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Revealed demand patterns of people with disabilities in on-demand ridepooling

Nico Kuehnel[1], Felix Zwick[2], Tom-Erik Kuhlen[3]

[1] corresponding author nico.kuehnel@moia.io, MOIA GmbH, Berlin, Germany; https://orcid.org/0000-0003-0527-8653
[2] MOIA GmbH, Hamburg, Germany; https://orcid.org/0000-0002-4067-4486
[3] MOIA GmbH, Hamburg, Germany; https://orcid.org/0009-0003-8312-0998

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Abstract

Since 2023, the MOIA on-demand ridepooling service has been operating as part of Hamburg's public transport system by integrating a wheelchair accessible service and offering subsidized fares for people with severe disabilities. This study analyzes one year of demand patterns in Hamburg following these enhancements to assess their impact on service usage and accessibility. The findings reveal insights into spatiotemporal user behavior patterns, offering valuable guidance for the development of large-scale urban mobility solutions. Rider feedback suggests high satisfaction with the new service.

1 Introduction

Modern mobility services such as app-based on-demand ridehailing and ridepooling offer convenient, digital alternatives of travel. Various providers such as Uber, Via, Lyft, DiDi or MOIA established their services throughout the world (Çetin, 2017). While ridehailing services resemble conventional taxi services where each request is served individually, ridepooling services aim to pool trips that are similar in space and time and thereby promise to be more efficient (Soza-Parra et al., 2024). On-demand services can be operated both publicly (often as part of the local public transport system) and privately. While some services cover the entire operation including drivers and vehicles, private services in particular are often established as platforms (transportation network companies such as Uber and Lyft) that merely act as an intermediary between customers and drivers.

People with disabilities (PWD) may profit from these new on-demand services. As shown in multiple studies (Neven & Ectors, 2023; J. Park & Chowdhury, 2018), PWD still face a lot of barriers in their daily mobility routines, despite efforts in improving access to public transportation. O'Neill & O'Mahony (2005) and Blais & El-Geneidy (2014) point out that PWD are far from being a homogeneous group with different types of disabilities (e.g.: visual, hearing or walking disability) correlating with different patterns in travel behavior which should be taken into account when planning inclusive mobility. Disabilities may influence mobility directly, e.g. by preventing people from walking or driving independently, or indirectly, in that people with disabilities carry out fewer activities and generally travel less (Nobis & Kuhnimhof, 2019).

The prevalence of disabilities is considerable. In the US, roughly 13% of the population has a disability (Houtenville et al., 2023). Similarly, the world health organization (WHO) reports an estimated share of 15% of the world's population (WHO, 2011) having a disability. In Germany, statistics on the type and number of disabilities are non-exhaustive, making predictions for future services a challenging task (Kurbjeweit, 2023). According to official data from the German statistical office, there are roughly 7.8 million people with a severe disability, which is about 9.4% of the total population (Destatis, 2022). The severe disability status is well recorded as it comes with various public support such as governmental subsidies. However, little is known about less severe disabilities. Even the number of people using a wheelchair is not recorded, but estimates vary between 1.5 and 1.8% of the German population (Wissenschaftliche Dienste des Deutschen Bundestages, 2021). According to the national household travel survey *Mobilität in Deutschland* (Mobility in Germany), 13% of the German population report having health impairments, with 7% experiencing mobility-related limitations (Nobis & Kuhnimhof, 2019). According to the same report, the prevalence of disabilities increases significantly with age, affecting approximately 20% of the population between ages 60 and 70 and rising to 50% among those over 80.

On-demand services may improve the mobility options especially for PWD that require wheelchair access or short access/egress walk times. Publicly operated or supported services may also offer subsidized rides for PWD who often face economic hardships (Jenkins & Rigg, 2004) and lack viable alternative modes of transportation. Many services already offer the transport of wheelchair users by employing specialized vehicles or additional installments such as lifts or ramps (Hassanpour et al., 2021). While studies and evaluations assessing these services exist, they often focus on the North American context (Hassanpour et al., 2021; Ong et al., 2024; CPUC, 2022) or on platform providers such as Uber and Lyft (Ward, 2017). Studies also suggest that accessible services need to be well designed and regulated in order to provide a satisfactory and inclusive offering (Ward, 2017; Neven et al., 2015; Gebresselassie, 2023; Goralzik et al., 2022) and worker satisfaction Gebresselassie,23 2025), requiring adequate data on demand patterns of PWD. While digital on-demand offers can offer a more convenient option than traditional paratransit services, service quality and availability may remain an issue, especially for wheelchair-accessible vehicle (WAV) rides (Gebresselassie, 2024).

This study presents data-based findings of the first year of introducing a fleet of WAVs as well as discounts for people with severe disabilities in the fully integrated (i.e., fixed vehicle pool and dedicated driver workforce) ridepooling service MOIA in Hamburg, Germany. It provides insights into the service characteristics and descriptive analyses of users and usage patterns, adding a European perspective to the existing research body. A regression analysis provides a detailed overview of the spatial demand distribution of the new service categories. The findings provided may help policy makers, planners as well as operators to carefully design new offers for PWD in a European context.

2 Literature Review

Patterns in travel behavior of people with disabilities (PWD) and accessibility requirements have received considerable attention in academic research (Shen et al., 2023; K. Park et al., 2023). For example, it has been found that PWD often perform fewer out-of-home activities which can be partially explained by the significant barriers they face during travel (Ralph et al., 2022; Cochran, 2020). In terms of trip purposes, PWD reportedly travel less for social and recreational purposes (Myers et al., 2022). In a study using survey data from Sweden, , Friman & Olsson (2023) identify that perceived accessibility and travel autonomy are important targets to consider to improve the mobility and well-being of PWD. Many PWDs rely on family members or caregivers to provide rides in addition to paratransit services that are often inflexible and require long booking horizons, if they are available at all (Deka, 2014). Thus, there may be a considerable amount of latent demand for ad-hoc and flexible rides. An additional use case for accessible on-demand rides may be first- and last-mile travel options to transit stops. Even if accessible transit exists, the access to stops may impose significant barriers (Levine, 2024; J. Park & Chowdhury, 2018). Uddin et al. (2023) analyzed mode choice behavior of PWD based on the national household travel survey for the state of New York. They find that PWD may need to accept longer access/egress times due to the lack of suitable accessible infrastructure. In addition, when considering walking, PWD may be more sensitive to weather conditions.

Before the onset of widespread adoption of digital on-demand services, accessible rides were often carried out by paratransit or special taxi services, as analyzed by Zhang et al. (2023), who studied a dataset of more than one million accessible taxi trips between 2018 and 2021 in the Toronto area, Canada. When looking at the origins and destinations of the trips they observe high spatial clustering around health-related facilities which led them to conclude that up to 30% of all accessible trips were health related. In a follow-up study, Zhang et al. (2024) identify that PWD who were using accessible taxis were also more likely to live in socially disadvantaged neighborhoods. The demand for paratransit has received some attention in the literature. The NCTR report by Goodwill & Joslin (2013) presents a demand estimation approach for the American context, using trip rates between 12 to 14.4 trips per year and disabled person (Bearse et al., 2004).

With the rise of on-demand ride services, an increasing number of studies examined the adoption of such services by PWD and their specific usage patterns. Shirgaokar et al. (2021) studied ride-hailing adoption among older persons in California using an online survey of almost three thousand respondents aged 55 and older. They find that PWD were more likely to be willing to use ride-hailing services when compared to people without disabilities. Ruvolo (2020) reports that, in a survey of 218 people, PWD were optimistic about accessible ride services. However, the respondents also expressed concerns about other new forms of mobility, such as scooter and bike sharing, which can block sidewalks. Cochran & Chatman (2021) analyzed the US National Household Travel Survey (NHTS) to identify the app-based ridehailing usage behavior of PWD. They find that the PWD use ridehailing services less than the general population but conclude that latent demand for these services may be high but hindered by inaccessible offers. Similarly, and also using the NHTS, Eisenberg et al. (2022) find that PWD use ridehailing offers less, but use it more frequently once they adopt it. In contrast, Ong et al. (2024) used a survey with more than

1,851 respondents in the Vancouver metro area and found a higher share of ride-hailing adopters among PWD and that PWD have a higher frequency of usage than people without disabilities. Brumbaugh (2018) finds that only 4.6% of the people with disabilities used ride-hailing services at least once in the last 30 days (compared to 12.4% of people aged 18 to 64 without disabilities). Kameswaran et al. (2018) present a study on the ride-hailing usage of people with visual impairments using qualitative interviews, which highlights the reported increased independence in travel. A comprehensive overview of on-demand transport usage for people with disabilities in the North American context is given by Choi & Maisel (2022).

In the context of MOIA's ridepooling service in Hamburg, Kostorz et al. (2021) presented survey-based findings on the service before the introduction of WAVs and discounts for people with severe disabilities in 2019. It was shown that roughly 4% of MOIA users reported having a mobility impairment and that the share of impaired persons correlated with age. The majority (52%) of impairments were related to walking impairments. 8% of reported impairments were visual. In addition, it was found that mobility impaired persons on average have a lower income than non-impaired persons. It should be noted that not all disabilities necessarily lead to a mobility impairment, so these terms should not be used interchangeably.

While the aforementioned studies mostly worked with survey data, exact numbers of observed accessible trips remain scarce. Existing studies analyzing observed trip data often do not report detailed numbers on accessible rides for PWD (Haglund et al., 2019; Perera et al., 2020). Figures like the ones published as part of the Public Accessibility Reports for the California Public Utilities Commission (CPUC, 2022) exist but are limited to US applications only. These are not easily transferable to European conditions, especially since public transportation tends to be more exhaustively available in Europe, providing additional options for mobility-impaired persons (given accessible infrastructure and vehicles). For the two larger companies Uber and Lyft, it can be seen that demand for WAVs stays well below 1% of the total number of served rides in California (CPUC, 2022). Brown et al. (2021) report that fewer than 1% of trips requested in a pilot program with the operator Via in Los Angeles were for WAVs. However, the report by Miller et al. (2021) suggests trip shares between 3-6% in specific months of the same service. An analysis of accessible rides offered by the *Handitran* service in Arlington, Texas and operated by Via is presented by Khan et al. (2021a) and Khan et al. (2021b). This analysis included a regression model that may be used to predict paratransit demand. The model included population, share of elderly residents and average income as predictors, among others. In Seoul, Son & Kim (2022) report that the local DRTD (Demand Responsive Transport for Disabilities) service received around 100,000 requests in per month in 2019, with up 683 vehicles being in service. A high share of the demand was reportedly observed for medical purposes.

Access to observed demand data for accessible services is crucial for planning and designing such services, for example by estimating and evaluating models (Bischoff et al., 2017; Macfarlane et al., 2021; Kuehnel & Zwick, 2022; Portell et al., 2025) or short- and mid-term planning of supply (Chandakas, 2020).

While there are studies examining on-demand mobility of PWD, most of the studies using revealed or observed demand data focus on a North American context, where ride-hailing offered by decentral transportation network companies is the predominant on-demand option. In contrast, our present study presents findings from a European context from a centralized operator that offers ridepooling instead of ridehailing and which is subsidized as part of the public transport network in Hamburg, Germany. In addition to raw request numbers, detailed temporal distributions as well as other behavioral aspects such as spatial distribution, prebooking and group booking behavior are presented. The data processed is obtained from one of Europe's largest individual ridepooling services.

3 Methodology

The on-demand ridepooling provider MOIA in Hamburg, Germany, introduced a fleet of 15 WAVs in 2023 along with discounts for persons with severe disabilities. The service is in place since 2019 and has been used by people with mobility impairments ever since Kostorz et al. (2021). MOIA became part of Hamburg's public transport system in 2023, accompanied by the WAV and discount introduction. In addition to the WAV subfleet, MOIA operates the - at the time of writing - largest individual ridepooling fleet in Europe with up to 300 (non-wheelchair accessible) vehicles in service. The WAV vehicles shown in figure 1 have four regular seats and room for one wheelchair. The experience is designed to be inclusive, meaning that wheelchair users may be pooled with other passengers along the trip. The newly introduced discounts for people with severe disabilities are provided for eligible customers who registered their severe disability status in advance. In that case, the ride for the customer and up to one accompanying person is free of charge, meaning a discount of 100%. First user insights have been described by Krohn et al. (2023).

Figure 1. Impressions of MOIAs wheelchair-accessible vehicle with rear lift and four additional seats.

In terms of accessible mobility, customers may also activate a flag in their user profile to indicate a **visual impairment**, in which case the drivers will specifically look out for the customers at the stop. In addition, customers can demand an **extended access time** in their request, which is taken into account for the access/egress routing, as MOIA operates on virtual stops at which customers may be picked up or dropped off.

The MOIA wheelchair service complements the dispersed paratransit system in Hamburg. The city of Hamburg (Hamburg Tourismus, 2024) lists 12 services that offer different types of transportation for wheelchair users, ranging from taxis that can transport wheelchairs to van rentals. What all these services have in common is that they must be booked in advance, making MOIA the only wheelchair service in Hamburg that is available on demand. The tariffs of the services are not transparent (but free for people with severe disabilities) and therefore difficult to compare with the MOIA tariff, which is between the tariff for public transport and taxis. The on-demand service *hvv hop* operates in the suburbs and countryside around Hamburg and is also capable of transporting wheelchair users.

To analyze the observed demand with respect to PWD, pseudonymized request data for the complete year of 2023 are evaluated. Since not every recorded user request eventually leads to a booking (users may not accept an offer or MOIA cannot make an offer), demand does not equal served rides. Besides pseudonymized customer ID, timestamp, group size and origin/destination, visual impairment, required extended walk access, the need for a WAV or the qualification for a severe disability discount is known for each request. Customers may select themselves via smartphone app that they have a visual impairment, require longer walking times to access a stop or need a WAV. In contrast, the qualification for a **severe disability discount** requires customers to register in person once. Analyzing the demand by visual impairment, wheelchair usage, extended walking time request and severe disability discount allows us to gain a deeper understanding between some types of disabilities but may not be exhaustive as less severe disabilities or non-disclosure of customers cannot be taken into account. Note that the data analyzed here relates to requests of the whole service including but not limited to the WAV subfleet.

In a first step, a detailed descriptive analysis of the trip characteristics mentioned above is provided. It contains a general overview with number of requests per trip type, temporal distributions, shares of prebookings, distances or group sizes. Each customer segment is analyzed with regards to their usage frequency. Where available, trip feedback data will also be analyzed for each segment. This fills the gap of data and insights for people with disabilities in on-demand mobility settings in Europe at the time of writing.

In addition to observed trip request data, we use customer provided per-trip feedback data to analyze customer satisfaction and stated trip purpose. The feedback is non-mandatory and is collected after the successful delivery of a trip. Customers may provide positive or negative feedback and select from the trip purposes *business, commute, errands, family time, airport access/egress, leisure, other* or *tourism.*

In a second step, we further analyze the data with the help of a regression model to understand the spatial distribution of trips by analyzing the relationship across various predictors with the observed demand. By doing this, we follow up on the study of Zwick & Axhausen (2022), who present spatial regression analyses for ridepooling demand on the example of MOIA. This study adds the analysis for user groups with the need for a WAV and the qualification for a severe disability discount. The idea of the regression analysis is to spatially join the origins (or destinations) of requests with a zonal system for which statistical information is available. The zone file, as defined by the government of the City of Hamburg (Authority for Transport and Mobility Transformation, 2018), is displayed in figure 2. It is filtered to the MOIA service area and contains 751 zones. We define the demand per zone as our dependent variable and use various spatial predictors as our independent variable in an ordinary least squares (OLS) regression using:

$$y = \alpha + \boldsymbol{\beta} \times \boldsymbol{x} + \boldsymbol{\varepsilon} \tag{1}$$

with y denoting the dependent variable *requests*, $\boldsymbol{\alpha}$ denoting the constant of the regression, $\boldsymbol{\beta}$ denoting the regression coefficients for each independent variable $\boldsymbol{x}$ and $\boldsymbol{\varepsilon}$ denoting the error term. While more complex (spatial) regression models may add additional insights, we decided to apply the OLS regression in this study to provide results that are directly interpretable and provide a good general overview. Although the independent variables do not show a significant effect in all models, we keep them within all models to ensure comparability.

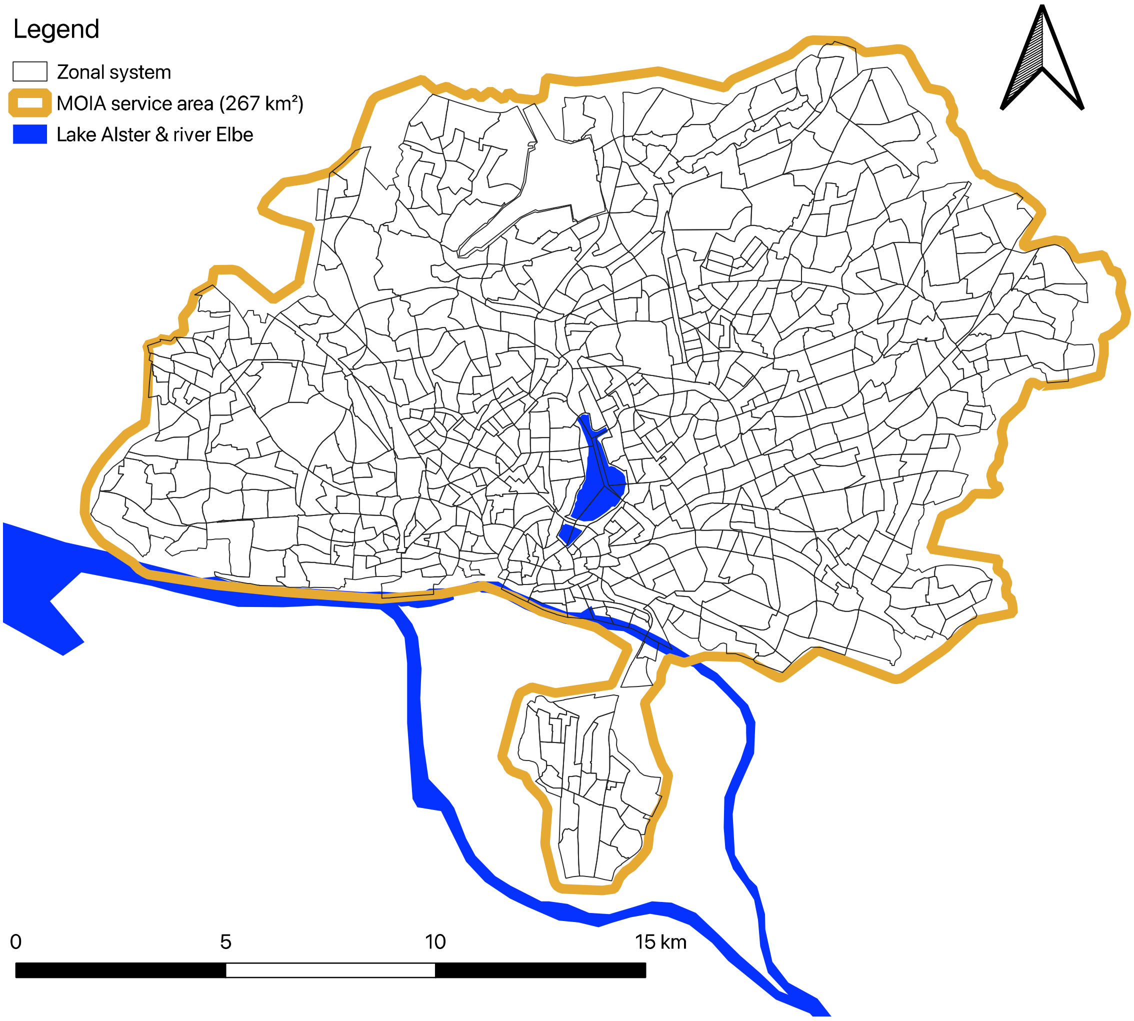


Figure 2. Zonal system used for spatial analyses and MOIA service area in Hamburg.

4 Results

In the following, the results of the descriptive analyses and of the regression analysis based on MOIA demand data are provided.

4.1 *Request data analyses*

1,952,724 requests have been estimated by MOIA in the entire year of 2023. Out of these, 213,104 or 10.9% qualified for a severe disability price discount. 80,969 requests were submitted with an extended access time notification, which corresponds to 4.1% of all requests. It should be noted here that an indication for extended access time does not necessarily translate to a disability, since people may just want more time or walk slowly, e.g., due to age. Still, it gives an indication for a possible mobility impairment. For the subsequent analysis, however, we do not include these requests for specific analyses. In terms of visual impairment, we observe 41,155 (about 2.1%) requests submitted by customers with the visual impairment flag activated in their profile. Lastly, 23,953 requests were submitted asking for a WAV, which is roughly 1.2% of all requests.

Among requests of wheelchair users, 22,303 (93.1%) also qualified for a severe disability discount, which means that there are quite a few wheelchair users who did not register for the discount, even though the vast majority should be eligible for it. For the requests involving visually impaired passengers, 40,385 or 98.1% qualified for a discounted ride. We want to emphasize here that people may actively not want to disclose and register their severe disability status, be it out of privacy concerns or barriers for registration. Similarly, and for the same reasons, people may not activate the visual impairment or extended access time flag in their profile, even though it would be meaningful.

This overview reveals that the different sets of disability related requests are far from exclusive, as multiple disabilities may be present (for example, there are 734 requests that were submitted by visually impaired wheelchair users). In addition, the severe disability status (and discount) may be applicable to a variety of disabilities. Figure 3 shows the different set sizes and their respective overlap in an UpSet plot (Lex et al., 2014). 1,719,864 or 89.0% of all requests did not show any of the mentioned and observable disability information. For the subsequent analyses, we stick to the color scheme of the plot, with the discount qualifying requests shown in blue, visual impairment related requests in red and WAV requests in green. Note here, that we always include the whole row sum of each subgroup in the differentiation, meaning that, e.g., discount eligible requests also include WAV requests or requests from visually impaired passengers that additionally qualify for the discount. We compare the three groups against *all* requests in the dataset that do not fall into the respective group (but may still fall into any of the other).

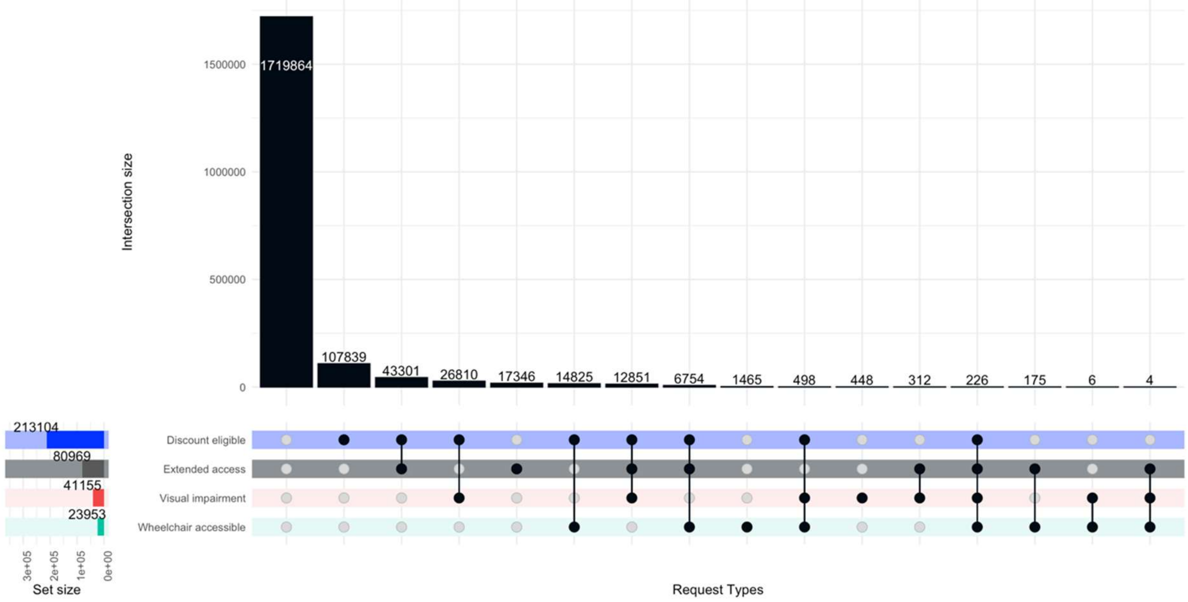


Figure 3. *UpSet plot showing the distribution of request types and their overlapping subsets in regards to discount eligibility, extended access, visual impairment and wheelchair accessibility. Created with the* ***ComplexUpset*** *R package (Krassowski, 2020).*

While the overview gives a good indication for the demand across the whole year, it does not capture the temporal dynamic of growing demand after the implementation of the new WAV service and the severe disability discount. Figure 4 shows the evolution of requests qualifying for the discount, indicating a visual impairment or requiring a WAV over the year. It can be seen that for discounted and WAV rides, the demand increased steadily at first and became more stable towards the end of the year. Especially in terms of WAV requests, it must be noted that the supply is also limited, as the WAV fleet is considerably smaller than the regular fleet of vehicles, so the saturation can also be an outcome of a demand-supply equilibrium. While requests of visually impaired customers showed an absolute increase, the relative increase is not as strong as in the other two categories. This can be explained by the fact that the in-app support for visual impairment was already present prior to 2023. The relative increase is likely a result of the additional discount that many visually impaired people are eligible for, which may make the service much more attractive.

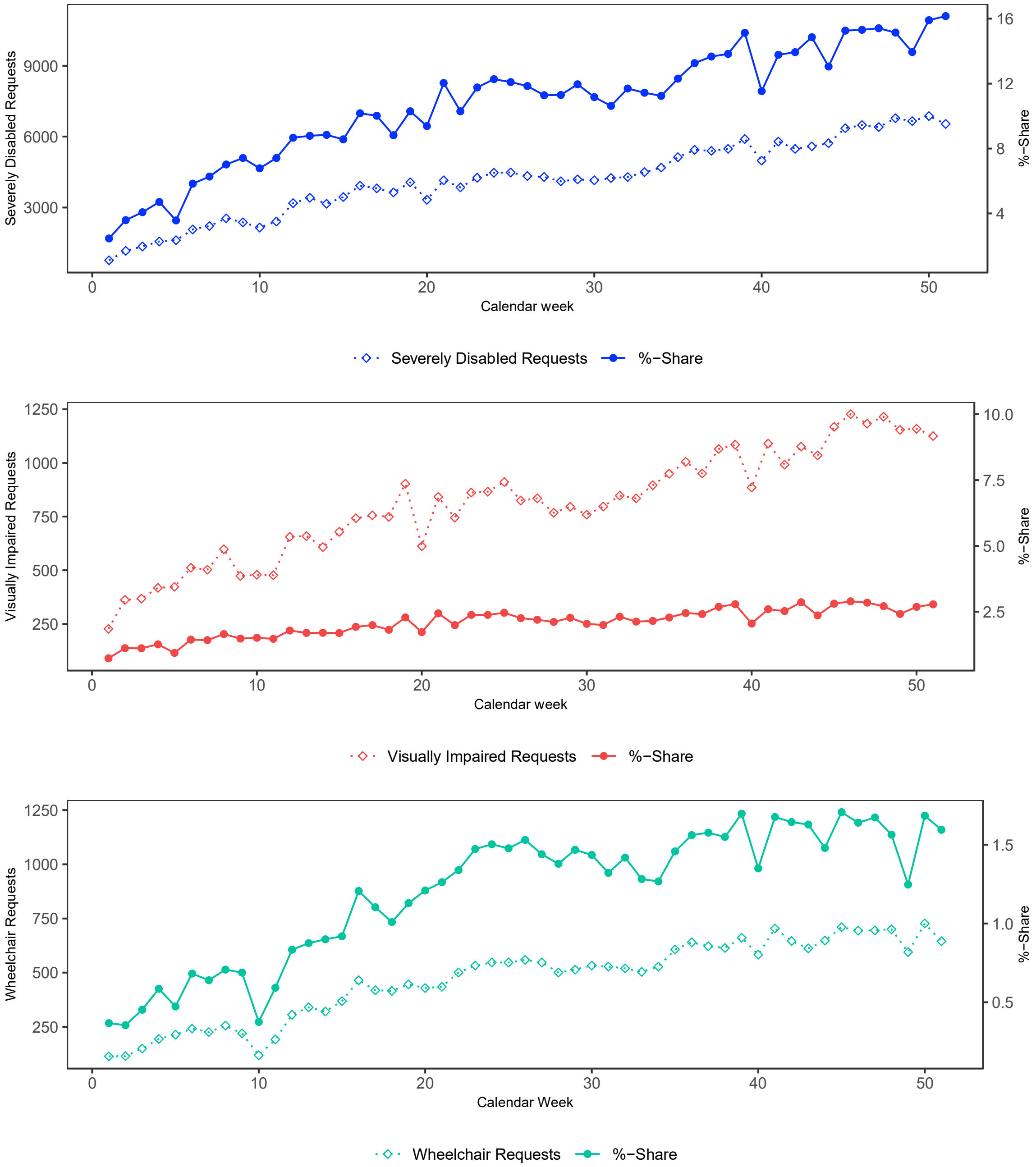


Figure 4. *Absolute number of requests and share of total requests of passengers qualifying for a severe disability discount (top), indicating a visual impairment (center) and requiring a WAV (bottom) over the course of the year.*

An indication of distinct usage patterns can be seen in figure 5, which plots the temporal distribution across day of the week and hour of the day for the three subgroups. It becomes clear that all three groups on average show different temporal usage frequencies when compared to the respective set of requests not falling in the subgroup. Considering the daily patterns, the demand of PWD is relatively more stable throughout the week and does not show a pronounced peak during the weekend, which is the usual peak for the MOIA service in general. Pairwise Chi-square tests with degrees of freedom were used to assess the significance of differences in weekday distributions among disability-related requests. For these, only exclusive sets of requests (those indicated with only one disability related indicator in figure 3) were evaluated. Significant differences at the Bonferroni-corrected 95% significance level were found between discount eligible requests and requests of visually impaired persons and between discount eligible requests and requests requiring a WAV. No significance difference was found between requests of visually impaired persons and requests requiring a WAV.

In terms of hourly usage distribution, PWD seem to use MOIA more during the day, whereas the typical MOIA demand curve shows a strong 'double peak' in the evening, when a lot of after-work leisure trips are taken. This may be an indication that PWD may use MOIA more for daily trips such as going to work, shopping or visiting a doctor. Pairwise Chi-square tests with 23 degrees of freedom among the exclusive sets of requests confirm significant differences at the Bonferroni-corrected 95% significance level between all three subgroups.

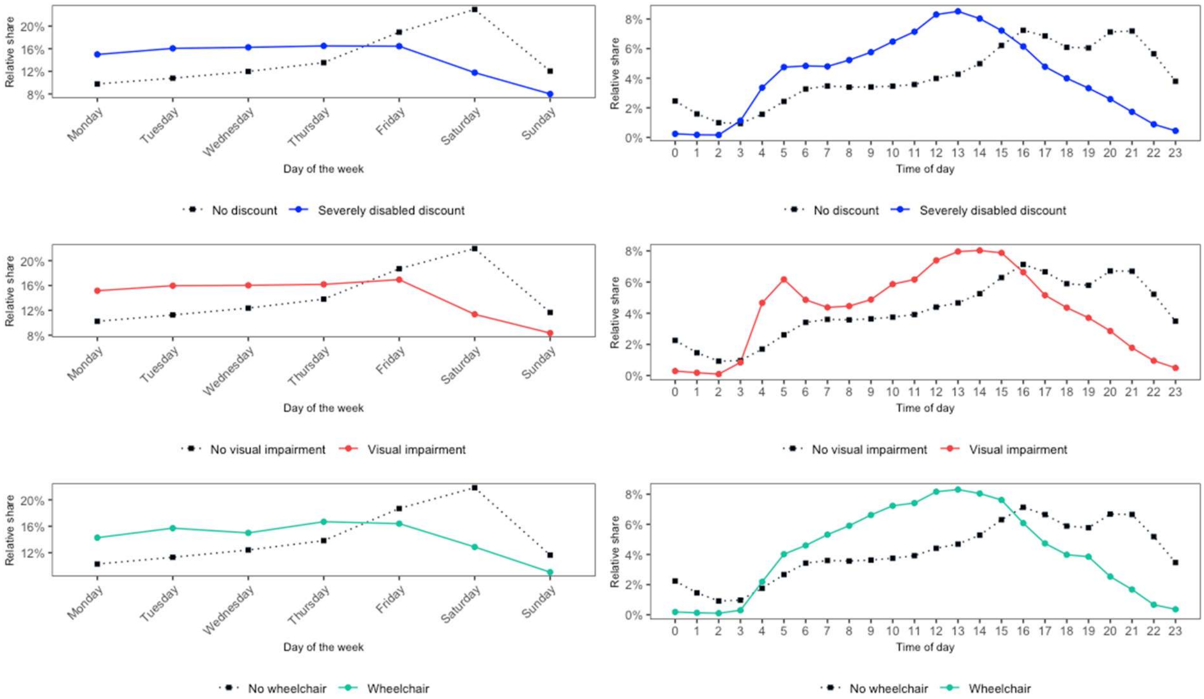


Figure 5. Temporal average distribution of requests across the day of week (left) and hour of the day(right) for the three subgroups of requests qualifying for the severe disability discount (top), requests of customers with a visual impairment (middle) and requests for a WAV (bottom). The sum of all points on each line sums up to 100%.

Another interesting finding concerns the usage behavior in terms of pre-booked versus ad-hoc requests. Before the introduction of the on-demand WAV fleet, wheelchair users often relied on paratransit services that had to be scheduled long in advance as pointed out in section 3. This user group is used to planning trips in advance, always having to consider the accessibility of vehicles and facilities. In addition, wheelchair users and persons with severe disabilities may be more reliant on a specific accessible option, given that there might be no alternative. As such, it is meaningful to use the pre-booking feature as these trips are not rejected after they have been confirmed. For some PWD, it may also take longer to get ready to depart. Pre-booked trips must be requested more than one hour and up to 24 hours in advance. The increased usage of pre-booked rides can be seen in figure 6. All three subgroups use the prebooking feature considerably more often than the general population. Out of all requests, 13.5% are prebooked. The total prebooking shares of 23.5% and 24.7% for discount eligible and visual impairment related requests are similar. WAV requests show a higher share of 32.4%. In addition, WAV requests tend to maintain higher prebooking shares across the weekend, whereas the shares are usually lower than weekdays for all other requests. Pairwise Chi-square tests with 6 degrees of freedom among the exclusive sets of requests confirm significant differences in the distribution of prebooking shares at the Bonferroni-corrected 95% significance level among all three segments. In addition to the usage frequency of the prebooking feature, figure 7 shows the distribution of prebooking slacks per disability-related subgroup. The prebooking slack is the time between request submission and planned departure. It is apparent that the distributions of all three subgroups are skewed towards higher slack times when compared to the general population. This is most pronounced for requests of wheelchair users, which in 36% of cases are booked more than 22 hours in advance.

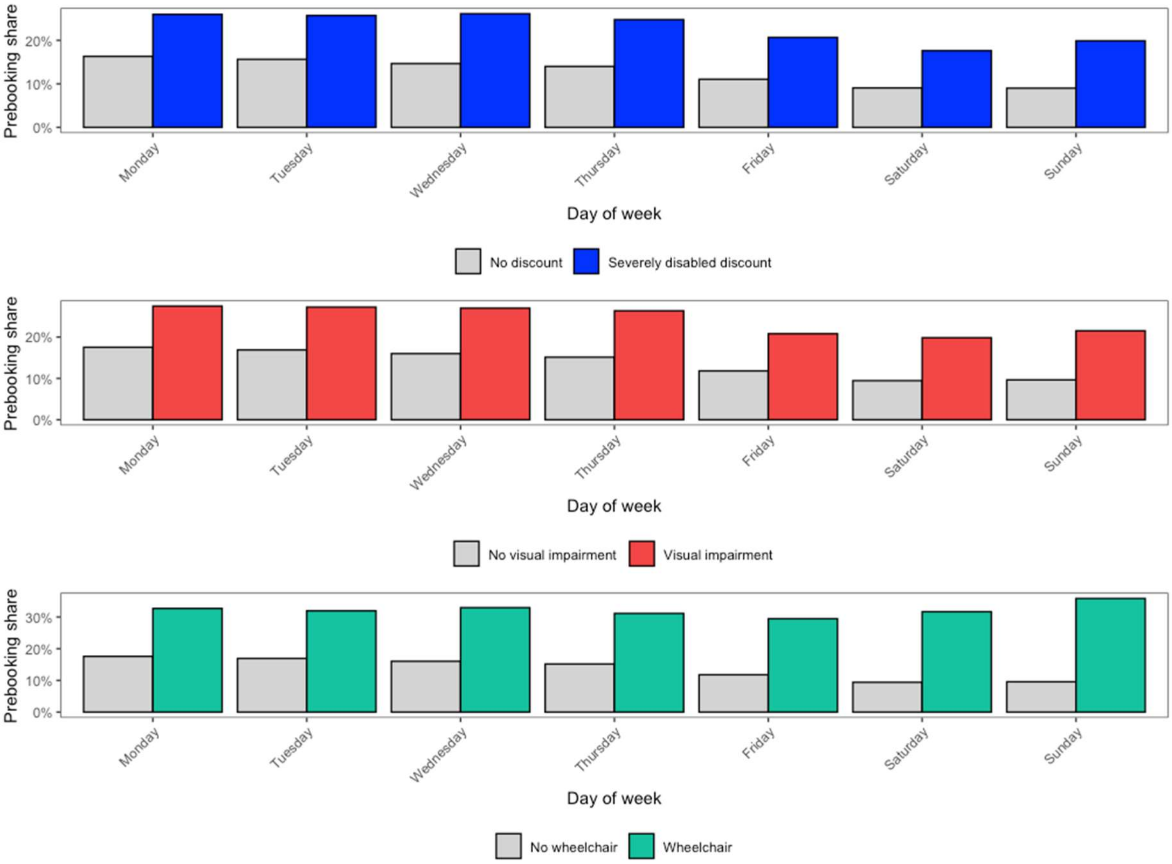


Figure 6. *Mean share of pre-booked rides per day of week for people with severe disabilities (top), people with visual impairments (middle) and wheelchair users (bottom), compared to all other requests, respectively.*

Figure 8 shows the distribution of requested group sizes. The group of requests involving a severe disability discount or visual impairment show a similar distribution when compared to the general population, although they tend to travel alone more frequently. A likely explanation could be the difference in trip purposes, which may be related less to social activities and include more private purposes like driving to health-related services. The distribution for wheelchair accessible rides looks different. People in this subgroup travel alone less and are more often accompanied by a second person when compared to all other requests. This may be because of the fact that wheelchair users may be more reliant on another person for assistance. In fact, 31.8% of all WAV rides included a (discount eligible) second person (51% among those that are eligible for the discount). In contrast, in the larger group of discount eligible rides in general, only 15.5% included an accompanying person in the discount. For requests of people with visual impairments, 22.1% included a discounted accompanying person (29% among those that are eligible for the discount). Note that the maximum group size for WAV rides is four, which is the seat capacity of the WAV subfleet.

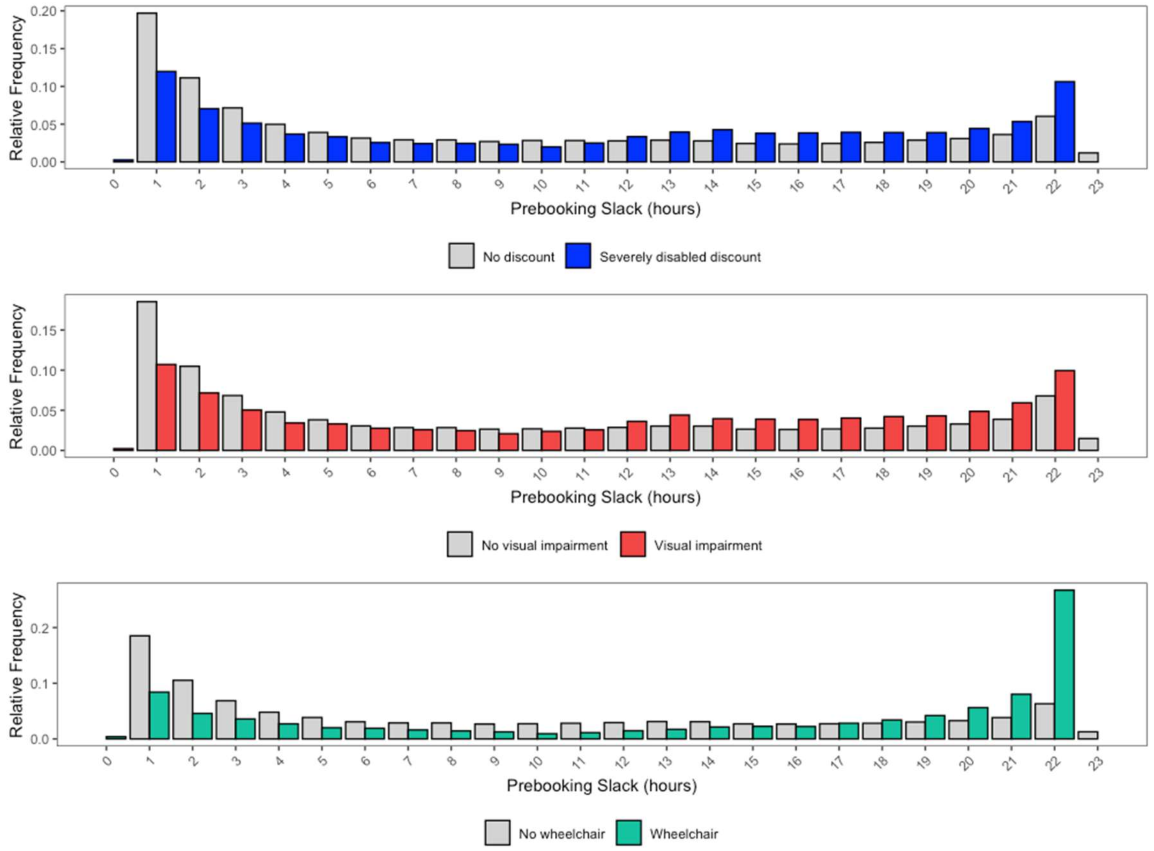


Figure 7. *Relative distribution of prebooking slack times for people with severe disabilities (top), people with visual impairments (middle) and wheelchair users (bottom), compared to all other requests, respectively.*

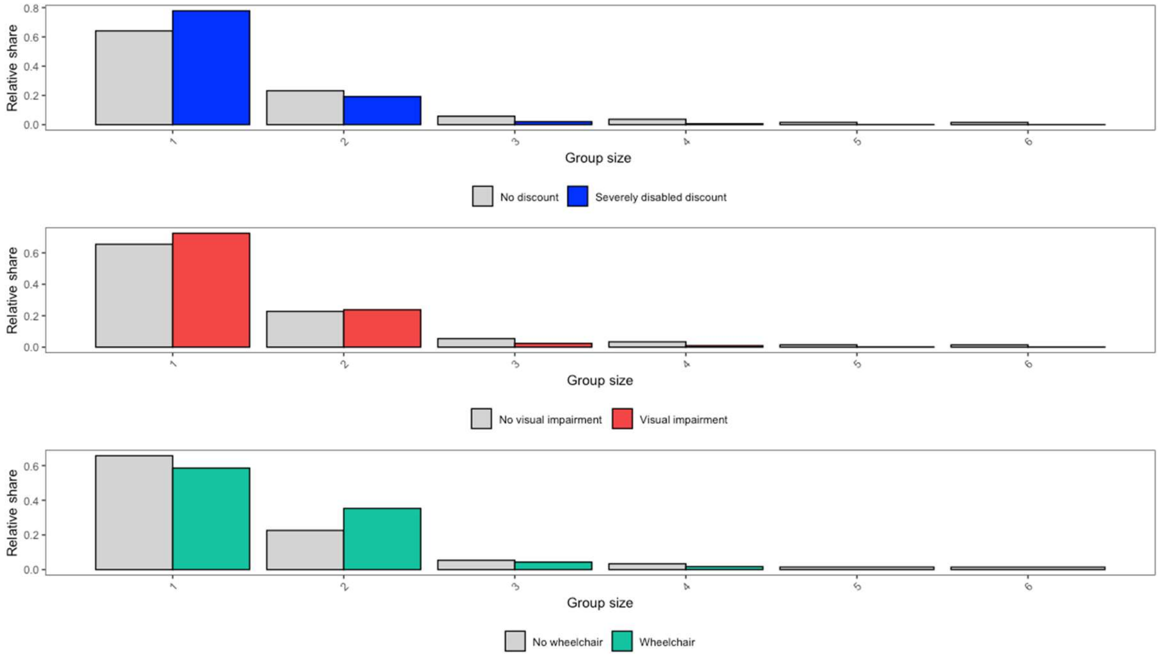


Figure 8. *Group party size distribution for requests of people with severe disabilities (top), visual impairments (middle) and wheelchair assistance (bottom).*

Another interesting finding is the difference in usage frequency as presented in figure 9. The majority of passengers without any of the observed disability status information request less than 20 rides per year. This is also true for customers using a wheelchair. However, most of the customers with a disability discount or visual impairment requested more than 20 rides per year. For all three subgroups the distribution shifts towards higher frequencies. For illustration, the mean number of requests per customer in the observation period is 7 when looking at all requests. For requests qualifying for the severe disability discount, we observe roughly 63 rides per customer and year. In the case of visually impaired customers, we observe about 94 rides per year while WAV customers requested roughly 20 rides per year. The mean for the three subgroups is highly distorted by comparatively few individuals who use the service quite heavily. Given limited mobility options and under the given discounts the service seems to be very attractive for PWD who adopt the service.

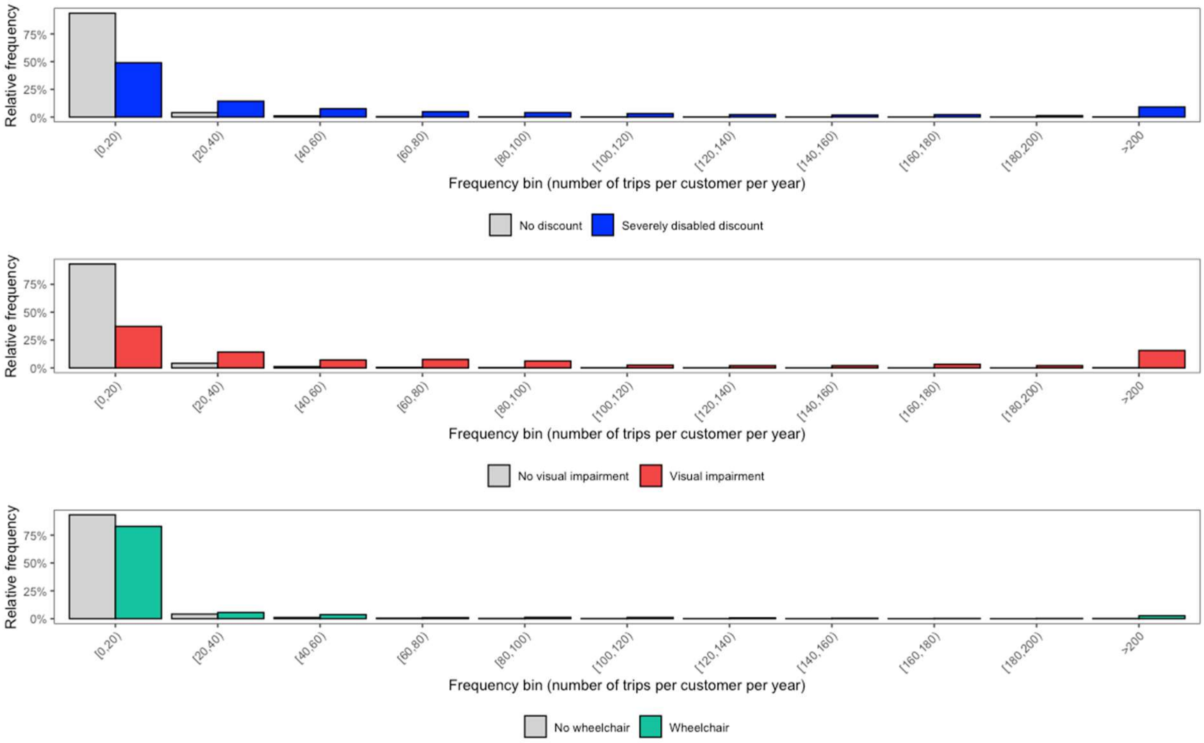
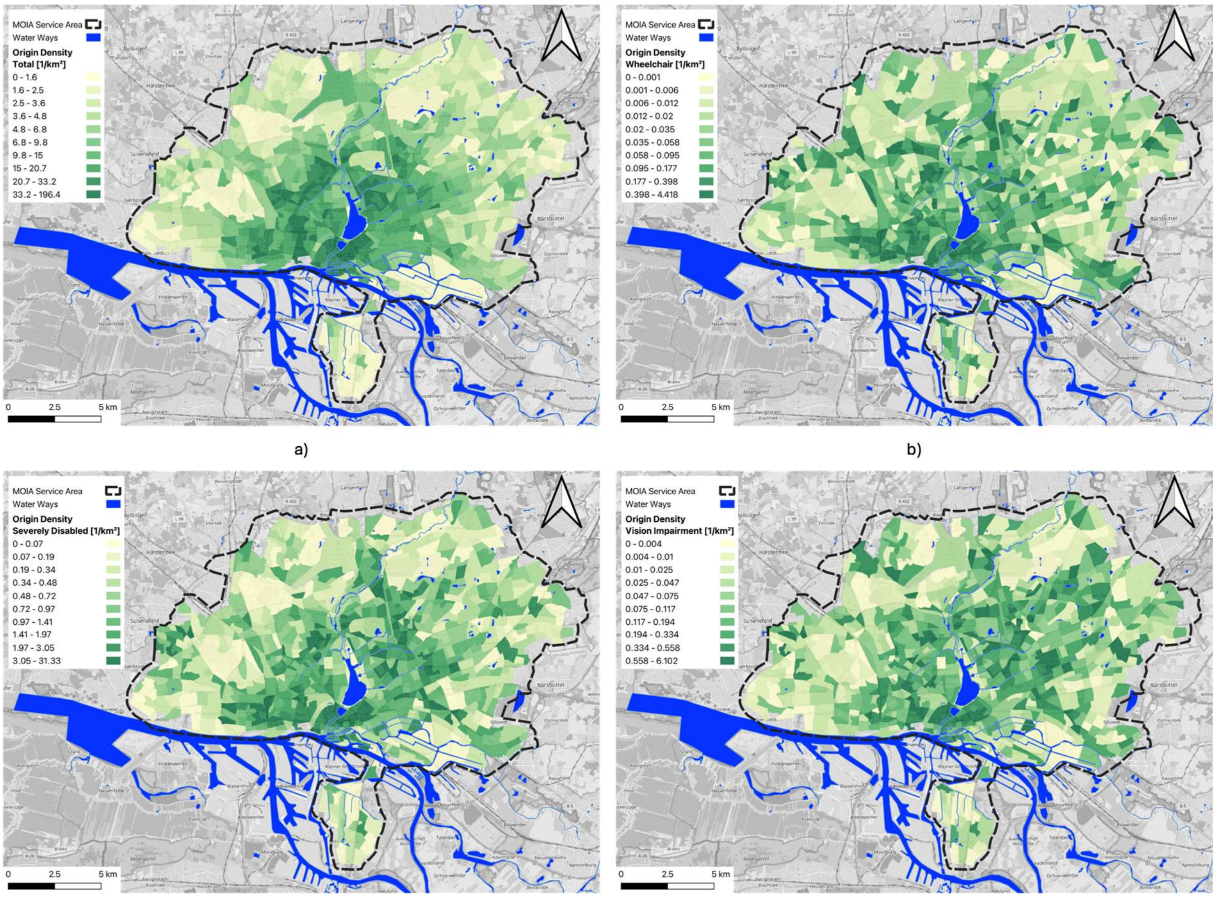


Figure 9. Comparative usage frequency per customer by segment.

Figure 10 illustrates the spatial distribution of origins densities for the three subgroups: all requests (a), wheelchair requests (b), requests with a severe disability discount (c), and requests with persons with visual impairments (d). These requests are aggregated to the previously introduced statistical zones. For comparative purposes, only zones completely inside the service area are shown, allowing for a consistent evaluation of requests per square kilometer.

Looking at all requests, they tend to be concentrated in the city center of Hamburg, around *Lake Alster* and at the airport. The spatial patterns of wheelchair users and persons with severe disabilities are different in that the outskirts of the service area attract considerany more requests. In particular, WAV requests are more equally distributed in the service area. A more detailed analyses is provided in the regression analysis in section 4.3. When looking at average direct ride distances (i.e., distances between origin and destination without detours introduced by pooling), there only seem to be small differences between wheelchair users (7.8 km), persons with severe disabilities (8.2 km) and all requests (7.7 km).



a) b) c) d)

Figure 10. *Spatial distribution of demand density. a) All requests b) WAV requests c) requests of people with severe disabilities d) requests of people with visual impairments.*

4.2 *In-App Feedback*

In total, we collected in-app feedback for 199,853 trips (about 10% of all requests). Out of these, 27,776 included a severe disability discount (12.7% of all trips with discount), 5,605 trips were requested by a visually impaired person (13.3% of visually impaired customer requests) and 4,063 required a WAV (16.6% of all WAV requests). Note that there is no feedback for requests that were not served.

Figure 11 shows the distribution of the stated travel purposes for each segment. In line with observed differences in temporal usage patterns presented above, the trip purposes differ for the segments referring to PWD. The most obvious difference is the reduced *relative* importance of leisure trips (22% versus 41% for trips with and without discounts, respectively). In contrast, *commute* and *errands* (including health-related purposes) trip purposes have a considerably high importance in comparison. For example, *commute* has a share of 34% among visually impaired customer trips and only 12% for trips not related to a visual impairment. This contrast is less pronounced for the WAV trips. Given the requirement to physically register for the discount in advance and the uniqueness of the service, *tourism* accounts for a very small share among PWD, whom we assume to be primarily local residents. *Business* and *airport* trips are relatively less frequent among disability related trips. Pairwise Chi-square tests with 7 degrees of freedom confirmed significant differences in trip purpose distributions between each customer segment at the Bonferroni-corrected 95% significance level.

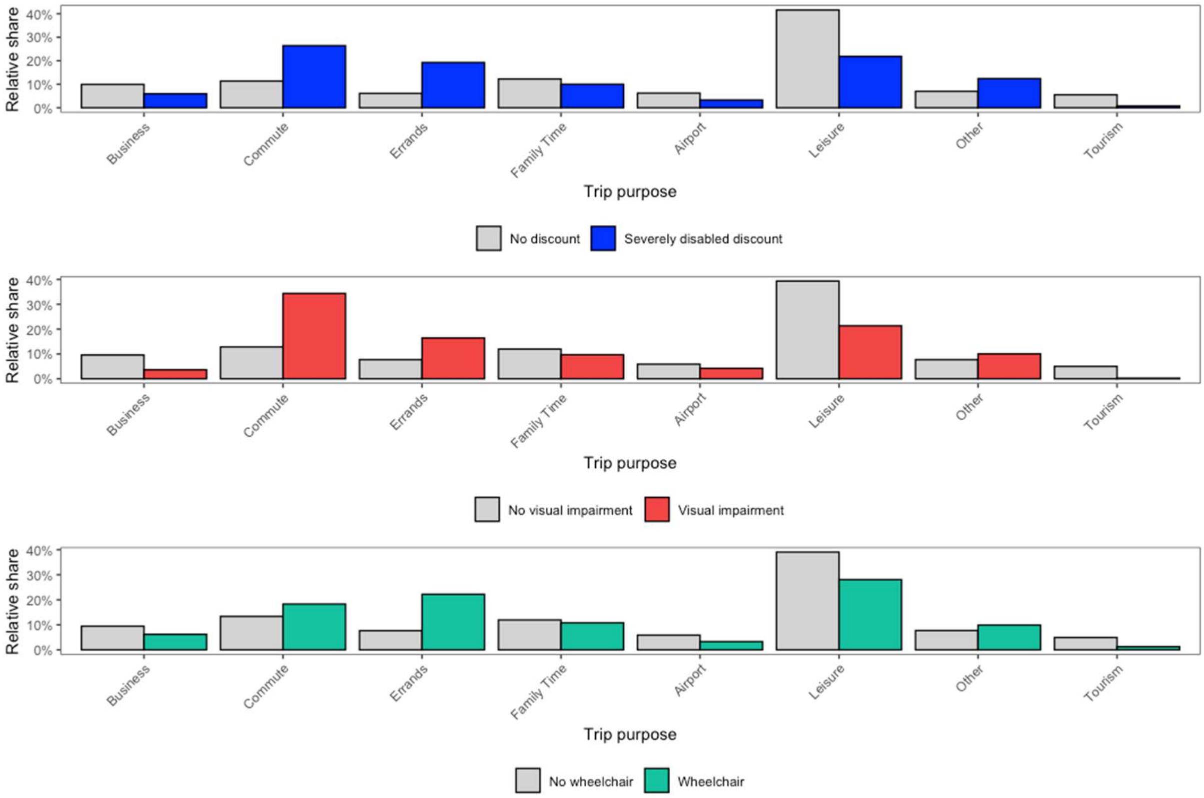


Figure 11. Reported trip purpose from in-app feedback after delivery.

Regarding customer satisfaction, 92.5% of customers without any known indication of disability submitted positive feedback. We obtain similar or slightly higher values for discounted trips (93.9%), trips of people with visual impairments (93.8%) and WAV trips (96%).

4.3 *Regression Analysis*

To gain a more comprehensive understanding of the demand of customers using a wheelchair and people with severe disabilities, we performed a regression analysis. This analysis uses observed trip data alongside additional data obtained from OpenStreetMap (OSM, OpenStreetMap contributors, 2023) and spatial data provided by the government of the City of Hamburg (Authority for Transport and Mobility Transformation, 2018). The OSM data, obtained in June 2024, included various points of interest (POIs). The spatial data included data on demographics per zone. Finally, the POIs from OSM were spatially joined with the statistical zones, resulting in a dataset with the following information per zone:

- Number of inhabitants
- Number of jobs
- Number of gastronomy amenities
- Number of culture amenities
- Number of shop amenities
- Number of airports
- Number of long-distance train stations
- Number of clinics
- Number of social facilities
- Number of doctor's practice

The dependent variable for our model was the observed demand, which was filtered and spatially joined with the statistical data. This resulted in the number of origins and destinations per zone for all requests, requests eligible for the severe disability discount and requests for WAVs.

To simplify the analysis and avoid biases from partial coverage, only zones completely within the service area were included in the regression, which reduced the total number of requests analyzed to 1,769,130. This approach eliminates the complexities of handling zones that extend beyond the service boundaries, where trips may not fully reflect the service area's infrastructure and amenities. Although this results in a smaller sample size, it enhances the accuracy of the analysis by ensuring that each included trip is entirely subject to the service area's conditions. Consequently, the regression results offer a more precise reflection of the service area's influence on travel patterns, free from external effects that could dilute or skew the findings.

Tables 1 and 2 show the regression results of linear regressions with the formula:

$$\begin{gathered}\#\,\text{Origins/Destinations} \sim \#\,\text{inhabitants} + \#\,\text{jobs} + \#\,\text{gastronomies} + \#\,\text{shops} + \#\,\text{airports} + \\ \#\,\text{culture amenities} + \#\,\text{train stations} + \#\,\text{clinics} + \#\,\text{social facilities} + \#\,\text{doctors}\end{gathered} \tag{2}$$

Each column in tables 1 and 2 represents a differently filtered dependent variable: the first column corresponds to the number of origins of all requests, the second to requests of people with severe disabilities, and the third to all WAV requests. Each row includes the estimates, the statistical significance indicated by the p-values, denoted by an asterisk, and the standard errors shown in the round brackets for each independent variable and the intercept.

The R^2-value of 0.84 for all requests indicates that the demand distribution is well explained by the independent variables, while the explanatory power for WAV requests and requests of people with severe disabilities is lower, with R^2-values of 0.24 and 0.50 respectively. This hints to the fact that the demand for ridepooling of PWD is less explainable by the chosen variables and confirms different usage patterns.

The results for all trip origins confirm that inhabitants, jobs, gastronomic and cultural facilities, long-distance train stations and the airport have a significant positive impact on demand. The airport and long-distance train stations are outstanding in their effect size indicating a high intermodal usage of MOIA in combination with long-distance travel.

Demand by users with a wheelchair show a different pattern. While inhabitants and jobs also have a significant positive impact, the airport, gastronomic and cultural facilities are insignificant. This finding is not surprising given the observations from the previous section in that temporal distributions and trip purpose distributions differ considerably from the general population. In contrast, social facilities and doctor's practices significantly impact wheelchair demand, locations that are mainly visited during the day.

The origins of requests from people with severe disabilities are also significantly influenced by inhabitants and jobs, but not by gastronomic or cultural facilities. In contrast to the general MOIA usage, requests of people with severe disabilities show a significant relation to shops and clinics, facilities that are usually visited during the day. This may explain the higher daily usage similar to wheelchair demand (see figure 5). In contrast to wheelchair demand, the airport shows a significant positive impact, but social facilities do not.

For both disability related groups, the *relative* importance of jobs compared to inhabitants is notably higher. Whereas the coefficient for jobs is roughly 31.3% of the coefficient for inhabitants for all trip origins, it is 59.7% and 64% for people with severe disability and wheelchair trips, respectively. This is in line with the higher prevalence of commute trips among those groups.

The results for trip *destinations* in table 2 largely mirror those for trip origins, with comparable coefficients and significance levels across most variables. However, there are a few key differences worth noting. One of the most prominent distinctions lies in the *Airport* variable, which shows a significant effect in the destination model for trips of wheelchair users but is not significantly influencing the origins for the same passenger category. In addition, the airport seems to be more important for explaining destinations than origins in the general population. Another notable difference is observed in the effect of *Doctor's practices*, which has a considerably higher coefficient in the destination model compared to the origin model for wheelchair users. In contrast to trip origins, *Social facilities* are a significant predictor for trip destinations of people with a severe disability. Similarly, cultural amenities are significant for destinations but not origins of trips for wheelchair users.

Table 1. Regression Results for factors influencing the trip origins for different customer groups

	Dependent variable:		
Independent variables:	All trip origins	All severe disability discount trip origins	All wheelchair trip origins
Inhabitants [per 1000]	600.95***	54.35***	6.73***
	(43.18)	(8.04)	(2.03)
Jobs [per 1000]	187.93***	32.45***	4.31***
	(22.18)	(4.13)	(1.04)
Gastronomy	104.77***	−0.96	0.24
	(7.00)	(1.30)	(0.33)
Shops	−27.05	29.95***	3.16**
	(32.04)	(5.97)	(1.51)
Airport	52,966.04***	656.83***	87.49
	(1,183.50)	(220.37)	(55.68)
Cultural amenities	203.74***	0.95	1.36
	(22.83)	(4.25)	(1.07)
Long-distance train stations	20,996.15***	3,870.40***	529.15***
	(1,229.63)	(228.96)	(57.85)
Clinics	311.36	129.05***	13.99
	(225.04)	(41.90)	(10.59)
Social facilities	−78.06*	10.71	5.98***
	(44.30)	(8.25)	(2.08)
Doctor's practices	33.34***	11.94***	1.12**
	(10.80)	(2.01)	(0.51)
Intercept	351.60***	46.37***	3.73
	(87.70)	(16.33)	(4.13)
Observations	751	751	751
R^2	0.84	0.49	0.24
Adjusted R^2	0.84	0.48	0.22
Residual Std. Error (df = 740)	1,177.35	219.23	55.39
F Statistic (df = 10; 740)	398.95***	71.46***	22.77***

Note: *p<0.1; **p<0.05; ***p<0.01

Table 2. Regression Results for factors influencing the trip destinations for different customer groups

	Dependent variable:		
Independent variables:	All trip destinations	All severe disability discount trip destinations	All wheelchair trip destinations
Inhabitants [per 1000]	502.54***	47.54***	4.50**
	(44.48)	(7.83)	(1.86)
Jobs [per 1000]	200.19***	32.11***	5.07***
	(22.84)	(4.02)	(0.95)
Gastronomy	101.54***	−0.91	0.35
	(7.21)	(1.27)	(0.30)
Shops	−37.77	33.51***	3.39**
	(33.00)	(5.81)	(1.38)
Airport	70,605.58***	635.87***	152.11***
	(1,219.10)	(214.72)	(50.91)
Cultural amenities	318.27***	0.93	1.76*
	(23.51)	(4.14)	(0.98)
Long-distance train stations	25,015.45***	3,470.06***	516.43***
	(1,266.62)	(223.09)	(52.90)
Clinics	565.74**	178.23***	13.26
	(231.80)	(40.83)	(9.68)
Social facilities	−86.54*	14.15*	5.78***
	(45.63)	(8.04)	(1.91)
Doctor's practices	40.01***	11.15***	2.09***
	(11.12)	(1.96)	(0.46)
Intercept	401.85***	51.48***	4.65
	(90.34)	(15.91)	(3.77)
Observations	751	751	751
R^2	0.88	0.49	0.31
Adjusted R^2	0.88	0.49	0.30
Residual Std. Error (df = 740)	1,212.77	213.60	50.65
F Statistic (df = 10; 740)	562.36***	72.09***	33.20***

Note: *p<0.1; **p<0.05; ***p<0.01

5 Discussion and Conclusion

The analysis of a full year of requested rides after the introduction of a wheelchair accessible service and a discount for people with severe disabilities showed distinct usage patterns of PWD and supports previous findings. The differences in the temporal distributions of trips are in line with the discussion of Hassanpour et al. (2021, who find that the national household travel survey in the US shows a strong single peak in the temporal distribution of trips of wheelchair users as opposed to the classic peak hour distribution during commute hours. The fact that a small share of customers is responsible for a large part of disability-related rides (i.e., customers with a high usage frequency) may confirm previous findings (Eisenberg et al., 2022; Ong et al., 2024), suggesting that PWD use these services more often than the general population. This has also been reported by the earlier survey of MOIA respondents by Kostorz et al. (2021). The spatial analyses support the previous works of Zwick & Axhausen (2022) and Zwick et al. (2022) in that ridepooling demand can be explained by a set of spatial predictors. However, the transfer to disability-related demand shows weaker goodness-of-fits. In fact, this is in line with findings from Khan et al. (2021a) who report a similarly low performance for their OLS model for paratransit demand in Arlington, Texas. The significance of doctor's practices and clinics that correlate with observed demand support the findings of Zhang et al. (2023); Kostorz et al. (2021) who emphasize the importance of health-related trips for PWD. The current data show that individual locations, such as assisted living homes, foundations for the blind, counseling centers, workshops for PWD, associations for the deaf, and schools for PWD, are among the most frequently visited places. However, these locations are often grouped into broader categories in datasets like OSM, which can dilute the specificity of the information. The results of the simple OLS approach could be improved by employing spatial regression models that capture spatial autocorrelation, which is a shortcome of our study.

The revealed demand patterns show that on-demand ridepooling services may be an attractive option for PWD. It becomes obvious that it may take some time for users to adapt to a new offer. Looking at the temporal and spatial distributions of demand, distinct usage patterns emerge when compared to the general population. When looking at the reported trip purposes, it becomes apparent that PWD may use the service differently than people without disabilities, who predominantly use it for leisure purposes.

A limitation of the study is that it is only recorded whether requests are eligible for the severe disability discount or not. There may be even more customers with a disability who have not yet officially registered for the MOIA discount. In addition, demand may even be underestimated, as limited supply can also lead to a long-term equilibrium in which demand levels have adjusted over time. This is especially true for wheelchair users, as the WAV fleet is only a fraction of the total fleet. The limited supply could also be another reason why prebooking shares are elevated for these customers.

Although revealed or observed demand data provide a realistic view of the current demand situation, they do not provide information on the latent demand for potential additional passengers with disabilities, for whom barriers to use may still be too high (Dorynek et al., 2022). Given that MOIA operates a stop-based service, customers still need to plan for access and egress trips. For public transport, Kwon & Akar (2022) show that walkability of the local environment may considerably increase its usage for people with disabilities. Similarly, Lee et al. (2024) identify vehicle access/egress among the most important barriers to travel for people with disabilities, among others. Requiring third-party assistance is another important barrier that should also be addressed in future autonomous services that are currently developed by various ride-sharing operators (Dicianno et al., 2021; Hwang & Kim, 2023; Sivakanthan et al., 2024; Riggs & Pande, 2022).

Another limitation is that we do not exactly know which kind of disability a customer may have. In addition to knowing nothing about the requests of customers with less severe disabilities, the severity of the disability itself incorporates many different types of disability, including the visual impairments and use of wheelchairs addressed in this study.

Further studies may incorporate survey data to also learn more about the sociodemographics of PWD using the service. In addition, interviews may help better understand the needs and demand of PWD. Some qualitative findings have been reported by Krohn et al. (2023) and Dorynek et al. (2022).

Assuming that demand shares and usage patterns are similar across cities or regions, the findings may help policymakers, planners, and operators prepare for new accessible (ridepooling) on-demand services in new areas and accurately plan for the correct supply. For example, the increased importance of social or health-related facilities that generate/attract demand may point to the need of dedicated infrastructure to ease (de-)boarding of PWD in these locations. This is especially true for WAV rides, as stop durations are typically prolonged. In addition, estimates of expected demand can inform decision-making for deciding on the extent of accessible vehicles in mixed fleet scenarios. Accessible vehicles with additional installations, such as lifts, can come at higher costs than conventional vehicles, meaning that planning with an appropriate share of accessible vehicles becomes crucial from an economic point of view. As accessible vehicles may require specifically trained driver personnel, the temporal distribution of expected demand is important for scheduling driver shifts and to balance supply and demand of the service. Although simple OLS models apparently struggle to explain observed demand patterns, insights into the extent of uncertainty help account for them. The presented figures may also help governmental institutions that struggle to regulate accessible services (Ward, 2017; Gebresselassie, 2024) by defining appropriate requirements and targets.

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Contributor Statement

Conceptualization: Nico Kuehnel
Data Curation: Nico Kuehnel, Tom-Erik Kuhlen, Mark Frawley
Formal Analysis: Nico Kuehnel, Tom-Erik Kuhlen
Investigation: Nico Kuehnel
Methodology: Nico Kuehnel, Tom-Erik Kuhlen
Validation: Nico Kuehnel, Felix Zwick
Visualization: Nico Kuehnel, Felix Zwick, Tom-Erik Kuhlen
Writing – Original Draft: Nico Kuehnel, Felix Zwick, Tom-Erik Kuhlen
Writing – Review & Editing: Nico Kuehnel

Conflict Of Interest (COI)

It is declared that at the time of writing all authors of this paper are employed at the ride-pooling operator MOIA.

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