world-wide in recent years. Section 3 gave insights into some of the services that were scientifically investigated. However, most of the existing commercial services are not evaluated scientifically.

An overview of the world-wide ride-pooling market is regularly given by Foljanty (2022) in his digitally available *On-Demand Ridepooling World Map* [1]. In his recent outlook on the ride-pooling market Foljanty (2022) found a continuous market growth in recent years, which is dominated by Business-to-Government (B2G) projects where public authorities fund the ride-pooling provider to provide its technology to operate the service. However, most projects only operate with small fleets of less than 10 vehicles because funding of small fleets is more feasible for public authorities if the operation is not profitable. This result is at odds with theoretical research findings that trip bundling is more efficient when demand density is high and vehicle fleets are large. A substantial proportion of projects serve as feeders to public transport, although it remains to be proven whether such systems attract many customers. The lack of research on most small-scale services does not allow for further evaluation of their transportation impacts.

5 Discussion and conclusion

The paper gives an idea of studies on ride-pooling and its multifaceted characteristics and implications on the transport system. The theoretical studies of hypothetical ride-

[1]https://www.google.com/maps/d/u/1/viewer?mid=1Ja3clE4L4ibLtUpF34-KZGJ3-8-0Y8dG, last accessed: 12/5/2022

pooling services revealed multiple positive effects that are expected by future ride-pooling systems, particularly in large-scale systems. The main benefit is found to be reduced VKT and fleet sizes compared to existing taxi or private car mobility. The acceptance of ride-pooling differs geographically as two survey studies by Alonso-González *et al.* (2021) in the Netherlands, Europe, and by Bansal and Kockelman (2018) in Texas, US, revealed. The willingness to pool was reported to be much higher in the Netherlands. If the differences are caused by societal discrepancies or differences in the mobility system remains unclear. Nevertheless, our findings suggest that a general acceptance of shared mobility modes also leads to higher acceptance of pooled rides.

The assessments of existing ride-pooling services revealed additional insights about users and their usage patterns. An interesting finding is that in Germany, where ride-hailing faces strong regulations, ride-pooling users are wealthier than non-users, whereas in the US and China ride-pooling users are less wealthy than ride-hailing users. However, this result highly depends on the societal structures and the overall mobility system in the countries and their respective cities. The idea of using ride-pooling as a feeder service for public transportation has not yet proven successful or attractive to customers.

A closer look on existing services revealed that despite all the potential positive implications of large-scale ride-pooling, it is predominantly implemented as small-scale services. Services with large fleet sizes (but not as high as current car fleet sizes) that have the highest potential to reduce VKT, emissions, and car fleet sizes are scarce. This indicates that manual driver costs are higher than the expected revenues, even in large-scale systems, and brings us to the conclusion that either public subsidies or automated vehicles are required for the breakthrough of on-demand ride-pooling services. The potential benefits that research has clearly shown should be reason enough for public authorities to incentivize ride-pooling usage over private car usage.

Future studies may shed light on the impacts of the numerous small-scale ride-pooling services that often operate as feeder services. Insights into their contribution towards a more sustainable and efficient transport system are yet to be provided. Additionally, the challenges of operating ride-pooling services with automated vehicles must be tackled as technology advances and test services are launched.

6 References

Agatz, N., A. Erera, M. Savelsbergh and X. Wang (2010) Sustainable passenger transportation: Dynamic ride-sharing, *ERIM Report Series Reference No. ERS-2010-010-LIS*.

Agatz, N., A. Erera, M. Savelsbergh and X. Wang (2012) Optimization for dynamic ride-sharing: A review, *European Journal of Operational Research*, **223** (2) 295–303.

Alonso-González, M. J., O. Cats, N. van Oort, S. Hoogendoorn-Lanser and S. Hoogendoorn (2021) What are the determinants of the willingness to share rides in pooled on-demand services?, *Transportation*, **48** (4) 1733–1765.

Alonso-Mora, J., S. Samaranayake, A. Wallar, E. Frazzoli and D. Rus (2017) On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment, *Proceedings of the National Academy of Sciences of the United States of America*, **114** (3) 462–467.

Bansal, P. and K. M. Kockelman (2018) Are we ready to embrace connected and self-driving vehicles? A case study of Texans, *Transportation*, **45** (2) 641–675.

Becker, F. and K. W. Axhausen (2017) Literature review on surveys investigating the acceptance of automated vehicles, *Transportation*, **44** (6) 1293–1306.

Behrens, R., S. Chalermpong and D. Oviedo (2021) Informal paratransit in the global south, in *The Routledge Handbook of Public Transport*, 236–251, Routledge.

Bischoff, J. and M. Maciejewski (2020) Proactive empty vehicle rebalancing for demand responsive transport services, *Procedia Computer Science*, **170**, 739–744.

Bischoff, J., M. Maciejewski and K. Nagel (2017) City-wide shared taxis: A simulation study in Berlin, *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*.

Bösch, P. M., F. Becker, H. Becker and K. W. Axhausen (2018) Cost-based analysis of autonomous mobility services, *Transport Policy*, **64**, 76–91.

Brown, A. (2019) Redefining car access: Ride-hail travel and use in Los Angeles, *Journal of the American Planning Association*, **85** (2) 83–95.

Cats, O., R. Kucharski, S. R. Danda and M. Yap (2022) Beyond the dichotomy: How ride-hailing competes with and complements public transport, *PLoS ONE*, **17** (1) e0262496.

Cervero, R. and A. Golub (2007) Informal transport: A global perspective, *Transport Policy*, **14** (6) 445–457.

Chiu, C. L. (2008) Lesson from jeepney industry in the philippines, *International Review of Business Research Papers*, **4** (1) 68–84.

Cordeau, J. F. and G. Laporte (2007) The dial-a-ride problem: Models and algorithms, *Annals of Operations Research*, **153** (1) 29–46.

de Souza, F., K. M. Gurumurthy, J. Auld and K. M. Kockelman (2020) A repositioning method for shared autonomous vehicles operation, *Procedia Computer Science*, **170**, 791–798.

Dean, M. D. and K. M. Kockelman (2021) Spatial variation in shared ride-hail trip demand and factors contributing to sharing: Lessons from Chicago, *Journal of Transport Geography*, **91**, 102944.

Duarte, F. and C. Ratti (2018) The impact of autonomous vehicles on cities: A review, *Journal of Urban Technology*, **25** (4) 3–18.

Engelhardt, R., F. Dandl, A. Bilali and K. Bogenberger (2019) Quantifying the benefits of autonomous on-demand ride-pooling: A simulation study for Munich, Germany, paper presented at the *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, 2992–2997.

Finn, B. (2012) Towards large-scale flexible transport services: A practical perspective from the domain of paratransit, *Research in Transportation Business Management*, **3**, 39–49. Flexible Transport Services.

Foljanty, L. (2022) The On-Demand Ridepooling Market in 2022 – further growth or signs of saturation?, `https://www.linkedin.com/pulse/on-demand-ridepooling-market-2022-further-growth-signs-lukas-foljanty/?trackingId=eBlCzqljSM6nADFpAy%2FzzQ%3D%3D`.

Gehrke, S. R., M. P. Huff and T. G. Reardon (2021) Social and trip-level predictors of pooled ride-hailing service adoption in the Greater Boston region, *Case Studies on Transport Policy*, **9** (3) 1026–1034.

Gkartzonikas, C. and K. Gkritza (2019) What have we learned? A review of stated preference and choice studies on autonomous vehicles, *Transportation Research Part C: Emerging Technologies*, **98**, 323–337.

Gurumurthy, K. M. and K. M. Kockelman (2018) Analyzing the dynamic ride-sharing potential for shared autonomous vehicle fleets using cellphone data from Orlando, Florida, *Computers, Environment and Urban Systems*, **71**, 177–185.

Henao, A. and W. E. Marshall (2019) The impact of ride-hailing on vehicle miles traveled, *Transportation*, **46** (6) 2173–2194.

Horni, A., K. Nagel and K. W. Axhausen (eds.) (2016) *The Multi-Agent Transport Simulation MATSim*, Ubiquity Press, London.

Hou, Y., V. Garikapati, D. Weigl, A. Henao, M. Moniot and J. Sperling (2020) Factors influencing willingness to pool in ride-hailing trips, *Transportation Research Record*, **2674** (5) 419–429.

Hörl, S., F. Becker and K. W. Axhausen (2021) Simulation of price, customer behaviour and system impact for a cost-covering automated taxi system in Zurich, *Transportation Research Part C: Emerging Technologies*, **123**, 102974.

Jing, P., H. Hu, F. Zhan, Y. Chen and Y. Shi (2020) Agent-based simulation of autonomous vehicles: A systematic literature review, *IEEE Access*, **8**, 79089–79103.

Joubert, J. W. (2013) *Gauteng: Paratransit—Perpetual Pain or Potent Potential?*, 107–126, Springer Berlin Heidelberg, Berlin, Heidelberg.

Kaddoura, I. and T. Schlenther (2021) The impact of trip density on the fleet size and pooling rate of ride-hailing services: A simulation study, *Technical Report*, Technische Universität Berlin.

Kagerbauer, M., N. Kostorz, G. Wilkes, F. Dandl, R. Engelhardt, U. Glöckl, E. Fraedrich and F. Zwick (2021) Ridepooling in der Modellierung des Gesamtverkehrs - Methodenbericht zur MOIA Begleitforschung, *Technical Report*, Karlsruher Institut für Technologie, Karlsruhe.

Kagho, G. O., J. Meli, D. Walser and M. Balac (2022) Effects of population sampling on agent-based transport simulation of on- demand services E ff ects of population sampling on agent-based transport simulation of on-demand services, *Procedia Computer Science*, **201** (March) 305–312.

Knie, A., L. Ruhrort, J. Gödde and T. Pfaff (2020) Ride-Pooling-Dienste und ihre Bedeutung für den Verkehr. Nachfragemuster und Nutzungsmotive am Beispiel von "CleverShuttle" - eine Untersuchung auf Grundlage von Buchungsdaten und Kundenbefragungen in vier deutschen Städten, *WZB Discussion Paper*, **SP III 2020-601**, Berlin.

Kostorz, N., E. Fraedrich and M. Kagerbauer (2021) Usage and user characteristics — insights from MOIA, Europe's largest ridepooling service, *Sustainability*, **13** (2) 958.

Krueger, R., T. H. Rashidi and J. M. Rose (2016) Preferences for shared autonomous vehicles, *Transportation Research Part C: Emerging Technologies*, **69**, 343–355.

Lavieri, P. S. and C. R. Bhat (2019) Modeling individuals' willingness to share trips with strangers in an autonomous vehicle future, *Transportation Research Part A: Policy and Practice*, **124**, 242–261.

Li, W., Z. Pu, Y. Li and X. (Jeff) Ban (2019) Characterization of ridesplitting based on observed data: A case study of Chengdu, China, *Transportation Research Part C: Emerging Technologies*, **100**, 330–353.

Lo, J. and S. Morseman (2018) The perfect uberPOOL: A case study on trade-offs, *Ethnographic Praxis in Industry Conference Proceedings*, **2018** (1) 195–223.

Lu, C., M. Maciejewski and K. Nagel (2021) Effective operation of demand-responsive transport (DRT): Implementation and evaluation of various rebalancing strategies, *Proceedings of the 27th ITS World Congress*, Hamburg.

Ma, S., Y. Zheng and O. Wolfson (2013) T-share: A large-scale dynamic taxi ridesharing service, paper presented at the *Proceedings - International Conference on Data Engineering*, 410–421.

Malik, J., F. Alemi and G. Circella (2021) Exploring the factors that affect the frequency of use of ridehailing and the adoption of shared ridehailing in California, *Transportation Research Record: Journal of the Transportation Research Board*, **2675** (5) 120–135.

Martinez, L. M. and J. M. Viegas (2017) Assessing the impacts of deploying a shared self-driving urban mobility system: An agent-based model applied to the city of Lisbon, Portugal, *International Journal of Transportation Science and Technology*, **6** (1) 13–27.

McCormick, D., W. Mitullah, P. Chitere, R. Orero and M. Ommeh (2013) Paratransit business strategies: a bird's-eye view of matatus in nairobi, *Journal of Public Transportation*, **16** (2) 7.

Mitropoulos, L., A. Kortsari and G. Ayfantopoulou (2021) A systematic literature review of ride-sharing platforms, user factors and barriers, *European Transport Research Review*, **13** (1) 1–22.

Mohamed, M. J., T. Rye and A. Fonzone (2020) The utilisation and user characteristics of Uber services in London, *Transportation Planning and Technology*, **43** (4) 424–441.

Narayanan, S., E. Chaniotakis and C. Antoniou (2020) Shared autonomous vehicle services: A comprehensive review, *Transportation Research Part C: Emerging Technologies*, **111**, 255–293.

Negro, P., D. Ridderskamp, M. Paul, H. Belzner, F. Fehn and K. Bogenberger (2021) Cost structures of ride-hailing providers in the context of vehicle electrification and automation, paper presented at the *2021 7th International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2021*.

Oviedo, D., Y. Scorcia, P. Guerrero, M. Delandsheer, R. Rodriguez-Molina and R. Dewez (2022) A snapshot of the informal organization of public transport operators in the Caribbean: Tap-tap services in Port-Au-Prince, *Research in Transportation Business Management*, **42**, 100733.

Özbilen, B. (2016) Integration of Dolmus as a paratransit mode to the existing public transport network: Ankara example, Ph.D. Thesis, The middle east technical university.

Pernestål, A. and I. Kristoffersson (2019) Effects of driverless vehicles : Comparing simulations to get a broader picture, *European Journal of Transport and Infrastructure Research*, **1** (19) 1–23.

Reck, D. J. and K. W. Axhausen (2020) Subsidized ridesourcing for the first/last mile: How valuable for whom?, *European Journal of Transport and Infrastructure Research*, **20** (4) 59–77.

Ruch, C., C. Lu, L. Sieber and E. Frazzoli (2020) Quantifying the Efficiency of Ride Sharing, *IEEE Transactions on Intelligent Transportation Systems*, **22** (9) 5811–5816.

Saddier, S., Z. Patterson, A. Johnson and N. Wiseman (2017) Fickle or flexible?: Assessing paratransit reliability with smartphones in accra, ghana, *Transportation Research Record*, **2650** (1) 9–17.

Shaheen, S. and A. Cohen (2018) Shared ride services in North America: definitions, impacts, and the future of pooling, *Transport Reviews*, **0** (0) 1–16.

Soria, J. and A. Stathopoulos (2021) Investigating socio-spatial differences between solo ridehailing and pooled rides in diverse communities, *Journal of Transport Geography*, **95**, 103148.

Tafreshian, A., N. Masoud and Y. Yin (2020) Frontiers in service science: Ride matching for peer-to-peer ride sharing: A review and future directions, *Service Science*, **12** (2-3) 40–60.

Tirachini, A. (2020) Ride-hailing, travel behaviour and sustainable mobility: an international review, *Transportation*, **47** (4) 2011–2047.

Tirachini, A. and A. Gomez-Lobo (2020) Does ride-hailing increase or decrease vehicle kilometers traveled (VKT)? A simulation approach for Santiago de Chile, *International Journal of Sustainable Transportation*, **14** (3) 187–204.

Vosooghi, R., J. Puchinger, J. Bischoff, M. Jankovic and A. Vouillon (2020) Shared autonomous electric vehicle service performance: Assessing the impact of charging infrastructure, *Transportation Research Part D: Transport and Environment*, **81**.

Zuniga-Garcia, N., K. M. Gurumurthy, C. N. Yahia, K. M. Kockelman and R. B. Machemehl (2022) Integrating shared mobility services with public transit in areas of low demand, *Journal of Public Transportation*, **24**, 100032.

Zwick, F. and K. W. Axhausen (2022) Ride-pooling demand prediction: A spatiotemporal assessment in Germany, *Journal of Transport Geography*, **100**, 103307.

Zwick, F., N. Kuehnel, R. Moeckel and K. W. Axhausen (2021a) Agent-based simulation of city-wide autonomous ride-pooling and the impact on traffic noise, *Transportation Research Part D: Transport and Environment*, **90**, 102673.

Zwick, F., N. Kuehnel, R. Moeckel and K. W. Axhausen (2021b) Ride-Pooling Efficiency in Large, Medium-Sized and Small Towns - Simulation Assessment in the Munich Metropolitan Region, *Procedia Computer Science*, **184**, 662–667.