Improving public transportation in rural regions by implementing public mobility

A case study on rural public mobility in South-Holland

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Cover image: top (Google Streetview 2025), bottom (Wiener Linien 2025)

Preface

This report was written as a master's thesis for the Traffic and Transport Engineering track of the MSc programme in Civil Engineering at Delft University of Technology. The research was conducted in collaboration with the Province of South Holland. It explores how public mobility can be implemented in rural regions and aims to identify which elements of public mobility should be introduced in such contexts.

I would like to thank my graduation chair, Niels van Oort, for helping to refine the research topic and for providing feedback throughout the process. I also thank Alexandra Gavriilidou, my daily supervisor at TU Delft, for her detailed suggestions and guidance during the many progress meetings. I am grateful to Martijn Timmers, my daily supervisor at the Province of South Holland, for his practical input during our weekly meetings, and to Ronald Haverman, my supervisor at the Province of South Holland, for his availability and support whenever needed. I also thank the Concession Management department of the Province of South Holland for their support and for the pleasant working environment during this research, together with the other interns at the province for contributing to the positive atmosphere. Finally, I much appreciate the help of my fellow graduating students in the thesis room and my friends, who were always willing to support me when needed.

Now that this report has been finalised, I look forward to continuing my weekly to bi-weekly cycling trips to the Krimpenerwaard, enjoying the landscape while focusing less on the topics covered in this thesis.

Yvar de Waaij
Delft, January 2026

Abstract

In rural regions public transportation is difficult to facilitate, low densities make it difficult to justify a dense bus network. Simultaneously also in rural regions people that are dependent on public transportation exist. These people should be served by the public transportation. To be able to compete with car users and gain more travellers local bus lines are frequently stretched to improve commercial speed. This enlarges the access and egress distances which may be (too) difficult to overcome. This thesis wants to investigate the potential of integrating public mobility into the public transportation system within rural regions for short local trips and access and egress to stretched bus lines (interlocal bus services).

To assess the potential role of public mobility, a literature study is first conducted to identify the benefits, functioning, and malfunctioning of different aspects of the public mobility spectrum. Both the node configurations through which public mobility is provided and the systems themselves are examined. Based on this literature study operational constraints are formulated and a selection of modes is made for use in the subsequent modelling phase. The selected public mobility types are demand responsive transportation (DRT), shared mobility, and ride-sharing, in combination with the existing interlocal bus service. Under the defined operational constraints, DRT may only serve trips between nodes and the nearest interlocal bus station, and vice versa. Battery-powered vehicles may only operate between any node and any interlocal bus station, conventional bicycles may be used for any trip, and ride-sharing is only encouraged from specific locations focused on the creation of corridors between villages and the interlocal bus service. Given these constraints a discrete-event, agent-based simulation with stochastic demand and mode choice is developed for the case area of the Krimpenerwaard.

The results of the model indicate that conventional bicycles, in combination with the interlocal bus service, form the backbone of the system. For longer access and egress trips to interlocal bus stations, electric bicycles offer clear benefits and are the primary mode. Ride-sharing is a dominant mode on few OD-pairs of the selected corridors. however, the overall share of trips made using ride-sharing remains marginal. The cabin scooter emerges as an important mode for people with limited mobility and providing shelter during rainy conditions. Due to its lower speed, trip distances are generally short, resulting primarily in trips to and from the nearest interlocal bus station. While it is not the preferred option for most travellers, it plays a crucial role in ensuring system accessibility for all users. DRT is the least-used mode, due to its operational constraints, it does not offer a fast alternative, and most DRT users lack viable substitutes. Therefore, it is essential that a DRT service is available to provide these users with a viable travel solution. Simultaneously due to the enormous costs for a DRT it is preferred to minimise the trips as much as possible, therefore it is not advised to improve the operational constraints to gain a higher usage. Although a 45 km/h scooter is included in the model, the most promising fleet compositions exclude scooters. This is the result of a competition between scooters and the interlocal bus due to both having a the higher velocity while the bus also has a high capacity the scooter is unable to deliver enough trips given the cost constraints. This results in an unstable system configuration, which should therefore be avoided.

The results further show that the lower the settlement density, the greater the potential improvements offered by public mobility relative to the existing system. In suburban areas, public mobility is unable to compete with local bus services. Under the model assumptions, and with a confidence level of 99%, the integration of public mobility increases ridership by at least 5.8%, while cancelled trips increase by no more than 17.6% across all more rural settlement typologies. In villages, the overall benefits are limited for most trips; however, the slowest 1% of trips experience a commercial speed improvement of at least 64.7%, contributing to a more equitable mobility system. During peak hours, villages generate trip volumes that public mobility services are unable to accommodate effectively, making bus services the preferable option. Outside peak hours, when demand decreases, public mobility becomes more advantageous than local bus services. In ribbon developments, average travellers experience a commercial speed increase of 55.5%, while dispersed settlements show an even larger improvement of 319.1% in average commercial speed. Based on these findings, it is recommended to implement public mobility in rural regions with a focus on dispersed settlements, ribbon developments, and villages, while ensuring the presence of a fast and frequent interlocal bus service and dedicated rush-hour bus services for villages.

Contents

List of Definitions

Embarkation point Centralized locations where people can meet with a demand driven or ride-sharing service.

Bus stop Location where bus takes people along but no other parts of the public mobility spectrum are available.

Share point Location to rent or return a shared modality vehicle. This may at some locations be a specifically defined area in a station but can also be free floating.

Hub Location where people can change to (multiple) public mobility aspects. In this report the term hub will not be used, instead see node.

Interlocal bus service public transportation bus line mostly running on through roads. This service is designed to move people over longer distances and therefore will only move as close to the village centre as the through road is located.

Meet-up point Designated stop to start a ride-sharing trip.

Node Location where people can change to (multiple) public mobility aspects. This term is used when all different categories together are meant otherwise more specified category names will be used which are Transfer station, Transfer point, Embarkation point and Share point all different categories are described within this list.

Public mobility The mix of all collective modes of transportation potentially functioning within a network organised by the transport authority. Examples are shared mobility like bicycles or scooters, demand responsive transportation and ride sharing.

Public mobility aspect the combinations of the used vehicle, the driver operating the vehicle, the manner in which the user is able to access, or make clear it wants to access the vehicle and the structure in which the vehicle is operating together with the operation tactics.

Public mobility system The mix of all collective modes of transportation actively functioning within a network organised by the transport authority.

Public transportation All universal accessible schedule based mobility services organised by the transport authority accepting payment by a universal fare card ("OV-chipkaart").

Point A signposted node without any additional facilities to start or end a public mobility trip that is very limited in size and may be limited to a geo-fenced area. Due to the limited size it is easily integrated along most existing street. The main focus of a point is to supply trips within the area.

Rural region Continuos area in which at least 50% of the predefined square kilometre grid cells have less as 300 inhabitants. (Eurostat n.d.)

Ride-share A car with a hail-driver and at least one passenger who both do have a shared stretch of a their trip, the origin and destination may differ. The passenger will be joining the hail-driver for (part of) the route.

Shared mobility Vehicles for rent which can be used for a single trip and may be delivered at different Share point.

Spatial settlement typology
manner in which to organise the case area into four different manners of

which the buildings in a area are organised. In this report the distinction is made between Suburb, village, ribbon development and dispersed settlement.

Stop A Point with more facilities as only a signpost for example a shelter a bench or a stopping bay.

Station A designated spot to start or end a public mobility trip that does have dedicated infrastructure to also accommodate non micro mobility vehicles for longer periods of time without interrupting other traffic. Capable of handling larger volumes of people and is a suitable location to dwell until the desired public mobility trips leaves. It has guaranteed availability of at least a single form of shared mobility. Besides the public mobility aspects it may have other communal functions included but is not required to. From a station any shared mobility mode may be delivered to any point.

Transfer point Location where shared mobility, ride-share services and demand driven transport meet and a trip can be started, ended or turned into a multi-modal trip. but no dedicated infrastructure is present.

Transfer station Hub with a Interlocal bus service and access to local transportation with shared mobility, demand-driven transportation and/or ride-share services.

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1 Introduction

In this chapter the research topic will be introduced. The main focus will be on why it is important, how the research is scoped and in which part of the topic already research has been conducted. A introduction to the research question will be given and how this will be answered with sub questions. Also a short report outline is given.

1.1 Research context

The province of South-Holland has a growing population together with a growing mobility need. However the province has limited available growth possibilities for car traffic (Zuid-Holland 2025) Therefore it is aiming to solve the growing mobility need with public transportation. The focus to reach this goal is by implementing more frequent and faster public transportation services. The province realises that faster bus services result in less winding routes and thus a longer access and egress distance. To solve this issue extra attention is currently given to solutions which overcome this distance while at the same time restricting new developments to locations with good public transportation access. (Zuid-Holland 2025)

Within Dutch rural regions a trend can be observed of people relocating to more urbanised areas which make rural areas shrinking areas (CROW 2024). Simultaneously car ownership is increasing (KiM 2024). For public transportation this is difficult because both result in shrinking rider-ship, while a decent volume of rider-ship is needed to operate a bus line(CROW 2024). Operators have a financial incentive to drive more profitable lines and try to reduce the amount of contracted scheduled service hours (ssh) on less beneficial lines. The operator may try to convince the transport authority to drive an equal amount of ssh as contractual obliged but shift the ssh to more profitable routes. The transportation authority may occasionally concede. This results in the current trend for public transportation in rural regions to phase-out less used local bus services and implement bus services running predominantly on through roads to gain higher commercial speed(CROW 2024). These faster services will be referred to as Interlocal bus service. As a side effect the location choice of a bus stop becomes different and also more important for the access and egress (Bastiaanssen and Breedijk 2022). Previously most bus stops where located within built-up areas with the service areas adjoined, and some less used stops outside the built-up areas (CROW 2024). In the new situation the stops are mainly located at the main roads. This creates larger distances between the bus stop and desired service area, because the service area also consist of towns and villages off the main road and not all towns will have a bus stop within the town centre any more(Durand et al. 2021). This creates larger access and egress distances which may be (too) difficult to overcome. Also it can be assumed that interlocal bus services reduce travel time for longer trips but increases travel time for short trips. The interlocal services are used as a substitution for local services but do not serve equivalent purposes(CROW 2024). The interlocal bus services offer great potential for a more financially feasible scheduled service, but this is only possible if alternative transport solutions are provided for travellers unable or unwilling to overcome access or egress distances via private transport. In the current system, this results in difficulties reaching many destinations and transportation poverty for people without private mobility in rural areas. This group of people should have access to a sufficient level of public transportation. This level is however ambiguous, not everyone perceives sufficient in the same manner which results in part of the riders satisfied and the other part unsatisfied. This ambiguousness can also be found in differences between public transportation concessions because sufficient is defined differently per concession(Bastiaanssen and Breedijk 2022).

Besides this major challenge a more nuanced reason can be found why a lack of public transportation within rural regions is a problem. Many trips from within the rural areas go towards urban areas were a desire exists to reduce car traffic for increased liveability (Nieuwenhuijsen and Khreis 2016). To reduce car traffic within the urban areas while keeping those areas accessible for people living outside active mobility distance of the urban areas must be accessible by public transportation from rural regions(Nieuwenhuijsen and Khreis 2016).

The lack of public transportation within rural regions is however a difficult problem to solve with traditional solutions. Increasing the frequency or network density will not be a viable solution to solve the problem

(Galarza Montenegro et al. 2024). Rural trips do have a low demand and diverse routing (CROW 2024). Therefore, a transport solution is difficult to solve by schedule-based services as currently dominating within public transportation (Galarza Montenegro et al. 2024). Alternatively, the currently present demand responsive transportation and ride-share services do require a (digital) reservation (long) in advance and are seldom part of the public transportation payment or route planning systems, which all create additional hurdles (Durand et al. 2021). Shared mobility is less expensive to operate but currently mostly on a for profit base, resulting in little to no shared mobility in low density areas which do have little profitability (Schilder et al. 2024). Ride-sharing services are cheap and may offer missing links between local villages and inter local bus services (Madani et al. 2022). Current fragmented implementation reduces impacts (Thao et al. 2021). Current schedule-based public transportation in rural regions is mostly financially unsustainable and above mentioned transportation options may offer a solution (CROW 2024). It is unknown how public mobility aspects may interact with each other and how they can improve each others functioning and the functioning of the public transportation system within rural regions. This makes it difficult to make educated decisions on the implementation.

This thesis examines public mobility. In this thesis, the term public mobility denotes all collective modes of transport that operate within a transport authority organised mobility network and is accessible to all users. The study aims to define which aspects of the public mobility spectrum are best suitable in a rural regions given the Spatial settlement typology, access and egress distances between inter local bus services and demographics. This will make future decisions about the accessibility of lower demand regions easier and show that a single aspect of the public mobility spectrum may have a different effect when synergizing with other options from the public mobility spectrum. By giving this insight the goal is to make the lower demand regions less prone to collateral transportation poverty due to uninformed decisions and keep car-reducing cities accessible from within rural areas.

1.2 Scope

This research focuses on introducing public mobility within rural areas where high quality inter local bus services are present on through roads. Not all rider-ship of the existing public transportation system is living within a walkable distance from the interlocal bus service stops. The research will only take the interlocal bus services into account as public transportation while connecting all other locations and times by means of public mobility. The existing system will be compared to public mobility configurations, in this manner the locations where public mobility is functioning better as the public transportation can be filtered out. CROW 2024).

The research will define multiple scenarios with different public mobility configurations for which the potential will be modelled. From the results of the scenarios a single scenerio will be investigated. No entire optimisation process will be completed. The results from the model will prove the potential of this scenarios public mobility configurations which can be compared to the existing situation and show the potential of different configurations.

1.3 Literature gap

Primarily the search engine Scopus is used(Scopus 2025). The applicable search terms are displayed in table 1. Only results that corresponded with the search terms in title, subtitle or abstract have been utilised. To have research about comparable locations the locations have first been limited to Europe but in cases to little results have been found also North-America is included.

Table 1: Search terms

Topic	Search term
DRT	(DRT OR (Demand AND responsive) OR (mobility AND on AND Demand) OR Micromobility OR (Request AND responsive) OR (on AND request) OR DART OR Demand responsive service OR (flexible AND transit)OR Micromobility) AND (Rural OR (Low AND (Demand OR Density)))
Ride-sharing	(Ride-sharing OR (Ride AND (Share OR Sharing)) OR Carpool OR Vanpool OR Slugging OR Mitfahrbank) AND (Rural OR (Low AND (Demand OR Density)))
Shared mobility	((Shared OR Common) AND (Mobility OR Transport OR Vehicle OR Bike OR Bicycle OR Scooter OR Car Or Micromobility OR Microcar)) AND (Rural OR (Low AND (Demand OR Density)))

After the results of the search terms have been utilised, backward snowballing is used to find well known literature which is generally cited and is well founded. However due to parts of the public mobility only having a relatively short research history also forward snowballing is used. This helps finding newer papers that are more recent and do have more chance of covering the desired topic.

Literature about different public mobility aspects is present. Depending on the aspect it is more focussed on rural or urban area's but combining different aspects is seldom done. in figure 1 a overview is given of the literature per combination and the lack of literature is clearly visible. For ride-sharing and demand responsive transportation literature is available for the rural setting or low demand area's. Shared mobility is described in literature mostly for urban environments, and to a lower degree in suburban settings and rural regions. Combination of all three main aspects nor the integration with public transport is described in literature. Combination of Ride-share and demand responsive transportation has limited research. For this research, the gap is found in the combination of public mobility aspects integrated in a public transportation system with the rural region.

It is unknown how the potential of public mobility can be improved by combining multiple aspects. Longer distances in rural regions create a more limited availability of literature. It is known what weaknesses and potential exists per public mobility type and how longer distances may affect this. However when all are implemented together a synergy may be formed as is known for the train-bicycle combination. The existence of this potential is unknown for rural areas.

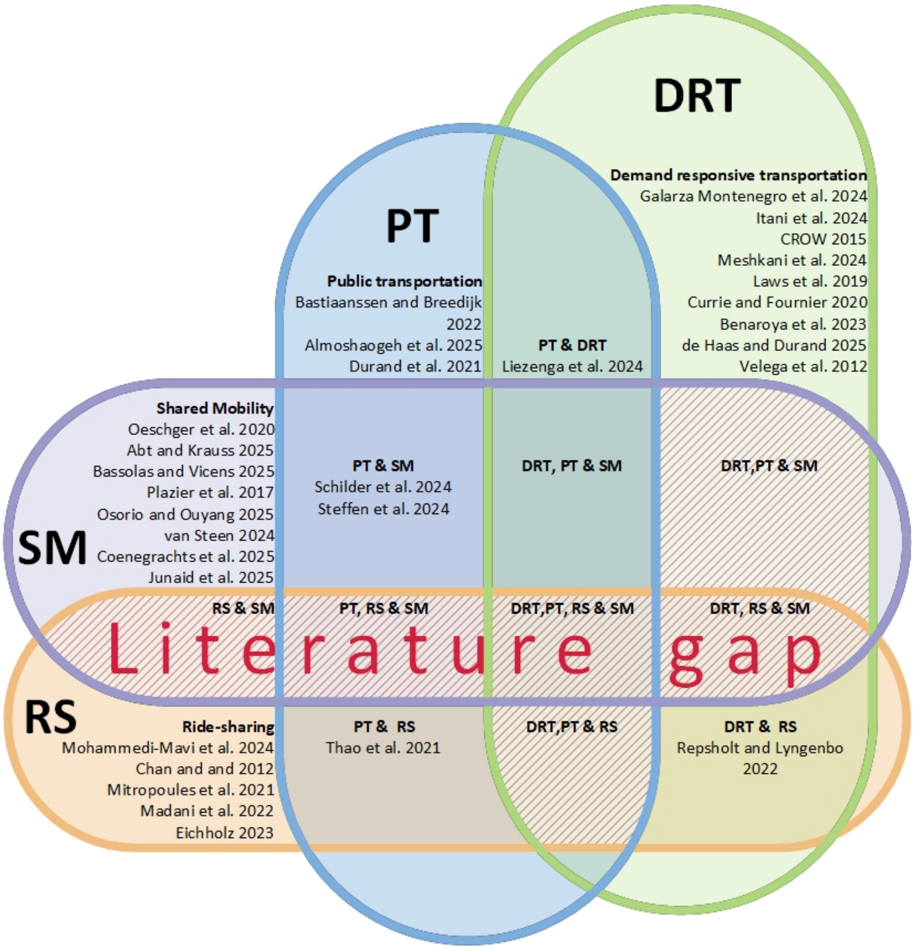


Figure 1: Venn diagram literature gap in rural regions

1.4 Research Question

To fulfil the aim mentioned in section 1.1 to explore how public mobility can improve rural non-private mobility by looking into the access and egress to high quality interregional bus services together with local movements within the rural region a research question is formulated. It seeks to determine when to apply specific aspects of the public mobility spectrum based on the spatial characteristics of the part of the rural region. From this, the main research question is formulated as:

Main research question

"How should public mobility be integrated into the public transportation system to improve the public transportation system?"

To study rural public mobility integration possibilities, two main options arise, modelling a potential system or a survey-based research. Both can predict a not-yet-existing system (Tordai et al. 2025;Kagho et al. 2020) The subject of this research is very important for a small group of people, everyone living within a rural region who are using non-private mobility, in an area where a conventional bus service is prone to discontinuation or has been suspended. To reach this small group of people with a survey is proved to be difficult. A study conducted by KIM on demand responsive services with a similar target group reached 34,000 respondents on recruitment questions, finally resulting in only 469 valid responses from people in the target group(de Haas and Durand 2025). Given this is a master thesis with less resources, the chance of reaching enough respondents for a survey to have any statistical certainty is limited. Therefore a model will be created. For most parts of the public mobility system, research is conducted, to some degree also within the rural region. To capture this knowledge the first two sub questions will be answered with a literature study aiming to give a insight in strengths and weaknesses and collect characteristics for modelling in the next phase. The first sub question will investigate the stationary part of public mobility, the node configurations while the second sub-question will investigate the dynamic part, of the system.

Sub question 1

"Which node configurations exist elsewhere for different public mobility aspects and which are best applied in rural regions according to literature?"

Sub question 2

"Which public mobility configurations are most promising to improve reachability within rural regions according to literature?"

When sub question one and two are answered. A limited list of promising public mobility aspects, the combinations of vehicle, driver, access type, node structure and operating tactic, is present. Based on this literature overview accompanied with the aspects specifications an educated hypothesis is formulated regarding when to use certain public mobility aspects.

Simultaneously data about the users and area is important. Not all public mobility aspects form a solution for all travellers and travellers are location depended. To include this, binary statistics will be collected with the percentage of people unable or unwilling to take a certain public mobility aspect or the ability to move physically for a given case area.

To model differences, in the system scenarios will be created to have a underlying framework that shows differences but is able to make a fair comparison. Scenario's are based on the availability of certain public mobility aspects while all other parts are kept constant. It however is important to know which scenario's should be taken into account. Therefore sub question three will define the different scenarios.

Sub question 3

"Which scenarios for fleet composition of public mobility aspects should be considered to model a public mobility given the geospatial indicators of the case area?"

With many scenarios created and modelled a insight is created in the impacts of the changing mode inventory. The differences must be analysed and the underlying relations why results may differ per location under given scenario's should be explained. This is done with subquestion 4.

Sub question 4

"To what extent can integrating public mobility into the public transportation system improve reachability within rural regions?"

1.5 Report outline

This report is structured as follows. Chapter 2 presents the literature review and answers sub-question 1: “Which node configurations exist elsewhere for different public mobility aspects and which are best applied in rural regions according to literature?” and sub-question 2: “Which public mobility configurations are most promising to improve reachability within rural regions according to literature?”. It provides insight into opportunities for public mobility in rural regions. Chapter 3 describes the model and explains the design choices and underlying reasoning. Chapter 4 motivates the selection of the case area, describes how the model is implemented, and outlines the data collection process. Chapter 5 presents and analyses the results. Finally, Chapter 6 provides the conclusions and recommendations. Chapter 7 discusses the findings, limitations, and recommendations.

2 Literature overview

Public mobility has a wide definition and different researches do consider different parts. This research does consider demand responsive transportation (DRT), ride-sharing and shared mobility as public mobility which should be integrated with the existing public transportation system (Oeschger et al. 2020). Due to the multitude of public mobility aspects and inherent transfers while making a trip the term hubs is often used instead of a bus stop. Due to this term being used for many different things, within this research the term node will be used when referring to locations where the public mobility system can be accessed or transferred to and from. Or more specificity as a point, stop or station as described in section 2.2. section 2.2 will explain the nodes the second part explains the network that connects the nodes.

2.1 Public mobility aspects within scope

The main considered aspects of public mobility consist of Demand responsive transportation (DRT), Shared mobility, ride-sharing, public transportation and specialized transport services for specific user groups. Within this thesis the focus is on the DRT, shared mobility and ride-sharing. Public transportation will be touched upon as the interlocal bus service will function as the backbone of public mobility but no special implication is used and will therefore be seen as a existing system that will be unchanged. Public transportation and specialized transport services for specific user groups are out of scope because these services are not accessible to all travellers. Within this section a explanation is given how different public mobility aspects function and what their strengths and weaknesses are.

2.1.1 Demand responsive transportation (DRT)

DRT is a transportation service which only drives when demanded by a passenger and will only pick up passenger(s) indicating to desire transportation. DRT is a formal service primarily consisting of 9-person minivans driven by professional and sometimes voluntary drivers who hold a licence and have had training for driving passengers. DRT is in most cases financially unsustainable, requiring high subsidies per traveller which makes DRT services expensive when the system is highly utilised (Laws et al. 2009; Currie and Fournier 2020). However, DRT services are promising within a small niche where a justifiable higher subsidy is accepted(Velaga et al. 2012). This may be areas where schedule-based transportation is too expensive or during only outside rush hour when demand drops. In areas where properly functioning public transportation is available, DRT is only financially sustainable when a strict target group is described and enforced to create a sustainable rider ship amount (de Haas and Durand 2025).

Lessons can be learned from kutsuplus in Finland (de Haas and Durand 2025). The transportation did know the high cost per passenger and did therefore not promote the service resulting in a small fraction of potential users knowing about the option. Simultaneously no explicit target group is defined nor is it enforced to restrict the DRT to routes without a existing bus connection. The result of this system was that many young higher income well informed travellers started using it as a private taxi service, while only paying public transportation fees and traversing routes where the normal bus would also drive. This improper usage oppressed the (target) group of people without alternative public transportation. Because the costs where capped no additional vehicles were purchased and the reliability decreased. Due to the lacking reliability and high costs, the service is terminated. (de Haas and Durand 2025)

Another example is the municipality of Innisfil, Canada. This village considered two options, a bus network with only three lines or a complete DRT service provided by Uber. Subsidy for a bus service is constant (neglecting inflation) while for DRT a subsidy per traveller is needed. The municipality decided for the DRT due to the low [initial, red.] costs. The DRT service became very well used resulting in a too high costs burden. To mitigate, the subsidy per trip went down and users are limited in the amount of subsidized trips. When more trips are desired the user can use Uber for commercial fare. Users who where dependent on the service are now unable to reach their destinations and people with lower income can not afford it any more.(Benaroya et al. 2023;Itani et al. 2024)

Both examples show how untargeted DRT systems shift out of balance and become financially unsustainable while providing a great travel solution for the users. To make the costs bearable most adaptations also harm the most vulnerable people (Meshkani et al. 2024). To prevent this from happening targeting is important. When travel-demand is too little, DRT subsidy per trip becomes too high, when travel demand is too high the absolute value of subsidy is deemed too high and (re)implementing scheduled services will reduce costs (Velaga et al. 2012). Additionally, when rider ship is low less enforcement on the target group will temporarily solve problems but long term decreases the systems viability. Half of the DRT initiatives are discontinued within seven years, mostly for financial reasons (Currie and Fournier 2020).

Currently in the Netherlands due to legal requirements DRT services may not compete with public transportation if it is not operated by the same company, it may only serve areas which are otherwise inaccessible(Ministerie van Infrastructuur en Waterstaat 2024). This limits the options of implementation and results in difficult checks if the requested DRT-trip is non-competing. Simultaneously this is a safety shield to prevent improper use because DRT is too expansive to operate parallel to public transportation(Currie and Fournier 2020).

Demand responsive services do have multiple common trade-offs. The system is both flexible for the passenger and the operator, but these flexibilities are negative correlated. When the advance time to reserve for the passenger is decreased the operator needs more vehicles because every vehicle can reach less access points still arriving "in time". Also, less trips can be combined. Increasing the advance time reduces flexibility of the user which may result in cancelled trips. Other parts of flexibility are the possibilities to reserve, this may be by phone, route planner application, own application or website. Every option costs money to sustain, but every option does create more travellers comfort. This amount of flexibility may be the difference for vulnerable people to be an active part of society or be left out (Bastiaanssen and Breedijk 2022). Besides the aforementioned trade-offs the complexity of the system is an important factor. (Currie and Fournier 2020)

2.1.2 Ride-sharing

Ride-sharing is defined as the act of a traveller joining a car driver for a ride within the driver's personal vehicle. Ride-sharing initiatives are currently focussed on suburban and rural areas. Multiple initiatives have been used as case study within literature for revealed and stated preference studies within rural regions(Thao et al. 2021;Madani et al. 2022). Some data analysis studies are available about the functioning of these systems(Eichholz 2023). This system has changing capacity over time, generally the predominant travel direction of motorists is the same as public transit users resulting in a automatic increase in capacity when intensity grows and reversed(Mitropoulos et al. 2021). A multitude of options are described in literature including application or bench based solutions(Repsholt and Lyngenbo 2022). Both are asserting solutions within rural regions. However, as literature points out bench based solutions are mostly functioning for short trips as access and egress towards a higher order public transportation service(Madani et al. 2022). Application based solutions are effective for longer trips but require a large base of participating drivers to function properly due to registration requisites and non registered drivers are overlooked. Safety may be a concern by participants which can be improved by requiring a certificate of conduct however this also makes it harder to register. Ride-sharing solutions thrive within suburban to rural areas. Ride-sharing can be divided into three basic groups: ad-hoc, acquaintance based and organisation-based. (Chan and and 2012)

Ad-Hoc ride-sharing can be seen as the most elementary form of ride-sharing. A passenger waits along the side of the road until a driver takes the passenger along based on good conscience. A ride is not guaranteed and the waiting time is unknown. Being an informal type of transportation does not limit governmental organisations to facilitate nor encourage this type of transportation. When the road has a high intensity, clear indication of the ride-share bench and desired destination with a available place to stop around 2% to 3% of drivers will stop to facili-

Figure 2: Ride-share bench indicating a desired ride to Hörstel (Own work, 2025)

tate a ride-share(Thao et al. 2021;Madani et al. 2022). An example of ad-hoc ride-sharing are ride-share benches, which are present in many locations throughout the German linguistic zone. Benches are placed beside main exit roads of rural villages. Next to the bench a pole is present on which limited locations in the extension of the road can be displayed indicating the desired destination of the passenger. The indicated locations are well known places, mostly neighbouring villages or bigger transportation stations. (Chan and and 2012)

Acquaintance based ride-sharing is driving along with a acquaintance, a family member or co-worker. In general the destination or origin of the driver and passenger is the same. People are mostly encouraged to do so by financial incentives of the employer or the social sense of obligation to prevent the mobility poverty of a acquaintance. This type of transportation can be facilitated by creating Kiss and ride zones or carpool parking.(Chan and and 2012)

Organisation-based ride-sharing is diverse. Depending on the platform passengers and drivers may be verified to increase trustworthiness(Mohammadi-Mavi et al. 2024). Depending on the platform both driver and passenger indicate origin, destination and time window, after which an algorithm matches the driver and passenger and communicates a pick-up time and location. This may be one of many predefined Points or another convenient deemed location (Eichholz 2023). Alternatively, the driver posts a ride on the platform and passengers can browse rides to select a desired one. Some organisation based systems are like ad-hoc systems but require passengers and drivers to register and verify identity to reduce road-side matching time due to increased trustworthiness. Also Ad-hoc options in which both hail-driver and passenger are registered exist. When ride-share is actively promoted and a village has a high social cohesion on average 11% of local car owners participating in a ride-sharing scheme is achievable with examples present of over 90% (Rezopouce 2024). Organisation base ride-sharing has the most viable ride-sharing examples.(Chan and and 2012)

2.1.3 Shared-mobility

Shared mobility consist of vehicles that are shared between users. Shared mobility can be divided by modality or by system. For this thesis interest is mainly into shared bicycle, shared e-bicycles, shared e-scooters, shared cars. Although other options as scooters(autopeds) are present, they are currently not deemed of important for this thesis. Shared mobility is a widely implemented type of transportation within urban areas. It excels in connecting transfer stations with destinations, and can therefore be found at many train stations(Junaid et al. 2025). Also within urban centres where a high demand and many destinations close-by exists(Schilder et al. 2024). Shared-mobility consists of a variety of different modes from bicycle to car or scooter. Shared mobility can make a profit under these circumstances, therefore many for-profit initiatives have risen and a wide variety of options is available. Due to the nature of for profit companies, the service is mostly available in financially feasible locations. Previous research however expressed the potential of shared mobility in rural regions(Junaid et al. 2025). This service could improve the catchment area of public transportation and generate more demand(Liezenga et al. 2024). Although limited studies for shared mobility into the bus-bicycle exist, train-bicycle and train-car combination also for lower demand regions are present(Schilder et al. 2024). Limited research has been conducted into sharing mobility in rural regions, while multiple examples of shared mobility in rural areas are present(van Steen 2024).

2.2 Nodes

For this research the functioning is important while the design is less so, therefore from technical perspective a limited comparison and categorisation will be made based on the transfer time between public mobility aspects, costs and comfort. Because comfort is a difficult scale to compare, the public transportation stop vision of the province of South Holland will be used, indicating a basic, comfort or luxurious level (Zuid-Holland 2022). While not being a complete grading system it will give a clear indicator.

2.2.1 Points and stops

Points have little to no infrastructural needs, The only necessity is communication about the location, digital and/or signposted to make them easily recognisable (Meshkani et al. 2024). This makes it possible to create many Points for low investment costs. When a point has more facilities as a signpost or bicycle rack it will be a subcategory refereed to as a Stop. The functioning is the same but the travellers comfort is higher like the financial expenditure to create one. This distinguish will only be made in chapters with a focus on financial or comfort aspects and otherwise just be refereed to as Point.

For indicating purposes in figure 3 multiple examples are given of Points. Figure 3a is a existing bus stop without any facilities and therefore classified as a Point. It is only used for a local bus service but it has all facilities to also be used for a DRT service or ride-share drop-off. Figure 3b is a Share point, created on a existing parking spot by placing a signpost. It could also facilitate all public mobility aspects of figure 3a. The last figure, figure 3c shows a Meet-up point, Given the Sheffield racks, signpost, bench and stopping bay it can also facilitates all aforementioned public mobility aspects. Because a Meet-up point attracts people from further away it is therefore desired to also facilitate two-wheeled private- or shared-mobility parking. Given the stopping bay it is categorised as Stop

(a) Local bus and possibly, neighbourhood bus and DRT(van Opstal 2018)

(b) Shared mobility and possibly, Local/neighbourhood bus and DRT

(c) Ride-share and possibly, shared mobility, DRT and local/neighbourhood bus (own work)

Figure 3: Various appearances of Points and a Stop between brackets the shared mobility aspects that could also stop at the displayed Point

For this research all Points will be a combination of a Share point and Embarkation point and possibly also a Meet-up point. Given the amount of Share points this will result in not all Points always having (all) shared mobility options available but can always be used for a termination of a shared mobility trip. For a Meet-up point a busy through road is desired because otherwise it will not properly function due to lack of supply (Thao et al. 2021). Therefore only limited Points will be Meet-up points. Due to the need of a safe stopping space for a Meet-up point it can most times be categorised as a Stop. A bus can also use a point when less as 100 persons embark during a working day (or 50 if the point is outside the built-up area)(Zuid-Holland 2022). Otherwise a shelter is needed and the Point will become a Stop (Zuid-Holland 2022).

Because every Point is a Share point the location choice is best (close to) a existing parking facility to avoid additional costs for infrastructural adaptations or returned vehicles in a bothersome spot. When a point has no clear boundary vehicles will be placed all around, when there is a clear boundary people tend to place the vehicles inside but when becoming filled the vehicles will easily be placed outside the point. A fence around a spot can creates the clear distinction where to place the shared mobility vehicle, but also creates a possibility to place anything against the (outside) of the fence resulting in undesired placed vehicles. Better alternatives are points surrounded by little bushes to keep vehicles within the area and avoid vehicles parked just outside the point. A Meet-up point does require a clear signpost for drivers passing by to understand a desired ride and the destination. Simultaneously a bench is desired due to the inherent waiting time with ride-sharing.

2.2.2 Station

Stations come in different forms and sizes even though all individual parts of stations tend to be standardised (Zuid-Holland 2022). Nearly no entire duplicates exists due to different local situations therefore three categories have been defined for this research, compact, average and scattered station (CROW 2023). Transfer times between bus and access or egress mode greatly differ due to different designs(Zuid-Holland 2012). Interregional bus service stops are generally located along a through road near a side road to improve the catchment area. Different designs place the stops at different locations but the handbook design criteria roads of the provincial South-Holland states a preference for a stop behind the intersection (Zuid-Holland 2012). This is a safer design but increases the travel time for public transportation users (CROW 2024). Anyone who uses the stops will always walk the distance in between both stops for every round trip. Given this distance is not unusual to be 300 metre this will increase daily commute time with nearly 3 minutes compared to a concentrated design with 50 metre in between. Simultaneously physically challenged people also need to traverse this distance making the system less inclusive.

(a) Compact Station **(b)** Spread Station **(c)** Scattered Station

Figure 4: Various appearances of Stations, light blue is the direct route, medium blue is the extension to walk along a bicycle shed and dark blue is the extension to walk along a safe stopping location if present. (Google 2025)

To use a objective transfer distance at stations the existing bus stops under control of the province South-Holland are used as a reference. Of all 695 bus stops within South-Holland's areal, 157 pairs exist with a interregional bus connection of which 42 are located within the rural area (Zuid-Holland 2022). For all 42 stations the distance in between both stops, direct, via the closest bicycle-rack and via the closest safe pick-up/drop-off place. These distances are the distances a commuter by DRT, bicycle / shared mobility or ride-share will need to walk on a round trip. To have a average transfer distance half of this distance between one and the other stop will be used as a single transfer distance for these modes shown in table 2. Based on the values found displayed in figure 5, three categories are created; compact stations, spread stations and scattered stations. The functions and facilities between the categories are exactly the same but due to geometric design choices the transfer distances are different. When plotting all distances cumulative a clear group with average distances of 180 to 190 metre is visible, this group will be referred to as the spread station group. another clear group can be found with distances in the range of 70 to 90 metre, the compact station group. Simultaneously many different distances are present to bundle groups with similar characteristics and the average of the group close to a frequent occurring distance three groups are created, compact bellow 130[m], spread 130 to 200 metre and scattered everything above 200 metre. Within the compact group multiple stations exist with the stops close together but fail to have connecting facilities close by creating on average very similar distances. within the spread group normally the shortest path between both stops is along both a safe stopping space and a bicycle shed making the values within this group very uniform. The scattered stations are a outside category with all values outside the 95 percentile reaching direct distances of 400 metre. Most scattered stations have stops at a distance from a intersection, mostly roundabouts at opposing exit lanes or opposing each other with only a distant crossing possibility.

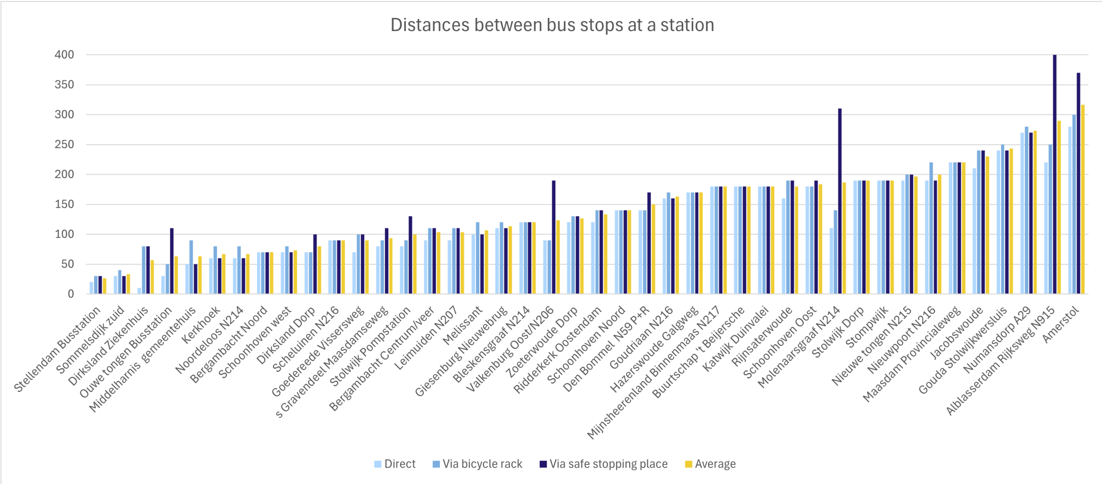


Figure 5: Distances between bus stops

For the aforementioned hub categories the relevant statistics are shown in table 2. The facilities are the criteria with which nodes can be distinguished and costs are calculated. The transfer distance are averages from measurements of satellite images of all rural inter regional bus stations present within rural regions in the province of South Holland. The costs mentioned are the purchase costs of station facilities and installation of the facilities and cables, the costs exclude the ground acquisition. When facilities are existing the costs are not applicable.

Table 2: Statistics of hub categories (Zuid-Holland 2022)

	Facilities						**Transfer[m]**				
Type	**Signpost**	**Bench**	**Shelter**	**DRIS**	**Two wheeled vehicles parking**	**Car parking**	**DRT** 1/2dist between stops	**Shared-mobility** 1/2dist between stops via bicycle shed	**Ride-share** to safe drop-off	**Cost [€×1000]** purchase & installation	**Comfort**
Point	yes	no	no	no	rack	no	n.a.	2	2	1	Minimal
Stop	yes	yes	single side of road	unlikely	rack/ shed	no	n.a.	2	2	20	basic/ comfort
Compact Station	yes	yes	yes	yes	shed	maybe	36	44	47	50	comfort/ luxe
Spread station	yes	yes	yes	yes	shed	maybe	82	85	93	50	comfort/ luxe
Scattered Station	yes	yes	yes	yes	shed	maybe	116	126	138	50	comfort/ luxe

2.3 Public Mobility classification

The different main concepts of public mobility are described in sections 2.1.1, 2.1.2 and 2.1.3 but all concepts can be adapted to many different forms, therefore on the levels of vehicles used, driver of the vehicle, access type, the system structure and operation tactics a split will be made. while for some levels the choice may be evident given the public mobility concept used the difference can be on a different level. in the end of this section a classification system will be shown based in these levels in which every part of the public mobility spectrum can be pointed out. This chapter will show the possible choices, the success factors of these choices and choices that result in unstable solutions which will be pointed out and should be avoided if possible.

2.3.1 Driver Professionalisation

Public mobility has different types of drivers the main difference can be made in professionalisation. A paid driver accounts for approximately half the operation cost of public transportation and therefore it can have major financial benefits when introducing a voluntary driver, hail drivers or let the vehicle be driven by the user itself (Benaroya et al. 2023). The earned wage for a professional driver is different per vehicle because a different collective labour agreement (CLA) exists. A single fte for a bus driver has annual costs of €60,000 to €65,000 with 950 to 1250 SSH (KNV 2024a;CROW 2021). resulting in €48 to €68 per scheduled service hour. the cost of a taxi driver are 27% lower resulting in €36 to €50 per scheduled service hour (KNV 2024a;KNV 2024b). This costs difference can be a incentive to not let a bus driver drive a van or car making the drivers less interoperable between modes (CROW 2015). In general drivers in the Netherlands drive for at least 2 hours due to the limitations of the CLA a bus driver must be paid for at least 2 hours resulting in a impossibility to scale up during the peak of the rush hour(KNV 2024a). A voluntary driver is not free either a single neighbourhood service club normally receives a set amount per year for the entire pool of volunteers which accounts for around €0,60 per scheduled service hour(CROW 2015). Hail drivers, autonomous vehicles and self-driving are solutions without driver loan which greatly reduce costs. Hail-drivers may be compensated depending on the system in which it is desired to operate and autonomous vehicles will have higher purchase and maintenance costs.

Simultaneously budget cuts can only be realised if the vehicle may be driven by all driver options. A bus may only be driven by a professional driver with special licence for whom it is expected to have a more advanced capability of handling difficult passengers or unexpected situations(Ministerie van Infrastructuur en Waterstaat 2024). Voluntary drivers in most cases will also receive a (limited) training on passenger handling and traffic operation (Ministerie van Infrastructuur en Waterstaat 2024). Voluntary drivers typically operate on low-demand routes and only during daytime hours, particularly in areas where incidents with travellers are unlikely. While voluntary drivers are not paid, making the service inexpensive, it is more difficult to maintain driver commitment due to the lack of financial incentives for the driver. While examples exists of real-life tests with autonomous driving buses this is still not a applicable solution although promising (Benjamin 2025). The driver may also bear liability or the transport authority may incur extra insurance costs. Because no paid driver is involved, the cost of this solution is relatively low for the transport authority. Hail drivers do not receive any training and also there are no checks of driving capability, only with organisation-based ride-sharing hail drivers may need to have some checks on driving or conduct of behaviour. Although checks are desirable from governmental and user perspective they may be felt as difficult for the hail driver(Thao et al. 2021). Because a hail driver normally only participates based on altruism, additional requirements may result in a lack of interest to participate in the scheme(Thao et al. 2021). This may result on a lack of rides and an ill functioning system. Also voluntary drivers operate vehicles out of personal interest, such as a passion for the vehicle or social involvement(CROW 2015). If a volunteer is dissatisfied with the operation, they may resign.

The best use for professional drivers is on buses and touring cars which may only be driven by a professional and on routes where a higher level of service or authority is necessary or the cost can be redeemed. Redeeming the loan cost is only possible with, depending on the route, on average 15 passengers paying public transportation fares or a higher fare. In rural regions it is difficult to reach this many passengers on average and with a different vehicle as a bus it is impossible to have enough ridership. Only a inter regional bus services or rush hour service can reach this. The other reason to choose for a professional driver is when higher service level is needed and the costs are justifiable with clients known to be physically challenged.Bastiaanssen and Breedijk 2022;Durand et al. 2021)

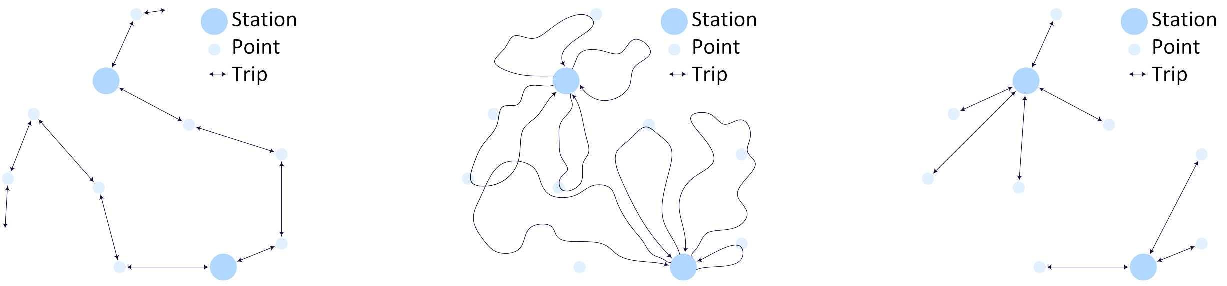
Self-driving refers to renting a vehicle and operating it personally. This requires a valid driving licence for the specific vehicle, which may exclude certain population groups.

2.3.2 Operating tactics

Operating tactics are especially important for cost containment and user satisfaction. The higher the costs or chance of financial instability the more important choosing the right approach is. Simultaneously the ease of use may deteriorate based on operating tactics. In rural regions it is extra important to review the operating tactics due to the low density and therefore bigger distances and higher costs associated with any trip. Different operating tactics can significantly influence service quality and efficiency.

A one-to-one system is visualised in figure 6b. A vehicles is picked up and returned to the same location. This offers simplicity and predictability. Especially when points are further apart like in rural areas, this setup works simple for the operator: it eliminates the need for vehicle balancing and gives full control over the number of vehicles at each Share point. For vehicles with a battery, this predictability allows for easier planning of battery swaps or optimized placement of docking points. However, the downside is limited flexibility, users can only return the vehicle to the starting Share point, which can be inconvenient for one-way trips and as long as the user is on the destination the vehicle is parked. This reduces the efficiency of the service. The traveller however will be sure that it still has a vehicle when it wants to return from the destination and may therefore appreciate this type of service. For ride-sharing and DRT this will not function as this will not supply a trip. However with a one-to-many tactic for all passengers in a DRT system the vehicle will drive a one-to-one service as it will drop-off and pick-up passengers en-route. This result in a enormous cost reduction for the operator.

Many to one service are unipolar services that at one end are fixed to a predefined location or Station, usually a Transfer station. At the other end many Points exists spread out within the catchment area of the Station. Many-to-few services are multipolar and drive between limited stations and many points. Both systems are similar but a few-to-many system will have more empty trips as a DRT vehicle is more likely to be waiting at a different station as a requested trip due to less bundling(Currie and Fournier 2020;Galarza Montenegro et al. 2024). An example can be found in the ”Vlinder” service. This service is present at a Transfer station when the inter local bus service arrives. It only drives to the destinations requested by the transferring passengers. Towards the Transfer station passengers need to reserve short time in advance. Shared mobility in a one to many system is likely to have limited balancing manoeuvres because all vehicles will likely be moving back towards the same Station. Within a few-to-many system more balancing will be needed as now not all vehicles are limited to the same island and can move outside of the catchment area of a Station. When to little vehicles are left in a Stations catchment area they need to be relocated here from different places. When many-to-one or many-to-few services are implemented, the system is kept relatively simple which make the system more resilient. Both help create a clear Transfer station and the Interlocal bus service system may have less stops achieving higher commercial speeds. Due to limited transfer stations it is easier to link a DRT service to the timetable of the scheduled service and require a shorter or no advance reservation time from the Transfer station side. Simultaneously a indication about the arrival time at the pick-up station can be given, because the vehicle needs to be back at the Transfer station to connect to the bus. Besides the operating benefits simplicity can also add to a system, for example with a bench-based ride-sharing system only a few points should be present with limited directions to improve predictability for both hail-driver and passenger to increase the effectiveness of the system.

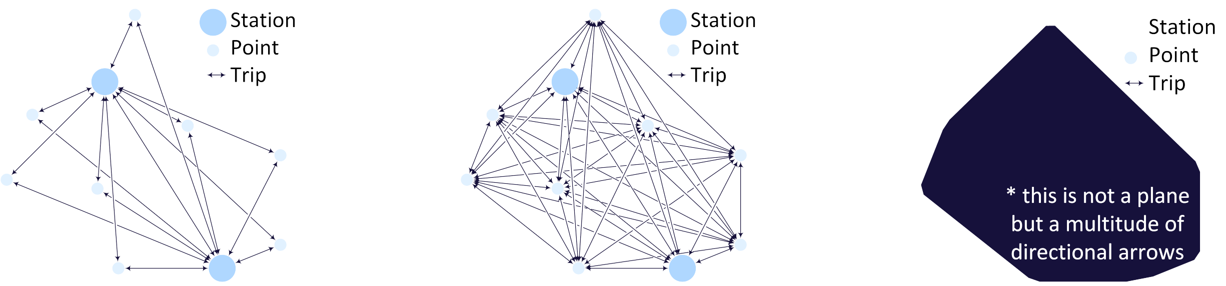


(a) Line tactic **(b)** One-to-One tactic **(c)** Many-to-One Tactic

Figure 6: Simple operating tactics)

Shared mobility benefits from a many-to-one/few tactic, ensuring every vehicle to often go along a Station allowing maintenance and electric infrastructure to be concentrated only at the Stations. Creating a moment in which it is possible to deactivate low battery or faulty vehicles for charging or maintenance. Especially in rural regions with longer distances the batteries empty out faster and battery swapping staff will encounter less swaps per kilometre if they need to drive along all points but when this is reduced to all stations effectiveness increases. This can result in important cost reductions while still having an abundant choice of destinations from any station(Abt and Krauss 2025).

Many to many or all to all services allow the user to make a trip from any Point or all locations to any Point or all locations. These systems provide the highest flexibility, allowing vehicles to move freely between any locations. While attractive for users, this model becomes very complex and costly to operate in rural regions. With DRT a near taxi service will be created with a small chance the vehicle needs to detour to pick-up another passenger. The example of Innisfill which is all to all within a defined zone has only 5% of the trips being shared with a unknown passenger (Benaroya et al. 2023). For shared mobility unlike urban areas where Share point density is high and balancing is easier, rural distances make rebalancing more time consuming and expensive(Schilder et al. 2024). For vehicles with a battery, charging infrastructure would have to be widespread, which is often not feasible(Bassolas and Vicens 2025;Curtale et al. 2021). In ride-sharing setups, this model also struggles, starting a ride anywhere along a route may not align with drivers willingness to detour, especially if there's no clear Embarkation point (Thao et al. 2021). As a result, while offering maximum user freedom, this model is often impractical for trip suppliers without significant investment or operational compromises(Currie and Fournier 2020; Madani et al. 2022). Simultaneously a desire for short trips which not necessary go outside of the region exists. For these trips it is very impractical to go along a Transfer station because it forms a major detour. To be able to supply shorter direct trips it is important to have more robust vehicles that do not need frequent interaction(Plazier et al. 2017). Therefore, a conventional bicycle can be used in this kind of operation (Plazier et al. 2017). Also when a bicycle is less efficiently used it is financially still more efficient due to lower vehicle value.



(a) Many-to-Few tactic **(b)** Many-to-Many tactic **(c)** All-to-All Tactic

Figure 7: Complicated operating tactics)

2.3.3 Access type

To access the system a Schedule based service is the easiest and in general is most liked by the users (de Haas and Durand 2025). A schedule based service is a service that will always be available at predefined times regardless of demand. This is aplicable to most buses but in some cases ride-shares may also follow a time table.

The alternative to schedule based service is a trip on request. this can be by phone or by application. This does create a additional hurdle and may result in digital illiterate people or otherwise obstructed persons to be unable to participate in society(Durand et al. 2021). A example can be found in ANWB Automaatje which targets older people under whom digital illiteracy is high this problem is solved by creating additional capacity for phone cal reservations.

2.3.4 System Structure

The system structure describes how the stops are structured. The more difficult it is to create a system within an existing civilised area the less omnipresent the stops will be. If no need for any adaptions exist to function the system can be ubiquitous. But not all systems are able to properly function without adaptions to the infrastructure. The differences in structure are depicted in figure 8 although this are different implementations of a shared mobility system, it could also have been a map of possible embarkation points.

(a) The Hague, Free floating **(b)** Zwolle, hybrid **(c)** Groningen, Station based

Figure 8: Different types of shared mobility systems with Felyx shared scooters in different cities. Rental periods may only be terminated within the circumscribed areas (in Groningen very small, mainly seen as dots). All images on the same scale. (Felyx 2025)

With **free-floating systems**, a trip can be started from any location to any desired destination within the providers service area where no limitations exist. This is possible because no adaptations to the infrastructure needs to be implemented for this system structuring. This is a system applicable for shared-mobility and DRT. With free-floating shared mobility, the user is trusted to leave the vehicle at a suitable location, however not all users do so, sometimes creating undesired situations with “parked” vehicles blocking other road users(Junaid et al. 2025). Examples of purely free-floating systems are therefore reducing due to municipalities taking action to keep vehicles out of undesired locations(Coenegrachts et al. 2025). A example can be seen of this gradual reduction in figure 8a, A free-floating system with limitations. In DRT-systems a free-floating system is normally referred to as door-to-door or curb-to-curb meaning that a pick-up and drop-off can be ordered at any desired location that can be communicated(Currie and Fournier 2020). A free-floating system creates a all-to-all operation tactic as a result, together with the high associated costs and travellers satisfaction described in section 2.1.1.

Node-based systems are the most common systems in public mobility, travellers expect a bus or DRT to stop at a bus stop or park a vehicle in a parking place or rack. When this is not the case the system is different as the expectations and creates perceived uncertainty (Durand et al. 2021;Bastiaanssen and Breedijk 2022). For this reason station and point based systems do have benefits even though restricting the users in their movements. To utilise these benefits it is important to have the predefined locations recognisable both digitally as in the real world (Durand et al. 2021). Shared mobility point based systems have predefined Points where a shared-mobility vehicle can be taken or left. Outside these locations it is possible to stop and park but the rental period can not be terminated. With most systems it is allowed to return the vehicle at a different collection point like "Donkey republic" but some systems do not allow this like "Leen scootmobiel Almere" or only for a fee like "OVfiets" (Donkey Republic 2025)(Stichting Buurthopper Almere 2025)(NS 2025). For DRT and ride-share systems Points function as a start location for the trip and for DRT also as a trip destination (Currie and Fournier 2020). By having a point based system recognisable in the real world the user feels more certainty about the trip being successfully compared to a in advance communicated start point (de Haas and Durand 2025;Laws et al. 2009;Velaga et al. 2012). Additionally with point based systems users can be forced to start a trip from a more easily reachable location creating higher efficiency within a system (Currie and Fournier 2020). Point-based systems may be nearly unrecognisable for non-users in the streetscape while users should be able to recognise the location. While points can be created with geofencing to maker it findable a confirmation in the streetscape is preferred. Facilities that may be present at a point are a signpost or a bench to wait but no infrastructural adaptions to the road itself. Station-based system however do have infrastructural adaptions with for example a bus bay to allow larger vehicles to stop without hindering other traffic or a physical docking station for parking shared mobility vehicles. A more indept differentiation between points and stations and how they will be used within this research can be found in chapter 2.2.2.

Hybrid systems are in between Free-floating and point based options. Termination areas are created which in general consist of geo-fenced areas and not only designated spots. Hybrid systems however may also have designated spots along with areas where the user may determine a suitable place. (Oeschger et al. 2020)

2.3.5 Vehicles

Differences between vehicles make certain uses more desirable than others. Therefore, in Table 3, multiple criteria on which the vehicles can be categorised are shown. In addition to the table, the strengths and weaknesses of each vehicle are described.

Table 3: Vehicles used within public mobility

Public mobility aspect	Velocity km/h[1]	Capacity [pers.][1]	Wheelchair accessibility[2]	License required[1]	Rain affected	Wind affected	Physical effort[4]	Manoeuvrability[4]	Ground space [m2]	Purchase cost [€ ×1000] Average +- 10%	Vehicle cost*** [€/km] Average +- 7%	Driver cost [€/SSH] Average +- 18%
Touring car	100	60	med.	no	no	no	no	low	30[5]	500[11]	3.20[11]	58[11]
Bus 12[m]	80	80	good	no	no	no	no	low	30[5]	500[11]	2.90[11]	58[11]
Van	130	8	good	no	no	no	no	med.	13.8[6]	60[6]	1.00[12]	43[6]
Car	130	5	low	B	no	no	no	med.	7.5[7]	15	0.96[12]	43[6]
Microcar	45	2	low	AM	no	no	no	med.	1.74[8]	12	0.93	n.a.
Cabin scooter	25	2	low	no[3]	no	no	no	high	2.5[9]	8	1.00	n.a.
Scooter 45km/h	45	2	n.a.	AM	yes	no	no	med.	1.24[10]	3	1.00[12]	n.a.
Scooter 25km/h	25	2	n.a.	AM	yes	no	no	high**	1.24[10]	2.5	1.00[12]	n.a.
E-bicycle	25	1	n.a.	no	yes	little	little	high	0.8[10]	1.75	0.95	n.a.
Bicycle	15.8*	1	n.a.	no	yes	yes	yes	high	0.8[10]	0.8	0.69[12]	n.a.

* Velocity is person dependent, ** Only if electric, otherwise not allowed on non mandatory bicycle lanes, *** All cost excluding wage, Cost are always case dependent.

[1]:RDW 2025, [2]:Almoshaogeh et al. 2025, [3]:Rijksoverheid 2025a, [4]:Rijksoverheid 2025b, [5]:CROW 2024, [6]:CROW 2015, [7]:Niroomand et al. 2021, [8]:Biro 2025, [9]:SWOV 2021, [10]:CROW 2023, [11]:CROW 2021, [12]:Abt and Krauss 2025

2.3.5.1 Traditional public transport operated vehicles

Touring cars and urban buses are best used in a scheduled service due to the need for higher passenger numbers for a financially feasible operation. Both vehicles must be operated by a professional driver with a special licence, which makes operational costs high. These costs should be compensated with higher ridership, which is possible due to the larger capacity of the vehicle. A bus is built to be easily accessible with level boarding with easy access for accommodate wheelchairs, although sometimes with a movable footboard that is manually deployed by the driver. A touring car is build for higher speed and has a higher floor level which makes it less accessible and wheelchair users must make use of a stairlift if present or are unable to make use of the service. Due to the design for higher speed a touring car may go 100 km/h instead of 80km/h like a normal bus. To achieve this every passenger must be seated and use a belt. This reduces capacity. The only reason to make use of a touring car is when the bus traverses a longer stretch with a velocity limit above 80 km/h and a significant time reduction can be obtained. Buses are not ideal with low passenger numbers, which may make them redundant during hours with low demand.

Buses excel in higher demand routes and can move people relatively fast. The flaw of a bus is that it only stops at bus stops and more bus stops reduces commercial speed. The result is access and egress time which depending on the distance may be a significant part of the journey time (Oeschger et al. 2020)

A Van may be driven by any person with a car driving licence (RDW 2025). Therefore, the driver may be a taxi driver or even a volunteer(de Haas and Durand 2025). This makes the absolute running cost lower as a bus and therefore a logical solution when demand diminishes. Due to the low requirements for the driver, it is an optimal vehicle for neighbourhood services which use voluntary drivers. It is also used for demand-driven transportation services because it can easily access all areas. For transporting physically challenged people, this is also the most used option. Due to its size, it is possible to transport wheelchairs, with limited travellers it is possible to make detours for each passenger while remaining relatively fast for others. Depending on the vehicle, it may have level boarding halfway through or a manually operable door with stairs at the front. Because of the higher speed, seatbelts are mandatory. Due to the limited number of passengers when a paid driver is present this is a very expansive vehicle to operate. Even when all costs are conservative estimated with €36,- an hour with €0.80 per kilometre (CROW 2015). The cost can be redeemed by the PT fare price of €1,13 + €0.161 per kilometre with a full van but whenever a single seat is unoccupied or the average trip length of passengers is longer this vehicle will loose money (Qbuzz 2025). An example for the use of a van is DRT. DRT has a average occupation of 1 to 1.4 passengers per trip, With growing ridership the occupation normally does not improve (de Haas and Durand 2025). This number still excludes all the waiting time of the vehicle which must also be paid for(de Haas and Durand 2025). As a result DRT services cost about €22,- to €88,- per passenger for the transport authority where regular public transportation averages out around €0,70(de Haas and Durand 2025). Another use of a van is to resupply electric shared mobility vehicles with full batteries, particularly in systems without docking stations(Bassolas and Vicens 2025). The vehicle is the same but a variant without seats is normally used. Multiple examples are present where a public transportation van is also used for good transportation depending on the time of day. Due to its size, malfunctioning micromobility vehicles and spare parts can also be transported (Bassolas and Vicens 2025).

A van should only be used within areas where a normal bus can not drive due to size restraint or low ridership (which must never increase above 8) (de Haas and Durand 2025). When a scheduled service is not sustainable any more a DRT service should be implemented with special attention to nudge people into using alternatives while still operating the DRT-service as a complete PT-service(Steffen et al. 2024).

Figure 9: DRT service operated in a van

A car has within public mobility multiple purposes. It can be used for demand-responsive transportation. Due to the low number of trips, it is expensive to have a vehicle on standby all day, so the service is often outsourced to local taxi companies. When it is known that the passenger has no mobility limitations, it is not uncommon to transport them by car instead of a van.(de Haas and Durand 2025) Another use case is shared mobility. Due to its size, the car excels in transporting baggage or goods, ranging from groceries to luggage for an entire holiday. The car has very good infrastructure access and can reach destinations quickly. The downside of a car in shared mobility is its size. It may be difficult to park, and a proper spot must be found. Shared cars are mostly available as one-to-one services. As a result, when rented out, the car will be unused for a while. Often, the user is responsible for refuelling the car, resulting in little operational cost for the provider. Statistics show that time spent in the car is often perceived as lost time, resulting in a desire to minimise it(Plazier et al. 2017).

The best location for car-sharing is within area's people do barely need a car and therefore will not own one but take the occasional trip with a shared car. These can be found within areas where all facilities are in close proximity and easily reachable with active mobility or public transportation. Generally spoken very urbanised areas and not the rural regions. Within rural regions the group of people who occasional needs a car but do not own one is small, because the costs for a car in rural regions are normally lower due to a lack of parking regulations and fees and people who need one will therefore easily opt to buy one resulting in a high car ownership (KiM 2024).

2.3.5.2 Electric battery powered vehicles

E-vehicles have the advantage of requiring no physical effort(Pasha et al. 2024). This can attract people who are unable or unwilling to engage in physical activity. The distance these vehicles can cover depends on the battery range (Bassolas and Vicens 2025). During acquisition, this is an important factor to take into account: what will be the expected trip length, and how often is it acceptable for the vehicle to require charging at a docking station or a labour-intensive battery swap(Pasha et al. 2024;Osorio and Ouyang 2025;Bassolas and Vicens 2025). E-vehicles are also relative to human power less affected by external conditions like wind.

Figure 10: Car operated as demand responsive transportation (Reizen Door Zeeland 2025)

A electric microcar looks like a car but is legally classified as a moped(RDW 2025). A moped driving licence is sufficient to operate this vehicle (RDW 2025). The benefit of a microcar is its limited size, it easily fits in most places and when a spot is needed for a Embarkation point, it may be much smaller as for a car. Typically, two or three microcars can fit in the space of a single car (Biro 2025). Due to the design of a car the vehicles may be confused with a car and surrounding vehicles may anticipate different behaviour which can lead to accidents (SWOV 2021). Due to the maximum weight of 350[kg] the vehicle has minimum safety features making the vehicle less crash resistant(SWOV 2021). These vehicles excel as shared mobility solutions in very dense (historic) urban areas where normal cars are too large to pass through and speed limits normally are below the maximum velocity capability of the microcar(SWOV 2021). While currently more microcar sharing emerges it is also a long present options in shared mobility with the "Witkar" operating in Amsterdam from 1974 until 1986 (Bendixson and Richards 1976). When the evolution between current systems and the "Witkar" are investigated it is important to note that currently the application based systems are seen as the only possibility to rent out vehicles in a many-to-many systems(Eichholz 2023). The existence of the "Witkar" proves also physical systems can function (Bendixson and Richards 1976). A physical system may be a better functioning system for digital illiterate people (Bastiaanssen and Breedijk 2022).

Figure 11: Former shared microcar system in Rotterdam (Rotterdam 2019)

The best place to introduce a microcar is within the urbanised area. Cities that are introducing GOW30 are the perfect location as the vehicle will be able to drive the maximum allowable speed on all roads. Within the rural region The maximum speed of 45 km/h is a major downside as the vehicle is only allowed on the car lane where other traffic usually has a speed limit of 50 km/h in the build-up area and 60 km/h outside. Here it forms a hazard for occupants and other road users as a unexpected moving speed reduction.

Electric scooters are general used for their higher speed combined with manoeuvrability within congested areas. Due to the size a scooter has the possibility to move through narrow spaces often bypassing traffic queue's and stopping close to any desired location. This all improves average velocity and is often the reason behind the popularity in use for delivery services. Within the public mobility domain scooters are used as shared mobility where they excel in the urban areas and commuting between suburbs and centre. Because a scooter has a faster (45 km/h) and slower (25km/h) variant the uses are slightly different. Both will be found within the core of the city but the faster variant will generally move further to the edge of the urban zone (Coenegrachts et al. 2025). The higher speed is less useful within the short inner-city trips where road design is less accommodating for higher speeds compared to longer commuting trips where the maximum velocity of 45km/h can more often be reached. The faster scooters have the advantage of a higher speed but are not allowed on cycling infrastructure, which limits their flexibility. In built-up areas, many cycling paths run parallel to roads. In rural areas, there are many provincial roads and recreational cycling paths, but both do not permit 45 km/h scooters. This restricts their freedom of movement. Simultaneously, the 25 km/h variant, when electric, is allowed on recreational cycle paths(RDW 2025). Providing greater flexibility creating a location based trade-off. A different look on scooters is the governmental aim of more physical exercise for inhabitants. The differences between a slower scooter and electric bicycle are minimal therefore a case can be made of choosing to supply a e-bicycle and not a slower scooter.

The best place to introduce scooters is in or connected to congested places where distances are longer and normal cycling is not a great solution.

Figure 12: Shared scooter (Felyx 2025)

A electric cabin scooter is a small vehicle classified as a mobility scooter but depending on the model looks like a car. The vehicle is designed for handicapped people but may be used by other users. The vehicle offers major benefits, anyone above 15 is allowed to drive the vehicle without a licence (Rijksoverheid 2025a). It may be used anywhere a pedestrian is allowed to walk This makes the vehicle highly versatile (Rijksoverheid 2025a). It is compact but generally accommodates two people or one person with luggage. The maximum capable speed by law is 45km/h but no cabin scooters currently exist with a maximum velocity above 25 km/h Simultaneously higher speeds may be undesired due to the limited amount of safety features it possess. The vehicle is comparably placed in the public mobility spectrum as an electric bicycle or slower moped, but due to the car-like design, the driver is fully shielded from external conditions, such as wind, rain, or cold. Due to the maximum width of 1.10[m] the vehicle can clearly be distinguished by other road users to not be a normal car and is more easily overtaken resulting in less dangerous situations(SWOV 2021).

These vehicles may be used in shared mobility systems because they excel in terms of equity, as the vehicles are accessible to nearly everyone and are better whether against outside conditions as most other shared mobility options.

Figure 13: Cabin scooter: Move E4

E-bicycle

The strength of the electric bicycle lies in its slightly higher speed compared to an ordinary bicycle, while requiring less physical effort. This makes it a good option for longer routes. Due to electric propulsion, the bicycle is less affected by wind conditions (Plazier et al. 2017). When the battery is empty it is a less preferable mode but still able to continue.

Figure 14: OVfiets electric bicycle (NS 2024)

A drawback of electric bicycles is their relatively high acquisition cost and very high operational cost, particularly because the battery needs to be replaced. When operated in an All-to-All configuration, battery replacement becomes financially burdensome. Therefore in rural regions a less labour intensive strategy is preferred.

2.3.5.3 Conventional bicycle

The strength of the **bicycle** lies in short trips to any location. It is highly manoeuvrable and can reach almost any destination. Due to its low acquisition and operational costs, the bicycle should be the financially preferred option in most situations. However, not everyone is able to ride a bicycle, and its range is limited. Additionally, financial incentives should not be the sole factor in measuring the effectiveness of public mobility. A disadvantage of the bicycle is the physical effort required, which reduces its range. Wind has a greater influence on cyclists, especially outside built-up areas. A cyclist is not shielded from the weather. Statistics show that health considerations are a reason people choose bicycles, as they offer regular exercise and fresh air (Plazier et al. 2017).

Figure 15: Shared bicycle (Jansen 2022)

2.4 Best configuration for rural regions according to literature

In this section the answer to sub question two will be described "Which public mobility configurations are most promising to improve reachability within rural regions according to literature?". The knowledge collected in section 2.2, the different node organisations a public mobility aspect can service. Together with other aspects of the mobility spectrum that show high and low potential within rural regions as described in section 2.3.This section will create a classification including a reasoning why certain public mobility aspects will be used within the modelling phase of this research. The last part of this section will explicitly mention the systems that should be avoided. All considerations mentioned within chapter 2.3 are displayed within figure 16. Any part of the public mobility spectrum can be categorised within this framework over all five levels. Given this classification system 306 different public mobility systems can be defined while only thirteen (a to m) will be used for further research grouped into the six categories displayed in the list below and figure 16. In figure 16, all public mobility categories are coloured with a distinct colour. All same coloured boxes together form the category (except for dark blue, these boxes are out of consideration). A box with multiple colours means that this classification is true for all different categories represented by the colours.

1. Interlocal bus service
    a. Bus, Professional driver, Scheduled service, station based, line tactic
2. Demand responsive service
    b. Van, Professional driver, Reservation based, Point based, One to many tactic
3. Neighbourhood bus
    c. Van, Voluntary driver, Schedule based, Point based, Line tactic
4. Ride-share
    d. Car, Hail driver, Reservation based, Point based, many to many tactic
    e. Car, Hail driver, Pick-up on arrival based, Point based, many to many tactic
5. Shared battery vehicles
    f. 45km/h scooter, Self driving,Reservation based, Point based, Few-to-many tactic
    g. 45km/h scooter, Self driving, Pick-up on arrival, Point based, Few-to-many tactic
    h. Cabin scooter, Self driving,Reservation based, Point based, Few-to-many tactic
    i. Cabin scooter, Self driving, Pick-up on arrival, Point based, Few-to-many tactic
    j. electric bicycle, Self driving,Reservation based, Point based, Few-to-many tactic
    k. electric bicycle, Self driving, Pick-up on arrival, Point based, Few-to-many tactic
6. Shared bicycle
    l. Bicycle, Self driving,Reservation based, Point based, Many-to-many tactic
    m. Bicycle, Self driving, Pick-up on arrival, Point based, Many-to-many tactic

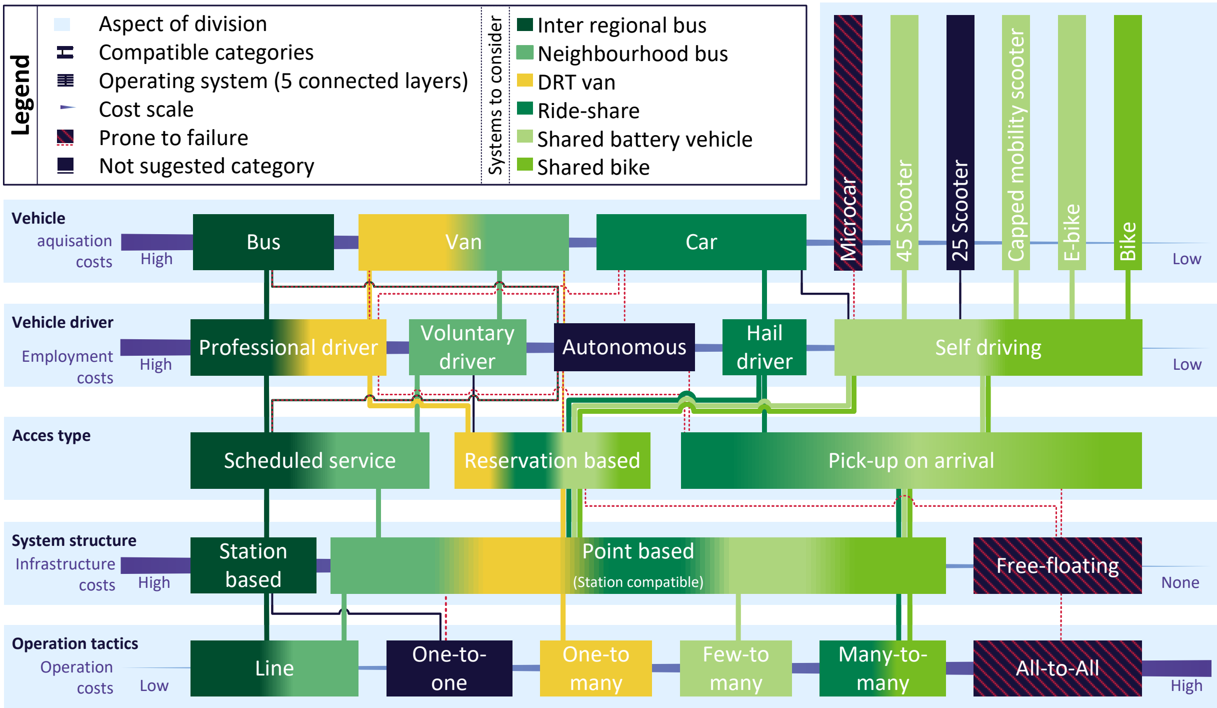


Figure 16: Public mobility classification

2.4.1 system choices and combinations

A demand responsive transportation (DRT) van must be retained within the system because it provides essential accessibility for those who are less mobile or lack viable alternatives. Although the cost per traveller is relatively high, a DRT van is still more cost-effective than operating a full-sized bus in low-demand areas. The higher financial burden is therefore justified as it ensures inclusivity and fulfils a public service obligation as described in section 2.1.1. However, to avoid unnecessary use and unsustainable cost escalation, travellers should be nudged towards alternative modes when possible As described in section 2.1.1. This is important because, as identified in the literature, higher ridership does not translate into better vehicle occupancy in DRT systems. Instead, it increases total vehicle kilometres travelled and therefore cost. While the difference in operating cost between a van and a car is limited, the van provides a higher service level and allows for multifunctional use, as discussed later in this section.

Shared bicycles must be present to accommodate shorter trips characterised by diverse routing patterns and decentralised demand. A bicycles operational efficiency is the relatively low purchase cost and minimal operational cost. Even with lower occupancy rates or limited turnover, shared bicycles incur lower financial losses per trip compared to all other alternatives. They are therefore a cost-resilient mode suited to rural travel behaviour, where lower demand and infrequent trips are prevalent.

Shared battery-powered vehicles are able to bridge the distance between interregional bus stations and destinations further away. Battery-powered vehicles have electric support or propulsion nwhich allows travellers to travel further or faster without physical effort, making Battery-powered vehicles suitable for rural regions where trip distances may be too long for cycling. To limit operational costs from charging and redistribution, their use will be restricted to trips between any node and a station. This containment ensures that charging infrastructure remains concentrated around stations, reducing the need for extensive battery logistics while still providing effective access and egress options.

Ride-sharing forms a low-cost complementary layer within the system. It primarily targets users who might otherwise utilise the DRT van. Because ride-sharing does not require direct operational subsidy, it can be offered at very low or no cost, creating a financial incentive for users to choose this option rather than the highly subsidised DRT service. In addition, ride-sharing appeals to cost-sensitive users with flexible time preferences. The success of such systems in rural regions depends heavily on community engagement and social cohesion. Literature indicates that ride-sharing initiatives are only effective when locally supported, and many externally-imposed systems fail within two years (Currie and Fournier 2020). For this reason community based system must be implemented. The system must have clearly recognisable meeting points and options for both reservation-based and ad-hoc travel. Inclusion of all travellers is preferable to maximise participation, while optional filtering with code of conduct certificates may be provided to support perceived safety and trust for travellers who do prefer this option.

Neighbourhood buses, when present, offer an important addition to the system due to their scheduled character, which is generally preferred by users as described in 2.3.3. Operated by volunteers, they are financially efficient and support groups such as digitally illiterate or socially vulnerable travellers. Because neighbourhood services typically do not operate during early morning peak hours, DRT and neighbourhood buses can share rolling without introducing vehicle conflicts. Neighbourhood bus inclusion supports continuity and predictability, particularly for passengers who require schematically over flexibility a low frequency less direct route is preferred over a direct route at any desirable moment.

Interregional bus services are essential within the overall framework as high-capacity arterial connections between the case area and destinations outside the case area. Inter local buses collect passengers from the stations and provide efficient inter local travel that cannot be matched by smaller-scale modes as described in 2.3.5. Their presence is crucial to the functioning of the entire mobility system, as they act as the backbone to which local modes must provide access.

Combining multiple public mobility aspects into an integrated service yields additional functional and financial benefits. The combination of bus services and shared mobility addresses the key limitations of each mode: buses provide rapid inter local travel but are unable to reach dispersed destinations, while shared mobility modes offer local access but lack the speed and capacity for interregional connection(as described in section 2.1.3 and 2.3.5. By ensuring minimal transfer distance between modes and harmonised rental and ticketing systems, the total journey becomes seamless, increasing both attractiveness and operational efficiency (section 2.2.2).

The integration of DRT and ride-sharing can stabilise demand responsive services. Ride-sharing offers flexibility and financial sustainability, while DRT guarantees universal access. By allowing ride-sharing to serve as the first option and reserving DRT for cases where ride-sharing is not available or not suitable, the overall system becomes more cost-resilient. This creates a natural enforcement mechanism whereby DRT is only used by the residual group for whom no lower-cost alternative is viable.

Finally, synergy also exists between DRT and shared battery-based micromobility. Electric vehicles require charging or battery replacement, which incurs high costs when these assets are dispersed. Meanwhile, DRT vehicles and their drivers often experience idle time between passenger trips. Utilising these idle periods to swap batteries or relocate micromobility vehicles reduces labour costs and improves asset availability. Additionally, the DRT van can transport malfunctioning or depleted vehicles back to a workshop or redistribution point without requiring a separate logistic fleet. This improves operational efficiency and system resilience while maintaining user service quality.

3 Model development

Within this chapter an explanation is given about the objective behind the model, the functioning of the model and the assumptions that must be taken into consideration when working with the model. This chapter only considers the development while the manner in which the model is applied is discussed in chapter 4.

3.1 Objectives and scope

The objective of this study is to analyse how the availability of different modalities within a rural region influences the reachability, accessibility, system costs and system performance. To do so the model must be able to generate trips within an area for variable asset configurations under the same conditions and circumstances. The purpose of the model is to compare the performance of various public mobility fleet compositions and evaluate their relative impact on the entire mobility system. To be able to conduct this research certain requirements exist for the case area. The study scope is a rural region, therefore the case area should be classified as a rural region. The Dutch standard of CBS is used which describes a rural region as a area with an address density below 1000 addresses per square kilometre (CBS 2025). Public mobility requires connection to the interlocal/regional public transport network to provide meaningful accessibility (Oeschger et al. 2020). However, this accessibility can only be generated by a direct public transportation connection which is frequent and comparable to the travel duration by car (van Steen 2024). Within rural regions direct public transportation connections are formed by interlocal buses and regional trains. Most train lines do go through the centre of the villages while provincial roads mostly avoid the village (cores) creating a different access and egress situation for a bus or a train (Kuiper and Spoon 2024). Due to this difference the scope of this research is limited to a single mode. Because more areas are served by inter local buses compared to regional trains, the decision is made to only take inter local buses into account (Kuiper and Spoon 2024). Most provincial road trajectories do not go through the villages, still the proximity to the villages differs. Therefore this should also be true within the case area. Within rural regions diverse spatial characters occur, villages may be different sizes and shapes(Kuiper and Spoon 2024). This case study goal is to give advice which is focused on a solution working within the diversity of the rural region. Therefore it is desirable that within the case area this diversity is present too. The case area therefore should contain a part of ribbon development, villages with different sizes and a clear distinction between the villages to have clearly defined boundaries. Besides requirements for the area itself also requirements exist for the availability of information, the area should be located within the transport authority influence to have hands-on experience and data about travel behaviour and trip data to have a foundation for the research.

3.2 Core concepts and entities

The model is built on a discrete representation of the travel system. It consists of nodes, modes, traveller groups, routes and trips. Each of these entities is defined explicitly to capture all components of the mobility system.

Nodes represent locations where trips originate or terminate. They are categorised into three types: stations, stops, and points, reflecting their relative importance and size in the network as explained in section 2.2. Each node has a defined service area and provides access to public mobility modes. The collection of nodes $\mathcal{N}$ is the union without overlap between points $\mathcal{P}$, stops $\mathcal{H}$ and stations $\mathcal{S}$ as described in equation 1.

$$\mathcal{N} = \mathcal{P} \dot\cup \mathcal{H} \dot\cup \mathcal{S} \quad (1)$$

Modes refer to the mobility options available in the model: walking, cycling, shared mobility, DRT, or schedule-based buses. This collection of modes $\mathcal{M}$ is described in equation 2. Each mode is defined by its nominal speed, availability constraints and restriction to certain routes. The average velocity for cycling is 12, 16 or 21 km/h depending on fitness of the travel group, 15 km/h for an electric cabin scooter, 22.2 km/h for an electric bicycle and 36.3 km/h for an e-scooter (SWOV 2020;SWOV 2024).

$$\mathcal{M} = \text{walk, bicycle, electric bicycle, e-scooter, cabin scooter, ride-share, DRT, bus,} \tag{2}$$

Traveller groups represent behavioural diversity in the population. Each group is characterised by its aversion to use specific modes. This aversion results from lack of a privately owned vehicle, physical disability or lack of social safety or the aversion to being unshielded against the rain. Simultaneously every traveller group has a fitness parameter that determines the velocity for active modes. This aversion will rule out certain travel options when choosing a trip.

Trips are individual travel events with an origin node, a destination node, and a departure moment. For each trip, the model constructs a set of feasible routes based on the availability of modes and their operational constraints from which the trip is selected.

Routes are feasible travel options between origin and destination. The routes do consider asset availability and traveller group compatibility. Therefore routes will not always consist of the same choice set between a given origin–destination combination.

Route-legs are segments of a route between nodes. Each route-leg $\mathcal{E}_m$ is unimodal and therefore the duration is pre-calculated. A route-leg has an origin node, a destination node, and a duration. The set of route-legs can be displayed of a table with the origin nodes as row labels and the destination nodes as column labels with the duration inside the cells. The set of route-legs is displayed as a matrix in equation 3.

$$\mathcal{E}_m \subseteq \mathcal{N} \times \mathcal{N} \tag{3}$$

The model is built on the assumption that people will choose their trips based on the perceived duration. The model calculates the perceived duration of a trip for comparison. Transfer times are generally perceived two and a half times as long as normal travel duration (Fan et al. 2016). To capture this in the model the perceived duration of the trips sums all durations of separate parts with a weight of 1 and the transfer time with a weight of 2.5. This allows different mobility options to be compared in a consistent manner. The perceived duration C for a trip t is defined in Equation 4:

$$C = t_{\text{walk}} + t_{\text{mode}} + 2.5t_{\text{transfer}} \tag{4}$$

Where t_{walk} is the walking time to reach a desired mode and the distance to walk from the final node to the destination node. t_{mode} is the time in a mode. t_{transfer} is the waiting time between reaching the station and arrival time of the bus or the time before a ride-share or DRT arrives. At each transfer a duration is added depending on the size of the node which includes walking between modes as described in section 2.2.

While travellers will base their choice on the perceived duration this does not always result in a traveller selecting the shortest perceived travel time. Therefore the model must prefer the shortest perceived duration while not always selecting the shortest perceived duration. With a certain probability the model should sometimes select a less short trip. To capture this uncertainty multinomial logit (MNL) is used. This method enables transforming all perceived durations into a probability, giving shorter durations a higher probability and longer durations a lower probability (Ben-Akiva and Bierlaire 2003). The probability of selecting route r with perceived duration C_r with the MNL function is shown in Equation 5.

$$P(r) = \frac{\exp\left(-C_r/\tau\right)}{\sum\limits_{r \in \mathcal{R}od} \exp\left(-Cr/\tau\right)} \tag{5}$$

Where $P(r)$ is the probability of route r being traversed, C_r is the perceived duration of route r, τ is a temperature parameter that controls the sensitivity to perceived duration differences, and $\mathcal{R}_{od}$ is the set of all feasible routes for the origin–destination pair.

3.3 Data requirements

The model requires a set of input data that defines the geospatial structure, travel demand, travel behaviour and available public transportation.

Node data forms the geospatial foundation of the model. Each node must have: A geographic location, a classification as a station, stop, or point, a service area defined by a maximum walking distance and travel time limit, demographic data of the service area, workforce data of the service area.

Travel demand data is required through an origin–destination probability distribution. Each trip is generated by sampling from this distribution. Let p_{od} denote the probability that a trip occurs between origin o and destination d. The origin–destination distribution satisfies:

$$\sum_{o \in \mathcal{N}} \sum_{d \in \mathcal{N}} p_{od} = 1 \tag{6}$$

Service data defines the mobility options available to travellers. Besides inventory constraints which will be formulated later The restrictions between which nodes services may operate together with the duration for every possible route leg. The scheduled departure and arrival time for scheduled services is needed. Also the booking order for DRT and the vehicle capacity of every vehicle is needed

Traveller behaviour data is required to have statistics on group dis-likeability of certain modes and rain. Also this data must contain the change to the average walking and cycling speed given the fitness or age of a certain group.

Network data forms the base for all distances and durations taken for all modes while connecting between different nodes.

This input set enables the model to construct feasible travel options, evaluate their perceived durations, and simulate traveller choices under different public mobility fleet compositions.

3.4 Model architecture

The Model architecture defines the chronological process of generating, evaluating, and assigning trips of the public mobility spectrum. Each simulation run represents one realisation of the public mobility system under a given fleet composition for a week. The travel behaviour on different weekdays consists of different patterns, during rush-hour on weekdays more commuter trips will show up while leisure trips will peak during weekends or evenings. To capture this behaviour every simulation will capture a single week. The workflow operates at the trip level. The model is structured as a sequential simulation that represents how individual trips are generated, how feasible travel options are constructed, how choices are made between these options, and when all trips are generated how performance indicators are evaluated. Each simulated trip passes through a series of processing stages. These stages collectively capture the interaction between the spatial structure, mobility services, and traveller behaviour. The functioning of the model can be seen in figure 17.

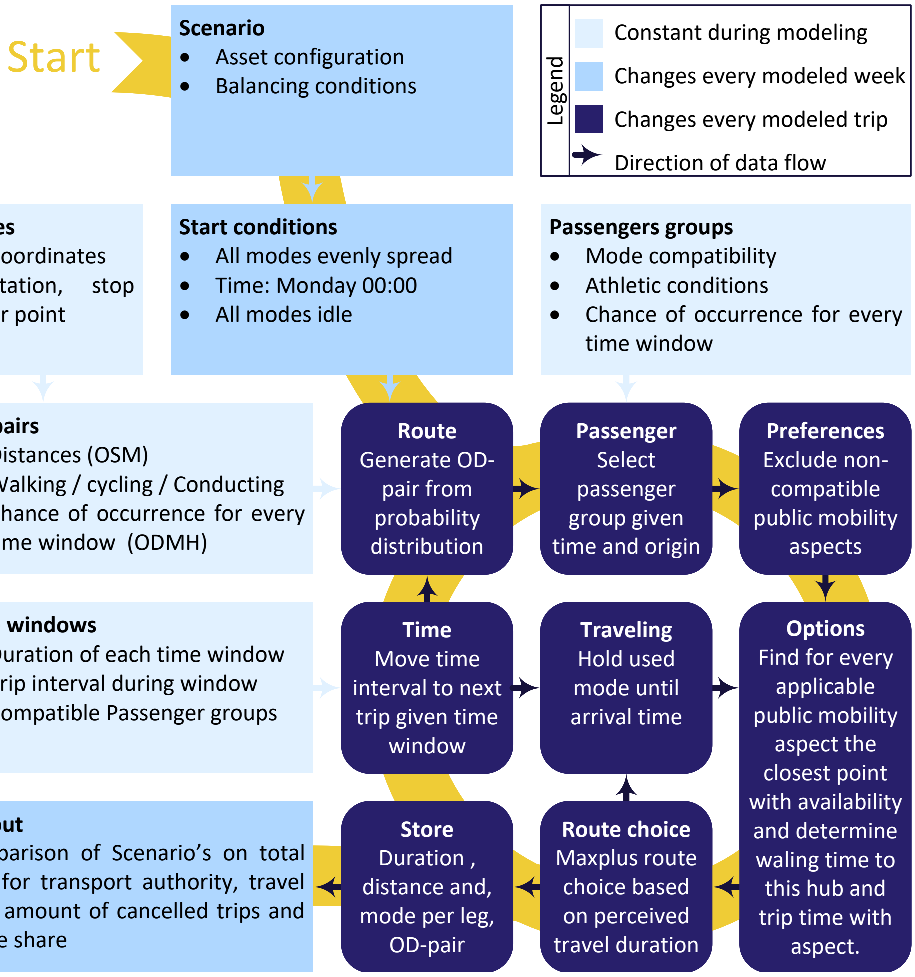


Figure 17: Methodology: Modelling

The model consists of four core components: OD-pair generation, feasible option construction, route and mode choice, and output aggregation.

Based on the measurements of trips during the day, multiple time windows are created. Every time window has a specific interval between generated trips. The duration of the interval is based on the average of the measured data within the time-window. The time-window should be created such that the window limits are correspondent with different phases of the data. Given the time-windows with specific intervals a list with time stamps of every departure time is created. At time stamps trips are generated using the origin–destination distribution p_{od} as defined in equation 6. Each generated trip represents a single travel demand event and is treated independently, ensuring that each realisation reflects the overall demand intensity. Given the demographic distribution of the origin's nodes service area, an age group is determined. Within this age group a travel motive is selected. For selecting the motive statistics on travel behaviour applicable to the region should be used. Given the age group and travel motive the travel group is identified. Given the travel group multiple modes or travel conditions may be ruled out, resulting in feasible routes.

Once an OD-pair is generated, the model identifies all feasible travel routes that connect the origin node o to the destination node d. Given the following constraints:

- A mode must be compatible with the user group (Equation 7).

- Battery powered modes must start or end at a station (Equation 8)
- Ride-share only operate between defined stop-and-station-pairs.
- DRT vehicles only operates in between points and the closest station to the specific point (Equation 9)
- Interlocal buses only drive between stations at a set time. (Equation 10)

The same restrictions formulated as mathematical constraints:

A mode m is considered available, denoted by χ to a traveller group g if it meets behavioural conditions, as defined in equation 7:

$$\chi_{g,m} = \begin{cases} 1, & \text{if mode } m \text{ is available for traveller group } g \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

$$\mathcal{E}^m \subseteq (\mathcal{H} \times \mathcal{N}) \cup (\mathcal{N} \times \mathcal{H}), \quad m \in \mathcal{M}_{\text{battery}} \tag{8}$$

$$\mathcal{E}^{\text{DRT}} = \{(p, \arg\min_{s \in \mathcal{S}} \text{dist}(p,s)), (\arg\min_{s \in \mathcal{S}} \text{dist}(p,s), p)\} : p \in \mathcal{P} \tag{9}$$

$$\mathcal{E}^{\text{bus}} \subseteq \mathcal{H} \times \mathcal{H} \tag{10}$$

It is however possible that not every mode is available at the origin node. To take this into account for every mode the closest node to the origin node with availability inventory $N_{m \in I}$ is determined. The distance between origin node and node with available mode is used to calculate walking duration which is added to the perceived travel duration. Simultaneously it is important to account for cancelled trips. When duration for a certain trip becomes too long it will be cancelled. The cancellation threshold is however ambiguous, not every person will be cancelling a trip in the same manner. For this model the cancellation threshold is set to three times the duration by car between origin node and destination node. Given the existing situation this is slightly slower than the slowest public transportation trip undertaken within the area but faster than walking longer distances. All options are depicted in figure 11(Fan et al. 2016). If the relative travel time of the available options becomes longer the likelihood of a cancelled trip becomes higher. Simultaneously the chance of a cancelled trip for a car owner is near zero. Even though this trip is not undertaken it is added with a perceived duration C_{cancel} to the set of feasible routes $\mathcal{R}$.

$$C_{\text{cancel}} = 3\,t_{\text{car}} \tag{11}$$

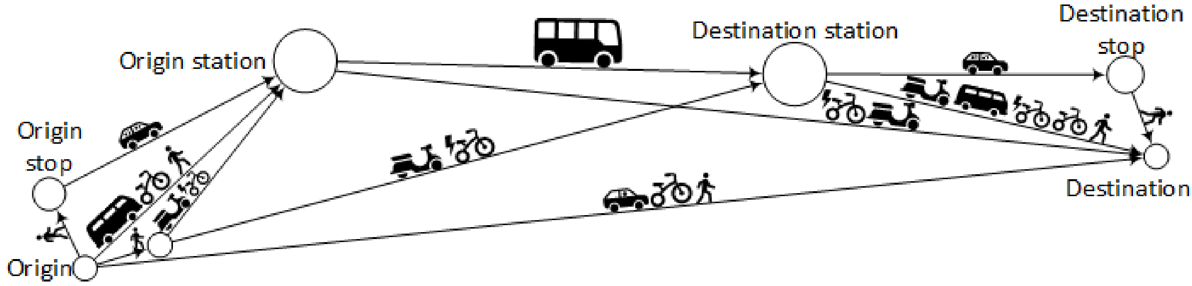


Figure 18: Possible routes taken into account

All constraints combined construct the set of feasible routes between origin and destination $\mathcal{R}_{od}$. These can be visually seen in figure 18. The perceived travel duration C is calculated using equation 4. The distance, duration, used mode, and origin and destination of each route-leg is recorded together with the OD-pair to use later for statistics. From the multiple route options a single trip must be selected. As described in section 3.2, this selection is performed using a MNL model (Equation 5). To mitigate the independence of irrelevant alternatives, the alternatives are grouped into five route categories Ben-Akiva and Bierlaire 2003.

1; direct routes with a private mode or walking, 2; routes with a shared mode using the inter local bus service, 3; routes that use shared mobility anywhere, 4; cancelled trips, and 5; all other routes. In the existing situation the share of direct routes with a private mode or walking is known. The heat parameter for the categories τ_1 should be calibrated such that the results of the model with the existing situation will have the same share of direct routes with a private mode or walking as the statistics show (Ben-Akiva and Bierlaire 2003). After finding the right value the heat parameter for the categories will be fixed for all model runs. When a trip route-category is selected using MNL a second MNL is conducted between all options within the selected route-category. The direct routes with a private mode or walking route-category. Within this option from statistics all values are known for the percentage of the different routes making it possible to calibrate the heat parameter for the route choice τ_2 on the share of car usage, bicycle usage and walking. The value for τ_2 is used in all categories for selecting the route from the route-category. After selecting a route for the trip the departure, arrival, and route-category are added together with the aforementioned characteristics of a route and stored in a logbook. This logbook will be used to derive statistics after an entire fleet composition simulation is completed. Simultaneously an order book is kept operable. In the order book the mode, departure, arrival time, and location are stored. This allows at the given time stamp to reduce or increase a certain mode at a certain node to reduce the modes to a finite number. After an order in the orderbook is realised it will be deleted. After this is completed the time will be changed into the next time step, the order book is checked for possible inventory changes and the aforementioned step of section 3.4 is repeated until the modelled week finishes. The sequential structure ensures that each simulated trip reflects both spatial accessibility and the behavioural response to service availability. Once the predetermined amount of trips in the simulation week is processed all characteristics recorded in the logbook will be used to compute the key performance indicators on which fleet compositions will be compared. The KPIs will be explained in section 3.5.

3.5 Fleet composition simulation logic

Fleet composition simulations are used to evaluate how changes in public mobility services influence travel behaviour and system performance. Each fleet composition simulation represents a distinct configuration of vehicle inventory. The purpose of fleet composition simulations is to compare the relative effects of different system designs. Every fleet composition simulation has a constant demand distribution, this allows the model to isolate the impact of service changes on traveller behaviour.

For each inventory-constrained mode m, a single-mode experiment determines the maximum effective fleet size $F_{m,\max}$. All other variable modes are disabled, except for the interlocal bus services because the interlocal bus services are served by public mobility for both access and egress. Not all modes will be able to serve a complete trip without the interlocal bus service, because only for cycling and private modes it is possible to service direct trips while other modes must be to or from a station. The fleet of mode m is increased until incremental usage gains become negligible. Formally, let $\phi_m(f)$ denote the realised trips served by mode m with fleet f in the single-mode experiment. The saturation threshold is explained in equation 12.

$$F_{m,\max} \;=\; \min\left\{ s \in \mathbb{Z}_{\geq 0} \mid \phi_m(f{+}1) - \phi_m(f) \leq \varepsilon \right\}, \tag{12}$$

with a small tolerance ε chosen as stop criterion in finding the maximum effective fleet size.

Fleet composition simulation levels for each variable mode m are defined as discrete steps. It is undesirable to model every possible combination, especially with a larger maximum effective fleet size $F_{m,\max}$. Therefore a step size ΔF_m must be set. For this research the step size is set to one 9th of the maximum effective fleet size to have ten steps from zero to the maximum effective fleet size. Fleet inventory must consist of integer units, therefore when deciding for the maximum effective fleet size only multiples of nine are used. This ensures integer step sizes. The choice for dividing every mode's fleet options into ten integer values is to limit calculation time. When the $F_{m,\max}$ becomes smaller than eight the steps become very small and a step size of one is used as explained in equation (13). With ten steps 200 thousand fleet compositions are created, if no $F_{m,\max}$ is below eighteen. Increasing the amount of steps would create infeasible calculation time. Reducing the amount of steps would make the step size too big to have a relevant outcome.

$$\Delta F_m = \begin{cases} 1, & \text{if } F_{m,\max} < 18, \\ F_{m,\max}/9, & \text{otherwise.} \end{cases} \tag{13}$$

Given the step size of every mode is known, all different fleet inventory levels that will be simulated for a mode m can be calculated with Equation 14.

$$\mathcal{F}_m = \{0, \Delta F_m, 2\Delta F_m, \dots, F_{m,\max}\}. \tag{14}$$

And when all simulated inventory levels per mode are known, every different combination for inventory level per mode should be realised to create a fully defined fleet composition (s) with an inventory vector across variable modes as depicted in Equation 15.

$$\boldsymbol{F}^{(f)} = \left(F_m^{(f)}\right)_{m \in \mathcal{M}_{\text{var}}}, \qquad \text{with } F_m^{(f)} \in \mathcal{F}_m. \tag{15}$$

3.6 Fleet composition comparison and selection

For each fleet composition, the model runs the full simulation process described in Section 3.4. The output of fleet composition simulation s is a set of several key performance indicators (KPIs), which can be compared across fleet compositions. In evaluating whether a proposed fleet composition could replace the existing system, the KPIs serve as comparative benchmarks. The order in which elimination takes place is listed below.

First, all fleet compositions which disproportionately disadvantage certain passenger groups are filtered out. All fleet composition simulations containing at least a single traveller group with more as half the trips cancelled are excluded. Besides filtering on disproportionately disadvantage no KPI will be created. Second, the total system cost must be addressed: a fleet composition is only deemed realistic if it does not impose higher overall costs compared to the current situation. The over al costs are defined as, all costs while not taking into account any revenues. This is decided because the fare-price is depending on policy which is out of scope. Cost-efficiency is fundamental because the budget for a certain region is part of a division of resources and more expenditure for the case area would result in less budget elsewhere (Zuid-Holland 2025). Third, the average travel time per passenger is critical. Travel time directly affects user satisfaction and system attractiveness; shorter average travel times generally increase the likelihood that potential users will choose the system. Simultaneously existing passengers would dislike the travel time being increased compared to the existing travel times (ITF 2024). Fourth, the performance for the slowest trips should not deteriorate. This is evaluated by analysing the commercial speed of the slowest 10%, 5%, and 1% of travellers, where commercial speed is defined as the straight-line distance between origin and destination divided by the actual travel time. Because performance is assessed relative to the existing situation, the cumulative distribution of commercial speed is likely already skewed and therefore uneven. Satisfying one threshold will therefore not automatically satisfy the others. This helps safeguard existing equity and prevents the new system from disproportionately favouring certain trips ITF 2024. Fifth, service availability, defined as the probability that a user can access a mode when needed within half an hour at the closest node. This is calculated by measuring the duration modes are unavailable with a minimum of half a hour. This measures the reliability and convenience of the system. For public mobility such reliability is essential to ensure predictability for the user and ensures trust from the user (Fedujwar and Agarwal

2025). If multiple fleet compositions meet these baseline requirements, further selection will be guided by additional, secondary criteria. One such criterion is fleet diversity reduction. Between equally performing fleet compositions, a less diverse fleet is preferred, provided none of the primary KPIs deteriorate. A less diverse fleet can yield higher operational efficiency, simpler maintenance, and cost savings due to economies of scale (Coenegrachts et al. 2025). Finally, a fleet composition with higher vehicle utilisation rate is a secondary KPI: when suitability is equal, the fleet composition where vehicles achieve higher utilisation rate has an efficiency and sustainability advantage.

The comparison between KPIs is relative. Let Φ_s denote the outputs of a fleet composition simulation and Φ_0 denote the original situation. By dividing the new fleet composition KPIs with the original situation, the change per indicator becomes clearly visible. The difference in performance is evaluated using Equation 16.

$$\Delta\Phi_{s,0} = (\Phi_s - \Phi_0)/\Phi_0 \tag{16}$$

Where $\Delta\Phi_{s,0}$ is the change between the fleet composition and the existing situation for every KPI.

The best fleet composition to select is ambiguous, depending on the objective what is best a different fleet composition will be selected.

For this research three visions for the best fleet compositions are described. With each vision the set of fleet compositions is reduced to a set of fleet compositions that comply with the vision. Because only a set of KPIs is available which is not all encompassing for selection after the procedure the set of feasible fleet compositions should preferably be around five different feasible fleet compositions but maximum ten. More feasible fleet compositions make it difficult to qualitatively compare the different fleet compositions.

three visions have been created which all envision a better system. Depending on the person one vision is better as the other, for this research the goal is to continue with the three visions and explore which modes are favoured by a certain vision and compare if there is overlap between fleet composition simulations or trends.

1. Maximum average improvement: Maximize all KPIs with a equal percentage. The goal of this vision is to improve all KPIs to make the system better on average, more benefits for the user with a lower system cost which may be a benefit for the transport authority, user or both. The slowest trips will become faster, the average duration shorter and the certainty to have a trip from the closest node higher. This set of fleet compositions will improve the system as much as possible for the biggest group of people. All KPIs will be calculated and the improvement $\Delta\Phi_{s,0}$ will be increased as long as only five different fleet compositions are over.
2. No deterioration anywhere: All fleet compositions will have a equal or better KPIs within each settlement typology compared to the current situation. the different settlement typology's consist of suburb, village core, ribbon development and dispersed settlement for every settlement typology the set of nodes is divided in these four subsets. All KPIs are again calculated per node-set based on the origin node.
3. Increase rider-ship: Increase the percentage of trips that are with public mobility (Trips which do no not entirely consist of private modes or are cancelled). The KPIs are created to determine the quality and functioning of the system. A different manner in which a system or fleet composition can be rated is by the amount of users choosing to use it. In the model all users do have the possibility to choose the public mobility solutions or private modes, therefore it is possible to see the rate change. This fleet composition increases the ridership increasement until only five different fleet compositions are left. while keeping all other average KPIs on present day level.

3.7 Assumptions and limitations

The model is based on a set of assumptions that enable the simulation of traveller behaviour and public mobility system performance in a consistent and computationally efficient manner. These assumptions are necessary for model tractability but introduce limitations that should be considered when interpreting the results.

Traveller decisions are modelled using a probabilistic choice mechanism based on generalised travel time. This assumes that:

- Travellers primarily seek to minimise perceived travel time.
- Behavioural preferences are captured in traveller groups. The travel groups are designed in such a manner that population wide statistics are the same when looking into the statistics when all travel group population together is investigated. However statistics are the averages of all outliers and near limitless set of combinations while traveller groups form a exhaustive list of options.
- Travellers have access to full information about all available options.

While this approach approximates realistic behaviour, it does not capture higher-level decision-making such as trip suppression based on activity utility or long-term adaptation.

Demand is treated as not effected and static. This implies:

- Origin–destination pairs are sampled from a fixed probability distribution.
- Trip generation is not influenced by changes in service provision.
- Travellers do not alter their destination choice in response to travel conditions.

As a result, the model evaluates behavioural response within a fixed demand structure rather than predicting system-wide changes in mobility patterns.

Public mobility services are represented using simplified operational parameters such as travel speed, operating manners and chance of catching a ride. The model does not simulate detailed operational dynamics such as vehicle dispatching, congestion effects, or interactions between modes besides the choice and multimodal trips. Inventory updates apply when a route-leg starts and finishes and the chance of a mode being taken by a different user before advancing to the specific route-leg is not taken into account nor the possibility that a mode may appear at a better suitable location during the trip.

Nodes represent discrete access locations and are associated with service areas based on walking thresholds. This discretisation introduces generalisation in the spatial network. Access and egress walking distances with their durations are approximations based on a probability of the person living close to the node or near the boundary of the service area for that node. This duration is always added. When a person can not obtain the desired mode at the closest node the traveller need to walk to the closest node with this mode. This may result in a traveller first walking to the node, continuing to the next node possibly walking back along its origin.

The traveller group is decided upon based on the demographics of the origin node, as a result the demographics of visiting travellers is not included resulting in only departing trips and no returning trips.

The model is designed for comparative fleet composition analysis rather than prediction of absolute outcomes. Conclusions drawn from the results should therefore focus on relative changes between fleet composition simulations rather than exact numerical values. In particular:

- Small changes in output metrics should be interpreted with caution if they fall within the stochastic variation of the model.
- Equity results reflect accessibility at the node level and may not capture intra-node variation.
- Cancellation outcomes depend on behavioural assumptions and the definition of the cancellation travel time in Equation 11.

Despite these limitations, the model provides a robust framework for evaluating public mobility interventions. By capturing the interaction between access, service availability, and behavioural response, the model can be used to explore how different system designs perform across diverse spatial contexts and traveller groups. The transparency of assumptions allows the model to be adapted or extended in future research.

4 Case area

Given the requirements discused in chapter 3, a case area must be determined. This research is conducted in cooperation with the province of South-Holland, however the province is not the transport authority for the entire province. In figure 19(a) the area's where South-Holland is transport authority are indicated in blue and therefore the case area is limited to these regions. To be able to do a investigation data must be available about the movements. Therefore a available model of the area is required that includes public transportation and cycling besides the car traffic. Within figure 19b the different mobility models are drawn on the map, the red area's are not applicable as a case area because they do not have all modes present or no data available. The scope is on rural regions, therefore the address density, which is used as urbanisation indicator, in a region overall should not be to high(CBS 2023). Villages should still be present and incidently a higher urbanisation level is desired. In figure 19(c) the address density per 500m square area is visualised. The dark red is preferably avoided and the majority of the area should be light blue. The presence of a inter local bus line is the last mayor requirement. The interlocal buslines are depicted in figure 19(d). For simplicity the area within three kilometre distance of the interlocal bus services is depicted as possible area's this however does not take all geographical boundaries into account and the actual service area of the bus lines may be smaller.

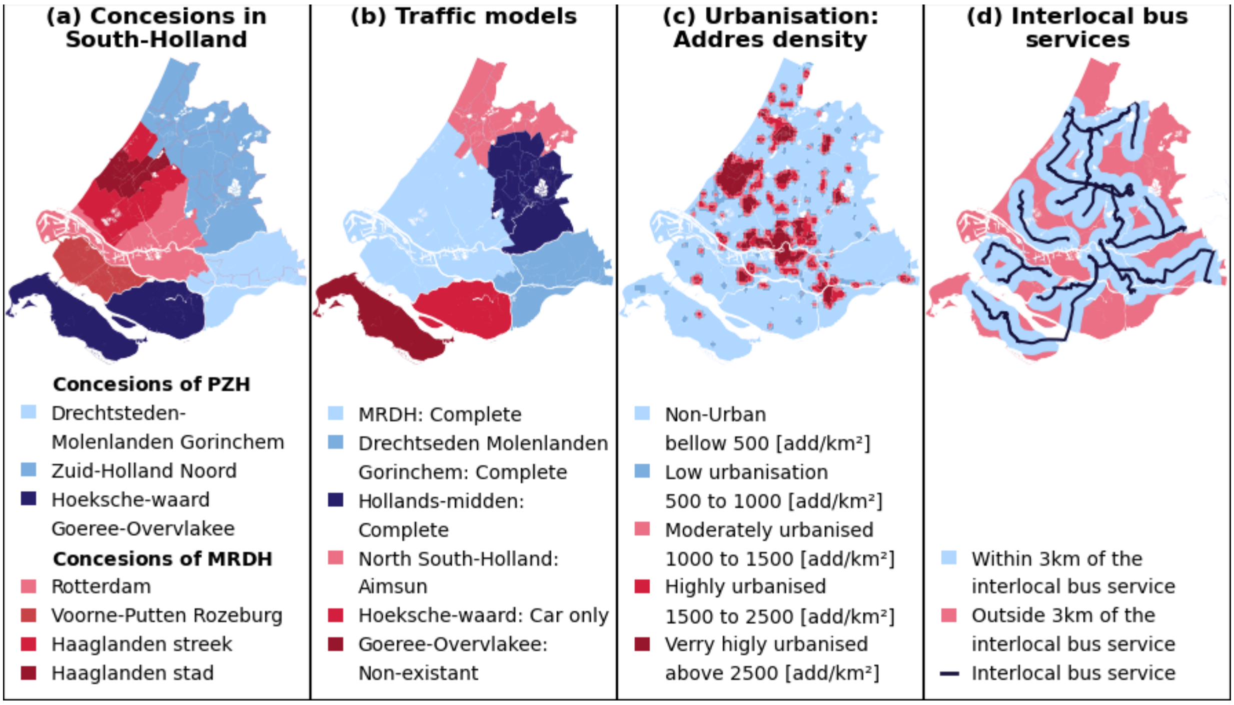


Figure 19: Case area selection criteria

All maps are added together in figure 20, this displays the fraction of the province which qualifies for a case area. Given the geographic boundaries three case area's are still a option, Alblasserwaard, Krimpenerwaard and Zuidplaspolder. When zooming further in on the Alblasserwaard the interlocal bus line primarily runs through the more urbanised southern part and the villages are not distinct or with different sizes. The Zuidplaspolder is lacking (distinct) villages and a clear boundary. Therefore the Krimpenerwaard is selected as case area.

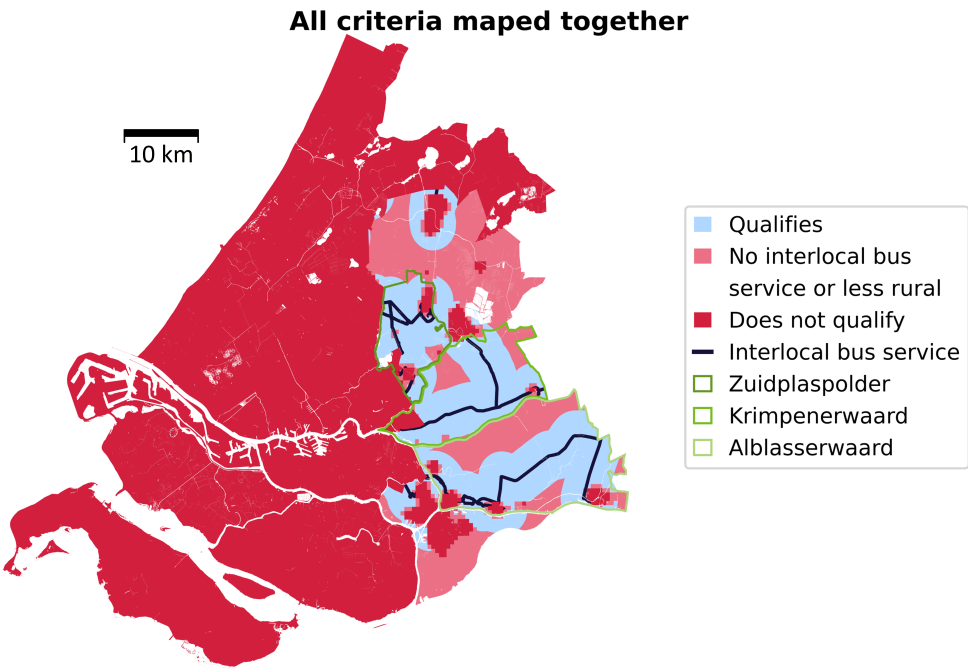


Figure 20: Case area selection criteria

The Krimpenerwaard is characterised by a spatial structure that includes distinct village of varying population sizes, dispersed ribbon developments, and varying degrees of proximity to interlocal bus services. Two interlocal bus services operate through the Krimpenerwaard, bus 295 and bus 497(9292 2025). The services provide access to the urban centres of Rotterdam, Gouda, and Utrecht(9292 2025). These services function as the primary public transport backbone of the region(opensetreetmap 2025). Figure 21 provides an overview of the Krimpenerwaard region.

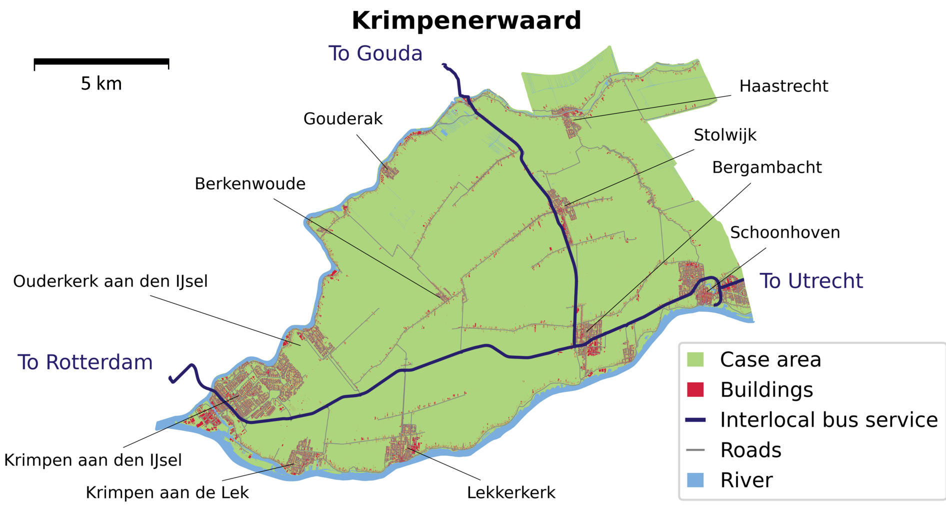


Figure 21: Case area: Krimpenerwaard

Table 4 summarises the population and access distance to the nearest interlocal bus service for each village in the case area.

Table 4: Village characteristics in the case area (CBS 2023)

Village	**Population (rounded by 5)**	**Distance to nearest interlocal bus stop (km)**
Bergambacht	7,150	0.5
Haastrecht	4,345	3.75
Krimpen aan den IJssel	29,505	1.5
Krimpen aan de Lek	6,770	1.5
Lekkerkerk	7,875	2.5
Ouderkerk aan den IJssel	6,865	1.75
Schoonhoven	13,570	0.5
Stolwijk	5,465	0.5
ribbon & dispaired development	5,660	3.75

4.1 Data sources and processing

The implementation of the model for the Krimpenerwaard case area requires the integration of multiple data sources. These sources provide information on population distribution, public transport services, spatial infrastructure, and mobility behaviour. All data were pre-processed to generate the node structure, define service areas, and establish the travel demand distribution used in the simulation.

Node data requires multiple parts, as described in section 3.3. The georeferencing is set using OpenStreetMap (opensetreetmap 2025), while the database of CBS postcodes is used for retrieving the demographics per node (CBS 2023). CBS, as national statistics coordinator, has all relevant data reliably available. The nodes must be organised in three levels (section 3.3). The station level node locations must coincide with interlocal bus stops as described in section 2.2. Therefore, stations are retrieved by filtering on bus stops with an interlocal bus service in OpenStreetMap. Stations are limited to at least half a kilometre apart. Due to the bigger service area of a station and the additional operational complications and costs, fewer stations are desired (section 2.3.2). The minimum distance between multiple stations is dependent on the traveller density, due to the DRT vehicle operating as a one-to-many tactic bounded to only serve the nearest station. It is desirable to have an entire village in the same service area, except when this reduces interlocal bus service connections (Laws et al. 2009). In the case area, this is realised with a half a kilometre boundary.

The stops are manually introduced. Every village without a station has a single stop. This is because ride-sharing services generally work best when a small set of both desired and known destinations is present along the same corridor (Thao et al. 2021). This is achieved by creating pairs between stations and villages along the same road. The location of this stop is based on the model of Omgevingsdienst Midden Holland (ODMH-model) at locations with a high amount of traffic towards the interlocal bus service while still being in the built-up area, preferably close to the core of the village.

The points must always be within a 400 metre walking distance from any dwelling if desired as a public transportation system (Ministerie van Infrastructuur en Waterstaat 2024). The user is not nudged more into using the system when the egress distance becomes less than 100 metres (Abt and Krauss 2025). Therefore, it is undesirable to have stops within less than 200 metres of each other, as the reduction of access/egress is no longer beneficial while the reduction is disadvantageous for the availability certainty. The exact locations originate from filtered OpenStreetMap features, hierarchically ordered with bus stops, bicycle racks, parking facilities, and multi-storey building entrances. It is preferred to have an access or egress option to a bus during operating hours, while outside operating hours the point remains a known location for the user, simplifying the system (Oeschger et al. 2020). Bicycle racks are normally placed at places of interest (Van der Spek and Scheltema 2015) therefore, points are preferably located at existing (bicycle) parking facilities, as described in section 2.2. For the same reason, points are created near parking facilities. The last category, multi-storey building entrances, ensures that points have a high service population. The resulting point set is filtered through the hierarchical order, removing stops located less than 200 metres apart as the crow flies to avoid spatial redundancies.

All nodes are organised as stations, stops and points. The nodes are displayed in Figure 22. For simplicity, every node is assigned a single character in ascending order from west to east. Stations use non-alphanumeric characters, stops use numeric characters, and points alphabetic characters.

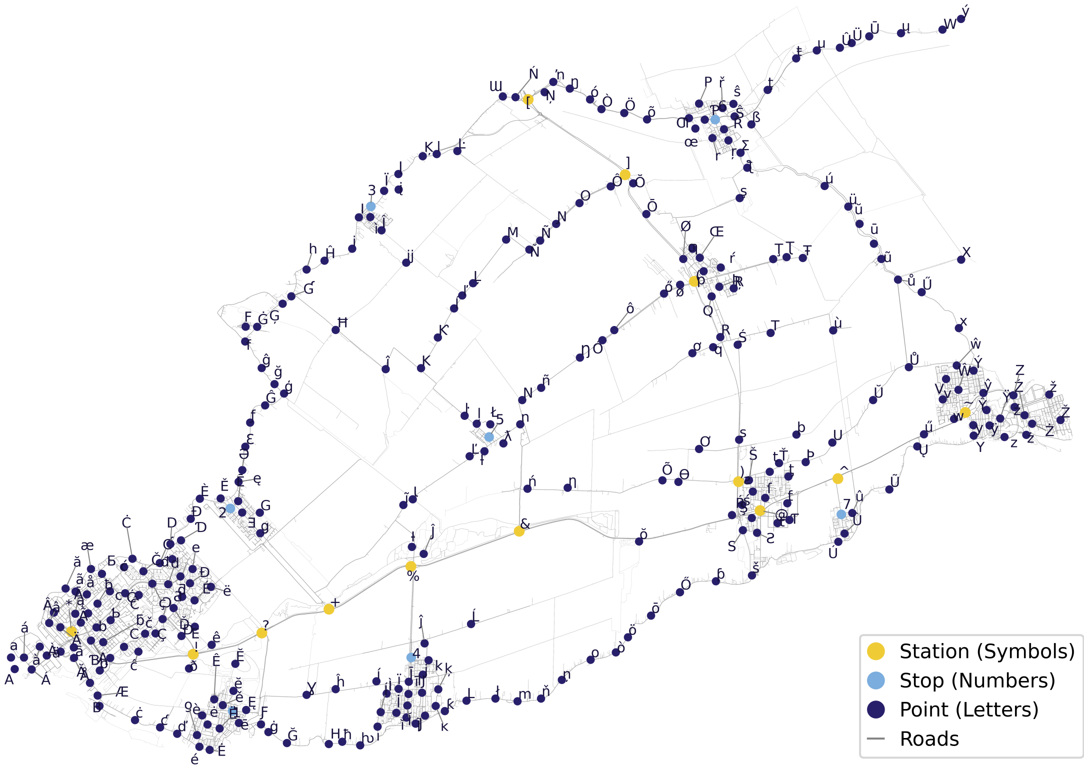


Figure 22: Nodes used in model

For each node a service area is determined, limited by both a five minute and 400 metre walking distance as required for a public transportation system (Ministerie van Infrastructuur en Waterstaat 2024). Overlapping service areas are confined based on a Voronoi graph with nodes as centres. This assumes people normally will use the closest node when travelling (Coenegrachts et al. 2025). Parts of the service area that are not overlapping but are outside the Voronoi box are conserved otherwise people within reach of a node which may not be the closest due to geospatial boundaries will be excluded from a travel option. Each resulting service area is used to assign the service population by age group. Therefore multiple potential data sources are available, square statistics per 0.1, 0.5 or 1 km square and postcode-4, postcode-5 and postcode-6 area. Preferably the coarsest source is used to have a limited error when grouping per node. All these sources, however, do round every value to the nearest five, and when values are below 5 the statistics are not available. With smaller areas, more locations have no data and the rounding error becomes more significant. Because Postcode areas are organised to receive approximately the same amount of post items (kamer 1978), they distribute the population more equally per defined area than predefined square blocks. The postcode-6 is most often too fine, resulting in many 0-entries. Postcode-5 very infrequently has this problem. This is deemed better than the postcode-4 areas which do aggregate data to a very coarse level. Therefore, to determine the values per node, postcode-5 data is used. Postcode-5 areas usually consist of multiple equal characteristic streets and are therefore assumed uniform, enabling the distribution of all data as a density across the road length within the observed postcode-5. The data is reduced to a population density per road length by dividing the total road length within the postcode-5 area. Later, this postcode-5-specific density is multiplied by the road length of the corresponding distance of the specific postcode-5 area within the service area of the node. Summing per node results in all demographics per node.

Travel demand data is collected via the traffic model of "Omgevings dienst Midden-Holland" (ODMH-model) using residents and workforce data per postcode-5 area with a gravitation model (Goudappel 2025b; CBS 2023; LISA 2024). The model consists of a OD-matice for all movements within the area, divided by mode. The OD-matrices of the ODMH-model are used for walking, cycling, and car-driving. This is not possible for public transportation as important links are not included in the model. Attempts to find alternative sources were unsuccessful as this missing link is persisted throughout all versions and different models. Higher level models lack the needed precision or are based on respondents, with too few respondents within the case area for relevant data.(MRDH 2024;Goudappel 2025b;Goudappel 2025a)

Within the ODMH model, the sum of all trip destinations over all modes per area is available, the total attraction for all areas. Assuming all trips start and end within the modelled week, each person is located in the same area at the end of the week as at the start of the week and no imbalance to/from outside areas is present, the total number of trip origins and trip destinations within each area must be equal. Therefore, the weekly production total per area equals the weekly attraction total per area (van Nes 2006).

To distribute the total production and attraction per area over trips of all modes between areas a gravitation model is created (equation 17). The resistance between each origin–destination pair (o, d) is defined with a resistance factor based on trip distance. The scaling factor consists of two variables, a distance decay parameter β and a scaling constant α. With this gravitation model an OD-matrix is generated consisting of all trips with any mode between between all areas. Subtracting the existing OD-matrix for car, bicycle and walking should results in a public transportation OD-matrix. This is however only true if the decay and scaling parameter are fitted. For eleven route legs a known amount of public transportation travellers is available on which iteratively the parameters are fitted.

. First the volume on each route leg must be calculated before fitting is possible.

$$\Omega_{o,d} = \frac{\alpha}{distance_{o,d}^{\beta}} \tag{17}$$

With o, d the origin and destination nodes in $PC5$, $\Omega_{o,d}$ the resistance factor between o and d and $distance_{o,d}$ the travel distance between nodes o and d. After computing the resistance matrix, trips are assigned iteratively using equation 18. For the first iteration, $T_{o,d}^{(0)} = \Omega_{o,d}$. The process continues until changes between successive iterations are negligible.

$$T_{o,d}^{(k+1)} = T_{o,d}^{(k)} * \frac{Production_o}{\sum_{D \in PC5} T_{o,d}^{(k)}} * \frac{Attraction_d}{\sum_{o \in PC5} T_{o,d}^{(k)}} \tag{18}$$

With $T_{o,d}^{(k)}$ the number of trips from o to d at iteration k. After many iterations an estimated OD-matrix emerges which encompasses all trips within the area, walking, cycling car driving and public transportation trips. Because the walking, cycling and car driving trips are calibrated to, and verified with measurements it is possible to extract these trips resulting in a estimation for the public transportation OD-matrix. Because at multiple route legs ridership numbers are known this estimation can be calibrated into a workable OD-matrix. Using the least-squares method the public transport OD-matrix is calibrated (Cascetta 1984). The result from this step is a probability distribution for trips between all nodes for all modes. $p_{od,mode}$.

To fit the distance decay parameter β and a scaling constant α of equation 17 the set of public transportation trips that pass through the measured route segment are summed ($\sum_{o,d \in \mathcal{E}}$) and compared to the known measurements of travellers at the segment ($T_{\text{measurement}}$) inherently a residual error e exists With the least-squares error method the scaling parameters α and β are modified to have the lowest residual error e. The process is described in equation 19.

$$\sum_{o,d \in \mathcal{E}} \left(T_{o,d} - T_{o,d}^{\text{car,bike,walk}} \right) + e = T_{\text{measurement}} \tag{19}$$

With $T_{O,D}^{\text{car,bike,walk}}$ the trips of private modes subtracted to isolate public transport demand. Given the scaling parameters the number of trips for each postcode-5 OD-relation with public transportation is known. The trips between model nodes are desired to know. Therefore with the same assumption of equal density within postcode-5 areas the trips are distributed from postcode-5 areas over the nodes by first calculating the trip destination density per road length for every postcode-5 area and later calculating the length of all roads from every postcode-5 area within a nodes service area and multiplying this by the corresponding density. From this data, all possible origin–destination pairs receive a weighted chance of occurring.

From the measurements used to calibrate the ODMH-model, the distribution of travel activity over the day is extracted to capture temporal variation in travel behaviour. Five time-window categories are defined: night, morning rush, daytime, evening rush, and leisure time. These categories refer to behavioural patterns rather than daylight conditions. Several traveller groups are inactive during specific time windows, which results in different weights for O–D relations across windows. For simplicity, the probability associated with each O–D pair is assumed constant within a given time window. Each time window is assigned a fixed interval for trip generation, applied uniformly throughout that window. As a consequence of this modelling approach, the total number of trips on any given weekday remains constant, and a single list of timestamps can be generated specifying all trip departures throughout the week. The different time windows over the week can be seen in figure 23

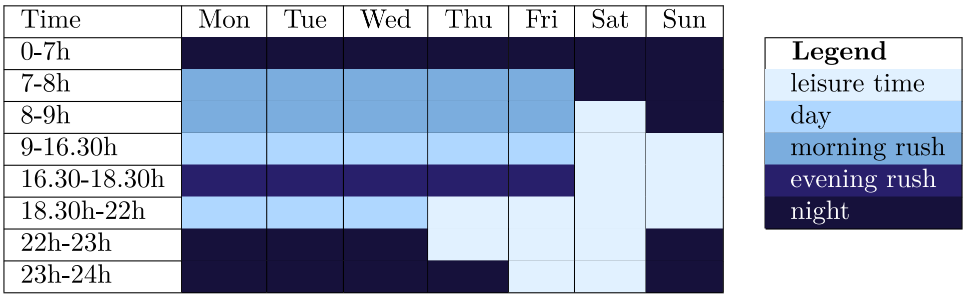


Figure 23: Different time-windows ordered over the day

Network data is collected from Openstreetmap (opensetreetmap 2025). For the underlying network, walking, cycling, and driving graphs are constructed using the osmnx library. These graphs provide the basis for computing shortest path distances between a predefined set of nodes that serve as candidate locations for origins and destinations. To create a smooth and fast model the computations of both distance and duration between all nodes are precomputed resulting in a OD-matrix with the duration and distance per mode. Human powered modes have three different duration matrices as the velocity per travel group may differ between three options.

Service data is collected via a online route planner (9292 2025). The travel times between all stations for bus 295 and 497 are calculated by this tool. For the base scenario all travel times between all nodes are retrieved in the same manner. As a result a OD-matrix with trip durations is created

Traveller behaviour data is provided via ”Onderweg in Nederland”(ODiN) this data shows the amount of trips people undertake for a select set of reasons and which vehicles the groups likely use for given travel motives.(Informatiepunt, ipwvl and Centraal Bureau voor de Statistiek 2024). From ODiN the amount of trips per motives per day have been retrieved. For every motive in table 5 a number of trips is presented.

This is the number of trips for the given age group with that motive. The database is for the entire Netherlands but subsets, for South-Holland and for rural regions are available. This research is interested in travel habits for the rural regions in South-Holland. Therefore the deviation to the national value for South-Holland and for rural regions is calculated after which both deviations are multiplied with the national value to retrieve the value for rural South-Holland. Within the same dataset also a subdivision is made in age groups. This makes it possible to define groups based on age and motive. These groups will be referred to as traveller groups and do receive a letter in table 5. In combination with the demographics of the trip's origin, the columns can be multiplied by the number of residents in a given age group. Based on the time window, certain rows can be excluded. Together, this allows the theoretical total number of trips by motive from this node at the given time to be calculated. The number of trips by travel group is weighted, and a traveller group is selected based on this weighted probability.

Table 5: Traveller groups based on trip motive and age with their corresponding amount of trips per day

	Age				
Category	**<15**	**15-24**	**25-44**	**45-64**	**>65**
To and from work	A (0.06)	B (0.46)	I (0.65)	I (0.60)	N (0.16)
Formal visit	A (0.00)	J (0.02)	J (0.04)	J (0.05)	N (0.01)
business trip	A (0.00)	J (0.05)	J (0.12)	J (0.15)	N (0.02)
Picking up/dropping off person	A (0.08)	G (0.05)	K (0.41)	N (0.14)	O (0.07)
Collecting/Delivering goods	A (0.04)	G (0.08)	E (0.08)	N (0.08)	O (0.10)
Education/Courses	A (0.94)	G (0.45)	D (0.05)	N (0.01)	N (0.02)
Shopping/Groceries	A (0.20)	F (0.39)	F (0.53)	F (0.55)	N (0.57)
Visiting/staying over	C (0.36)	H (0.25)	Q (0.26)	N (0.23)	P (0.24)
Touring/Walking	A (0.14)	L (0.09)	K (0.23)	K (0.32)	O (0.28)
Sport/Hobby	A (0.46)	B (0.32)	D (0.21)	E (0.20)	O (0.15)
Other leisure activities	A (0.42)	M (0.26)	K (0.28)	N (0.22)	O (0.17)
Service/Personal care	A (0.07)	J (0.03)	J (0.05)	J (0.10)	P (0.11)
Other motive	A (0.08)	E (0.09)	E (0.08)	E (0.04)	P (0.03)

The formulated traveller groups serve as a structured representation of the general population within the study area. Because real-world travel behaviour has effectively an near infinite range of combinations, direct modelling of individual variability is not feasible. Introducing traveller groups enables controlled heterogeneity within the model. Each group is assigned a distinct set of behavioural rules, some groups are incompatible with specific transport modes, and the speeds associated with human-powered modes vary across groups. the specifics per travel group are displayed in table 6. By introducing variability between simulated passengers the available choice set may differ and in the results it slower but more accessible modes will receive a bigger share.

Table 6: Characteristics per travel group

Traveller group	Licensed	Ride-share	Velocity	Wind resistant	Rain resistant
A	No	No	Fast	Yes	Yes
B	AM	Yes	Fast	Yes	Yes
C	AM	Not dark	Fast	Yes	Yes
D	Yes	Yes	Fast	Yes	Yes
E	Yes	Yes	Med	Yes	Yes
F	Yes	No	Fast	Yes	Yes
G	Yes	Not Dark	Fast	Yes	Yes
H	No	Not Dark	Med	Yes	Yes
I	Yes	No	Med	Yes	No
J	Yes	No	Med	No	No
K	Yes	No	Slow	Yes	No
L	No	Yes	Med	Yes	Yes
M	No	No	Slow	Yes	Yes
N	Yes	No	Slow	No	Yes
O	Yes	No	Only Walk & Slow	No	No
P	No	No	Unable	n.a.	No
Q	Yes	Yes	Med	No	No

5 Model results

The results section is ordered in the initialisation of the model to determine the different fleet configurations tested, a overview of all fleet compositions without filtering. The visions with which all fleet compositions are filtered to reduce all towards the potential best fleet compositions, The statistical certainty of the potential best fleet compositions and lastly the single potential best fleet composition is investigated in more detail.

5.1 Initialisation

To initialise the model, the maximum fleet size (ΔF_m) of each mode must first be determined. This yields the results shown in Table 7. For all modes, the maximum fleet size is divided into ten steps, ΔF_m is $F_{m,\max}$ divided by nine, only the demand responsive transportation which is below 18 as described in equation 13. When multiplying the amount of steps per mode all possible fleet configurations are found. Together, these settings produce 240,000 different fleet configurations must be evaluated.

Table 7: Maxima and Step-sizes of each node

Mode	Maximum fleet size $F_{m,\max}$	steps	Step-size ΔF_m
Bicycle	468	10	52
Electric bicycle	315	10	35
Cabin scooter	342	10	38
E-Scooter	261	10	29
DRT	11	12	1
Ride-share	Available	2	Available/Unavailable

From the set of fleet compositions, the feasible fleet compositions must be selected. This selection is based on the KPIs and visions defined in Section 3.6. To account for stochastic variability, which may cause the outcomes to deviate from their expected values, each fleet composition is evaluated three times. Although three runs do not provide full statistical reliability, the number of repetitions was limited due to computational constraints, each additional repetition would require approximately one extra week of runtime given the available resources. Due to the use of classified corporate and governmental data in the KPI calculations, all results are presented as percentages relative to the current situation rather than as absolute values. Since all KPIs describing the entire area are required to improve. The resulting solution space shown in figure 24 is not a set of feasible fleet composition's. Although large reductions and improvements can be achieved, these typically come at a cost. For example, a 100% cost reduction would severely degrade performance on all other KPIs because it would imply that no transport system remains. Nevertheless, the figure provides insight into the maximum achievable improvement per KPI as well as the ruggedness of the system, reflected by the worst performance observed across the calculated fleet compositions. Improvements in travel duration reduction and commercial speed are clearly possible, but they can improve less as for example the average commercial speed for the slowest 1% of trips.

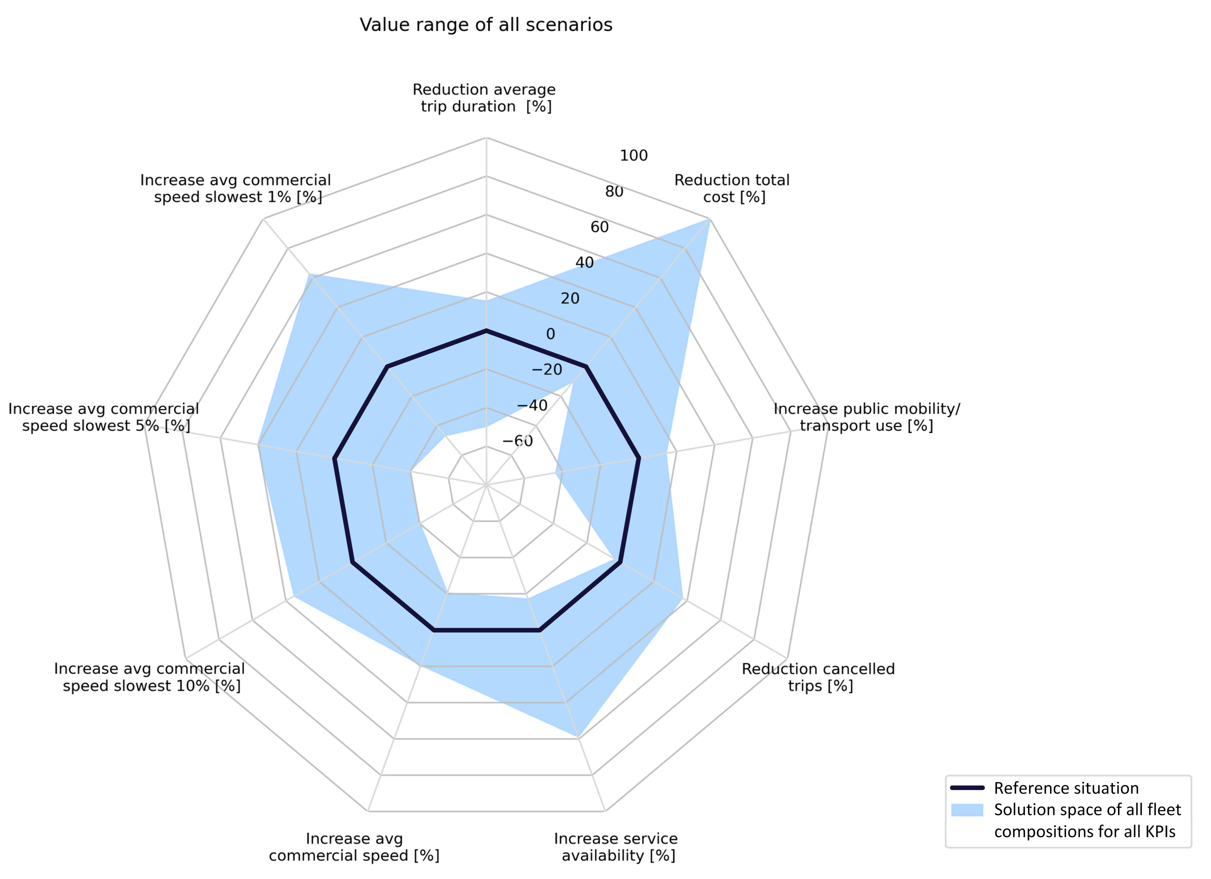


Figure 24: The range of relative improvements compared to the current situation of all 240,000 fleet compositions

5.2 fleet composition filtering by vision

Based on the visions described in Section 3.6, the fleet compositions are filtered according to three different visions: maximum average improvement, no deterioration anywhere, and maximum increase in ridership. The fleet compositions are named according to the number of vehicles present. For example, the fleet composition "B260 eB280 C342 S0 D11 R1" means 260 **B**icycles, 280 **e**lectric**B**icycles, 342 **C**abin scooters, 0 **S**cooters, 11 **D**emand-responsive vehicles, and **R**ide-share available.

The results are shown in radar plots, where the axes represent the KPIs and the lines represent fleet compositions. Within each plot, the fleet compositions selected after filtering are shown with solid lines. The fleet compositions later selected as potentially best are further referred to as scenarios 1, 2 and 3 and are shown in green, yellow, and pink, respectively. To reduce uncertainty, which will be explained in Section 5.3, additional runs are undertaken for the selected ones. These additional runs is shown with dotted lines in the corresponding colours. This highlights the difference between the initial 3 runs and the 30 or 32 runs (n=30 or n=32 in figures 25 to 29). It also shows how the filtered fleet compositions relate to the finally selected scenarios.

The first vision used for filtering is the highest average improvement. A uniform minimum improvement threshold is applied across all KPIs and is gradually increased, rejecting all fleet compositions that fail to meet the threshold for at least one KPI. This process is continued until only five fleet compositions remain; this point is reached at an improvement threshold of 10.21%. The five remaining fleet compositions are shown in figure 25. It is evident that, for both the percentage of cancelled trips and travel duration, all remaining fleet compositions achieve reductions only slightly above 10.21%, with small variation between them. Although fleet compositions with large cost reductions do exist, these reductions become smaller once the constraints imposed by the other KPIs are taken into account. The reductions in average trip duration and cancelled trips show little variation among the five fleet compositions, whereas the increase in average commercial speed for the slowest 1% of travellers and the increase in service availability vary more. Another observation is that the fleet composition “B260 eB280 C342 S0 D11 R1” performs best on most KPIs. However, when examining this composition per spatial settlement typology, several KPIs worsen in some typologies, suggesting that it may not be the best overall option despite its strong aggregate performance.

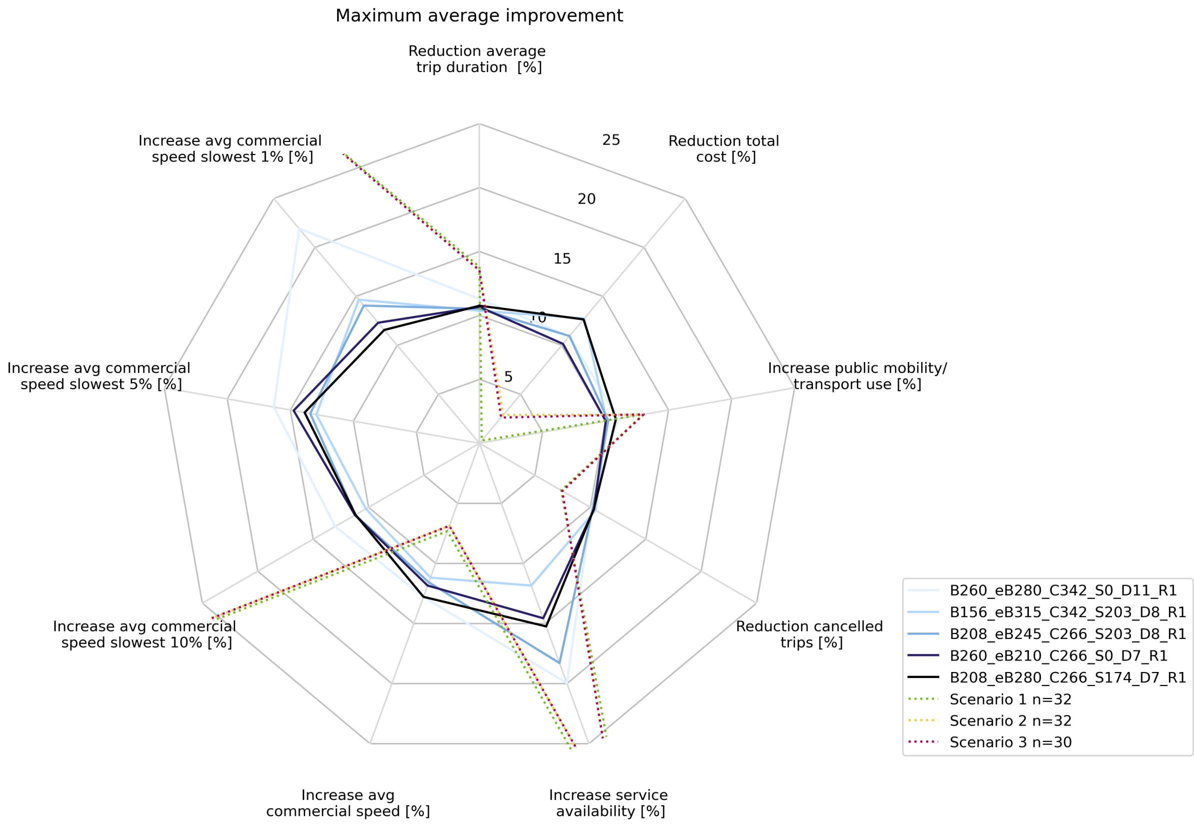


Figure 25: The range of relative improvements compared to the current situation

The second vision is maximizing ridership improvement. The goal is to increase "public mobility/transport use" as much as possible without lowering the region's existing average KPIs, until only five fleet compositions remain. The results show that increasing ridership leads to a different budget allocation that is generally not reduced, producing fleet compositions that differ from those obtained under the maximum average-improvement objective as shown in figure 26. Another observation is that higher ridership is associated with increased service availability. This is expected, when availability is higher, users can access their preferred mode more directly, reducing access time because they do not need to walk to a less convenient node. In addition, since perceived travel time is used as a trip-selection criterion, shorter perceived durations increase ridership.

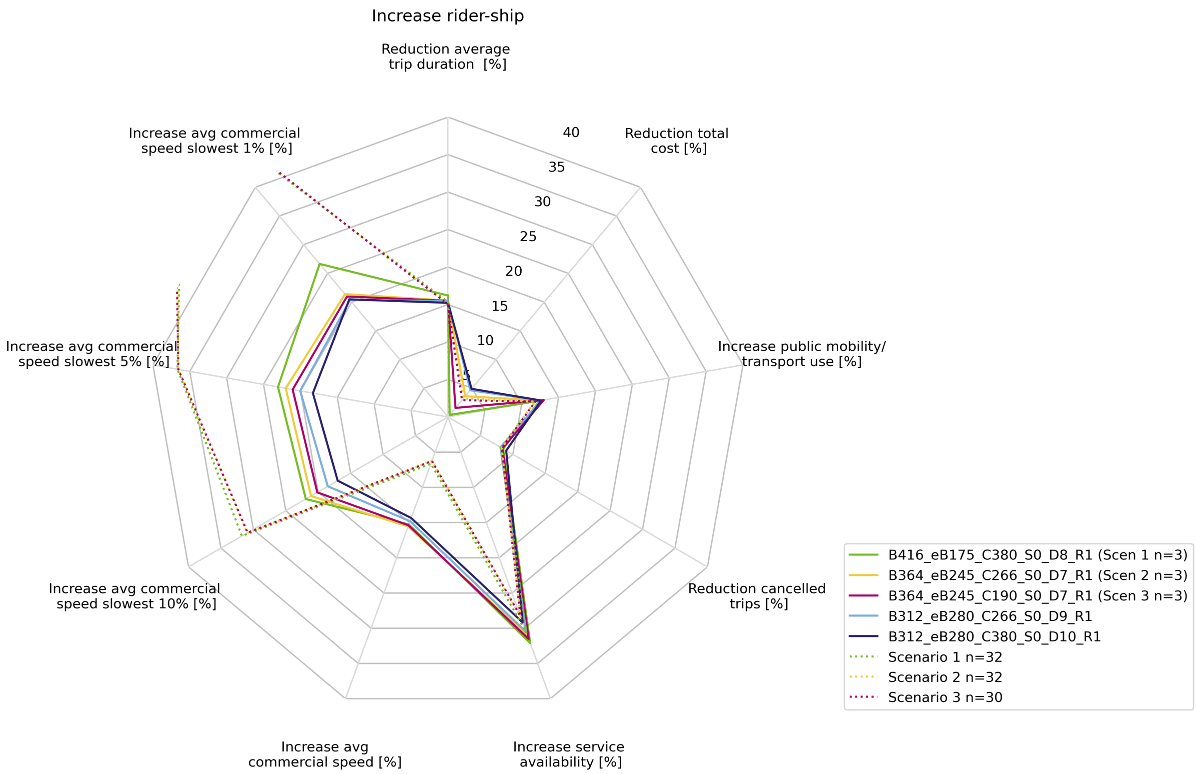


Figure 26: explanation of fleet compositions

The third vision requires that all spatial settlement typologies perform at least as well as the baseline on every KPI. Under this constraint it becomes apparent that for the suburban typology the current public transport system is difficult to outperform with public mobility. In particular the cancelled trips KPI in suburban areas is a binding constraint, 98% of fleet compositions fail to meet the baseline for cancelled trips, and the remaining 2% that meets the cancelled trips requirement fails to meet one or more other KPIs. If the cancelled trips KPI is excluded while all other KPIs must still meet or exceed the baseline within each typology, 23 fleet compositions remain.

During operational hours, buses provide a reliable, fast, high-capacity service. By contrast, public-mobility services may face capacity limitations, especially during peak demand periods, which can reduce vehicle availability and thereby lower effective service levels. The minimum and maximum KPI values across the qualifying set are shown as the range of the remaining fleet compositions in figure 27. Three fleet compositions also qualify under the ridership maximization objective and are highlighted as well. Within the remaining set, only 2 of the 23 fleet compositions include scooters, and 22 of the 23 include ride-share. This pattern is consistent with ride-share's relatively low cost and its usefulness in specific locations or time periods. Scooters appear less frequently because, like the public mobility within suburban contexts, scooters can substitute for trips that overlap with interlocal bus corridors in all spatial typologies. However when demand is high, scooter capacity constraints reduce reliability compared with interlocal buses. The variability for dispersed settlement is relatively low. This is because this area will mostly be served by walking for short distances towards the interlocal bus services because stations are generally located within dispersed settlement. Other parts of the dispersed settlement are generally located further off from the station and therefore mostly served by electric bicycles. throughout all fleet configurations the amount of electric bicycles is relatively constant which results in the lower variation.

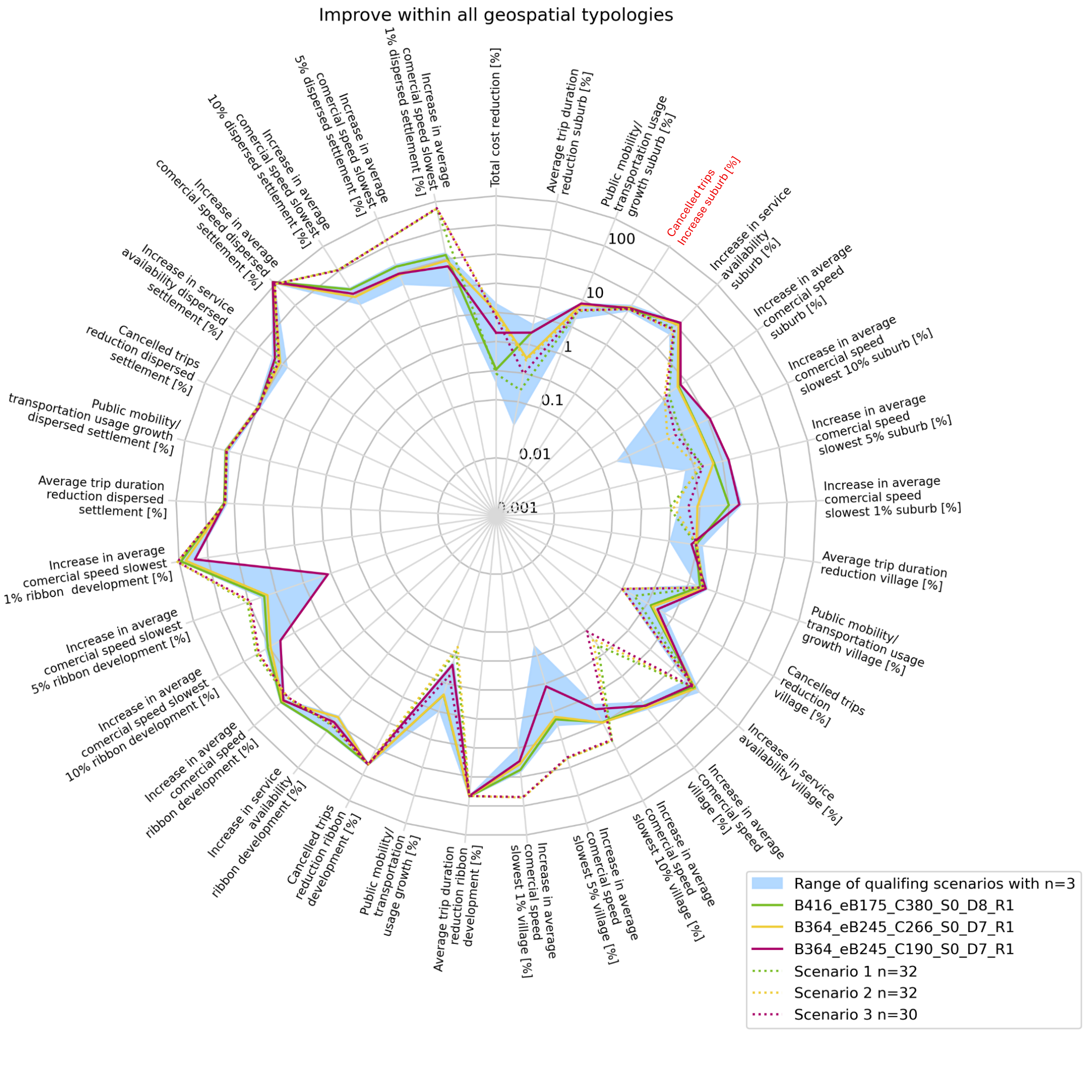
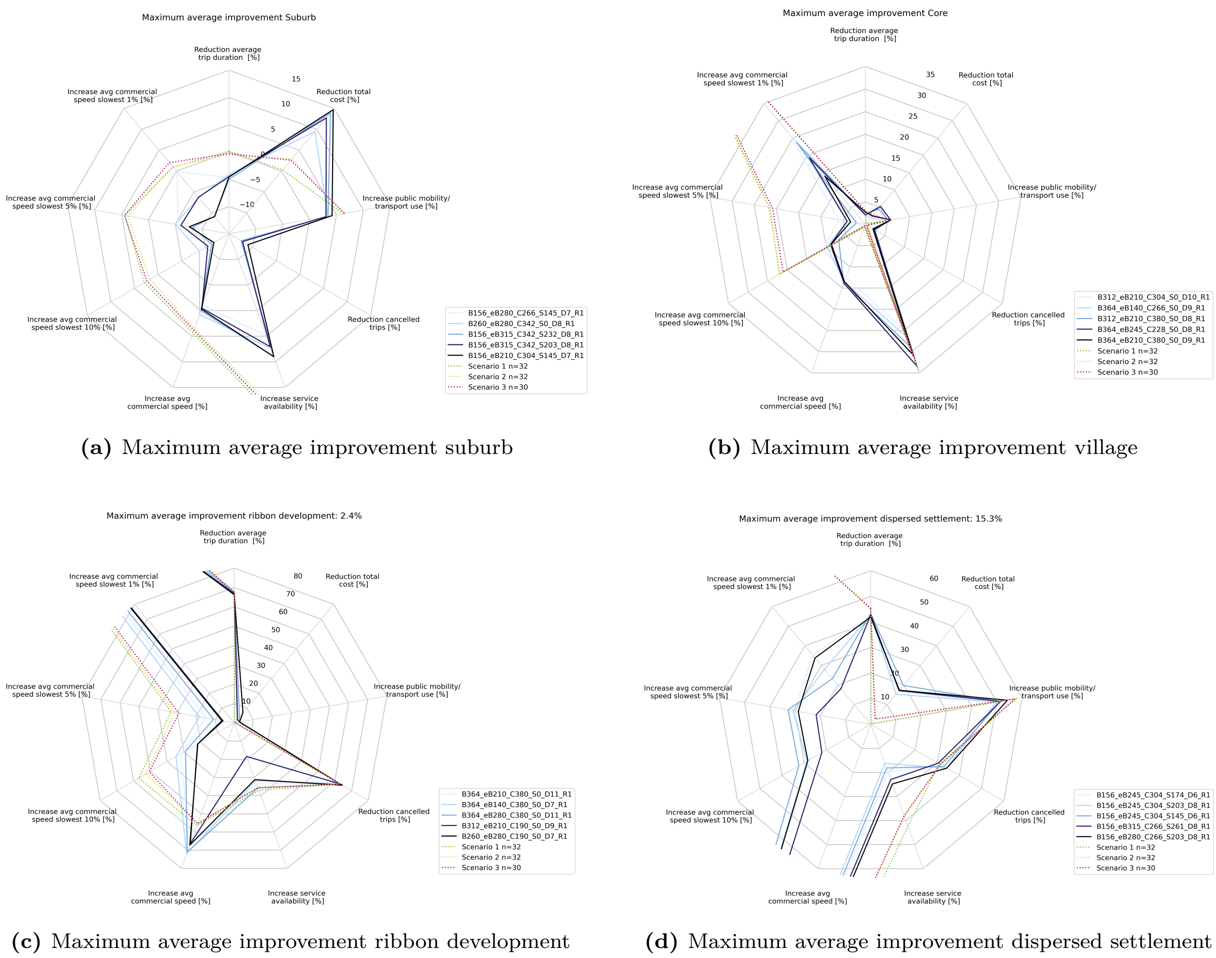


Figure 27: The range of relative improvements compared to the current situation

Besides filtering all fleet compositions to identify the best overall option, the same process can also be applied separately to each spatial settlement typology. This yields fleet compositions that are beneficial for a single typology but do not necessarily improve performance across the rest of the case area. Doing so provides insight into which modes are most beneficial within a given typology. When filtering all fleet compositions for the highest overall improvement, it again becomes clear that the lowest-density typology can achieve the greatest overall improvement. In contrast, for the suburban typology, even the fleet composition with the fewest disadvantages still shows a maximum detriment of 12.4%, as shown in Figure 28. Another observation is that, in both the suburban and dispersed-settlement typologies, the scooter is a relevant component of the fleet configuration (Figures 28a and 28d). In suburban areas, bus services are generally frequent enough to compete with scooters, so scooters take a smaller share from the bus. In dispersed settlements, trip distances are longer, making a faster mode more useful. At the same time, bicycle mode share is lower in these areas. This is likely because people more often choose a scooter for direct trips rather than using a bicycle as an access or egress mode to the interlocal bus.



(a) Maximum average improvement suburb

(b) Maximum average improvement village

(c) Maximum average improvement ribbon development

(d) Maximum average improvement dispersed settlement

Figure 28: Maximum average improvement per spatial settlement typology

Filtering for the largest ridership improvements per spatial typology yields no results for the suburban typology, because introducing public mobility leads to a detriment in ridership rather than an improvement. For all scenarios that remain after filtering, public mobility is used primarily as access and egress to the interlocal bus rather than for direct trips, except for trips shorter than two kilometres. This also explains why no scooters are included in any fleet composition because most are used for direct trips. Similarly, the number of electric bicycles is generally at the lower bound, and they see limited use for direct trips longer than two kilometres.

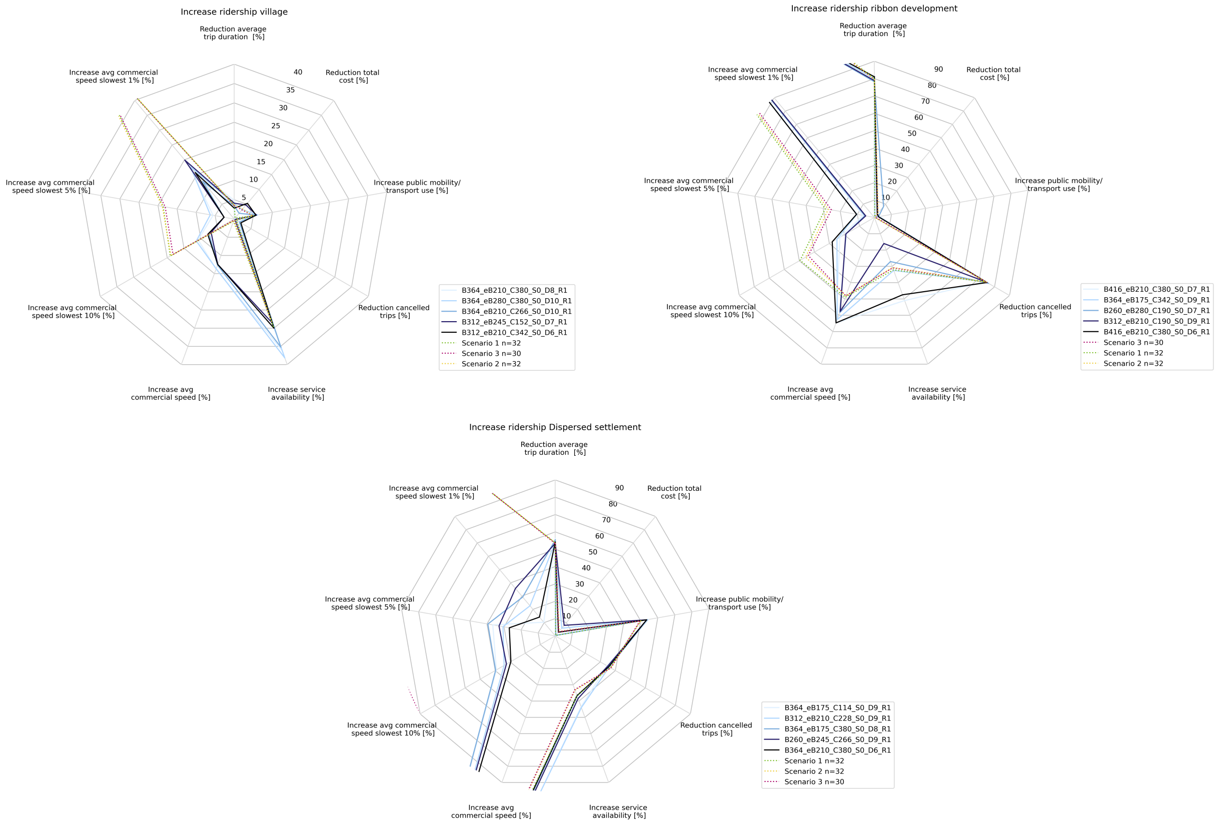


Figure 29: Maximum ridership improvement per spatial settlement typology

5.3 Certainty of potential best fleet compositions

Among the feasible fleet compositions, the fleet compositions “B416 eB175 C380 S0 D8 R1”,hereafter referred to as scenario 1, “B364 eB245 C266 S0 D7 R1”, hereafter referred to as scenario 2, and “B364 eB245 C190 S0 D7 R1”, hereafter referred to as scenario 3, appear in both the ridership increasing vision and improvement for all typologies. Because these three fleet compositions are inside the feasible set for two visions, these will be the potential best fleet compositions. Due to stochasticity, the outcomes differ between runs. Therefore, the fleet compositions may or may not be the best under repeated sampling. All fleet compositions were originally simulated three times, this reduces the buigest uncertainty. To investigate which of these three fleet compositions satisfy the KPIs with higher certainty at least 27 additional fleet composition runs for these best three fleet compositions are undertaken. To quantify the certainty per KPI, a one-sided hypothesis test is applied. The corresponding test statistic is described in equation 20 and equation 21. Because the current situation is modelled in the same model, this also has a certain uncertainty. The existing situation has 50 simulations to reduce the uncertainty on this side.

$$t \;=\; \frac{\mu_1 - \mu_0}{\sqrt{\frac{\sigma_0^2}{n_0} + \frac{\sigma_1^2}{n_1}}} \tag{20}$$

t is the t-value of the specific fleet composition, μ_0 is the reference KPI value, μ_1 is the KPI sample mean of the specific fleet composition, σ_0 is the KPI standard deviation of the reference situation, σ_1 is the KPI standard deviation of the specific fleet composition, n_0 is the number of reference fleet composition runs, 50 in this simulation and n_1 is the number of runs for the specific fleet composition(scenario 1 and 2 $n_1 = 32$, scenario 3 $n_1 = 30$).

$$\nu \;\approx\; \frac{\left(\dfrac{\sigma_0^2}{n_0} + \dfrac{\sigma_1^2}{n_1}\right)^2}{\dfrac{\sigma_0^4}{n_0^2\,(n_0-1)} + \dfrac{\sigma_1^4}{n_1^2\,(n_1-1)}} \tag{21}$$

With ν denoting the degrees of freedom, the t-table is used to quantify the confidence that a KPI improves upon the KPI of the existing situation. The t-table shows the relationship between the degrees of freedom, the significance level, and the corresponding t-value. Using the t-statistic from Equation 20 and the degrees of freedom from Equation 21, the significance level or confidence can be determined. This significance indicates how likely it is that the observed KPI difference is not due to random variation. The results are shown in the first three columns of Table 8. Many KPIs achieve 100% significance for these fleet compositions, while others yield lower confidence levels.

For KPIs that are not statistically significant, it is useful to quantify the worst-case deterioration that cannot be exceeded with 95% and 99% confidence. Conversely, for KPIs that are statistically significant, it is informative to know the minimum improvement that can be guaranteed with 95% and 99% confidence. Although one bound corresponds to a minimum increase and the other to a maximum decrease, both are the lower confidence bounds and can therefore be derived in the same way. Given the degrees of freedom and the 95% and 99% confidence level, the critical t-value (t_{crit}) is obtained from the t-table. Substituting t_{crit} into a adapted form of Equation 20 yields Equation 22, which provides the critical KPI change for a given fleet composition.

$$improvement \;=\; \frac{\mu_1 - \mu_0 - t_{crit} \cdot \sqrt{\frac{\sigma_0^2}{n_0} + \frac{\sigma_1^2}{n_1}}}{\mu_0} * 100\% \tag{22}$$

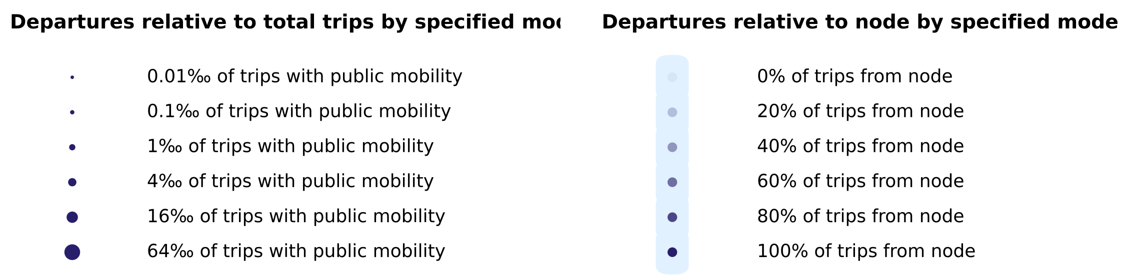
with *improvement* the procentual increase of the critical KPI value which is negative if a deterioration may occur, given the significance level of critical t-value. The results are shown in the last 6 columns of table 8. This table shows the extend in which the public transportation system can be improved with the given public mobility fleet compositions on certain KPIs. Given the stepwise implementation of fleet compositions and the selection based on few runs it can not be explicitly stated this are the best options. The only statement that can be given is how much these three potentially best fleet compositions can improve the system with a 95% and 99% certainty. The results indicate stronger evidence that scenario 1 outperforms the other fleet compositions.

Table 8: Certainty of fleet compositions per KPI

		Certainty KPI is above threshold[%]			**95% certain least guaranteed improvement [%]**			**99% certain least guaranteed improvement [%]**		
	KPI	scen1	scen2	scen3	scen1	scen2	scen3	scen1	scen2	scen3
Average	**Total cost**	85.4	100.0	100.0	-0.2	2.5	2.2	-0.4	2.3	2.0
	Average trip duration	100.0	100.0	100.0	13.6	13.4	13.3	13.4	13.3	13.3
	Public mobility usage	100.0	100.0	100.0	12.8	12.8	12.9	12.8	12.7	12.8
	Cancelled trips	100.0	100.0	100.0	7.1	7.2	7.3	7.0	7.1	7.2
	Service availability	100.0	100.0	100.0	32.4	30.1	30.1	31.9	29.6	29.7
	Commercial speed	100.0	100.0	100.0	7.1	6.6	6.7	7.0	6.5	6.6
	Com. speed slowest 10%	100.0	100.0	100.0	33.7	33.0	33.1	33.2	32.6	32.7
	Com. speed slowest 5%	100.0	100.0	100.0	38.9	39.1	39.1	38.3	38.6	38.7
	Com. speed slowest 1%	100.0	100.0	100.0	58.1	60.3	60.9	56.9	59.4	60.1
Suburb	**Average trip duration**	77.1	0.3	10.4	-0.2	-0.8	-0.7	-0.4	-1.0	-0.9
	Public mobility usage	100.0	100.0	100.0	5.9	6.1	6.2	5.8	5.9	6.1
	Cancelled trips	0.0	0.0	0.0	-17.5	-17.1	-17.1	-17.6	-17.3	-17.3
	Service availability	100.0	100.0	100.0	25.7	23.2	24.7	24.7	22.3	23.8
	Commercial speed	100.0	100.0	100.0	3.9	3.1	3.4	3.7	2.9	3.2
	Com. speed slowest 10%	99.9	98.0	99.8	1.5	0.4	1.0	0.8	-0.2	0.5
	Com. speed slowest 5%	100.0	100.0	100.0	2.9	2.5	3.2	2.3	1.9	2.6
	Com. speed slowest 1%	77.5	85.4	95.8	-1.1	-0.7	0.1	-2.1	-1.4	-0.7
Village	**Average trip duration**	100.0	100.0	100.0	2.6	2.8	2.6	2.4	2.6	2.5
	Public mobility usage	100.0	100.0	100.0	5.6	5.4	5.5	5.5	5.3	5.4
	Cancelled trips	96.2	88.4	91.4	0.0	-0.1	-0.1	-0.2	-0.3	-0.2
	Service availability	100.0	100.0	100.0	32.6	30.9	29.6	31.8	30.3	28.9
	Commercial speed	99.9	99.8	98.8	0.3	0.2	0.1	0.2	0.1	-0.0
	Com. speed slowest 10%	100.0	100.0	100.0	20.5	20.8	20.0	19.8	20.3	19.5
	Com. speed slowest 5%	100.0	100.0	100.0	19.7	20.6	19.5	19.0	20.1	19.0
	Com. speed slowest 1%	100.0	100.0	100.0	66.4	69.0	67.5	64.7	67.7	66.3
Ribbon developm.	**Average trip duration**	100.0	100.0	100.0	67.6	67.2	67.2	67.5	67.1	67.1
	Public mobility usage	81.2	75.1	99.3	-0.2	-0.3	0.2	-0.5	-0.6	0.0
	Cancelled trips	100.0	100.0	100.0	62.9	63.0	63.2	62.8	62.9	63.1
	Service availability	100.0	100.0	100.0	34.3	32.6	33.0	33.1	31.4	31.9
	Commercial speed	100.0	100.0	100.0	55.8	54.6	54.7	55.5	54.3	54.4
	Com. speed slowest 10%	100.0	100.0	100.0	54.4	50.3	48.1	53.2	49.2	46.9
	Com. speed slowest 5%	100.0	100.0	100.0	30.8	29.2	27.0	29.8	28.3	26.1
	Com. speed slowest 1%	100.0	100.0	100.0	325.4	329.4	330.6	322.0	325.5	328.1
Dispersed settlem.	**Average trip duration**	100.0	100.0	100.0	45.3	45.1	44.8	45.1	45.0	44.6
	Public mobility usage	100.0	100.0	100.0	56.9	56.8	56.3	56.6	56.5	56.0
	Cancelled trips	100.0	100.0	100.0	30.5	31.1	31.0	30.4	31.0	30.9
	Service availability	100.0	100.0	100.0	39.8	36.0	35.5	38.7	35.0	34.3
	Commercial speed	100.0	100.0	100.0	320.0	319.0	317.2	319.1	318.3	316.2
	Com. speed slowest 10%	100.0	100.0	100.0	102.8	102.6	100.1	101.5	101.5	98.4
	Com. speed slowest 5%	100.0	100.0	100.0	121.9	121.7	120.8	120.1	120.1	118.8
	Com. speed slowest 1%	100.0	100.0	100.0	229.3	233.1	236.6	226.1	229.8	233.3

5.4 Description of potential best fleet composition

The potential best fleet composition is scenario 1. This fleet composition consists of 416 Bicycles, 175 electric Bicycles, 380 cabin scooters, 8 demand responsive transportation vehicles and ride-share is available. Because it is the potential best fleet composition, the functioning of this fleet composition is investigated. All (multimodal) trips of all runs of this fleet composition simulation have been split into separate route-legs per mode and are sorted by OD-pair and mode. within this chapter the findings are presented per mode. For every mode the trips are plotted on the road map of the case area. Depending on the number of trips for a given OD-pair, the corresponding line is displayed thicker and less transparently. To show the usage of each mode the trips are for bikes and electric bicycles are split into direct trips and trips in combination with public transportation to help explain how the modes are used. For every mode also a map is present that shows the share of the total trips within the case area that is departing from a certain node and the share of trips departing from the specific node is by this specific mode. the legend for all these figures is shown in figure 30, note that this figure is at the same scale and the size of the nodes is therefore directly comparable.



(a) Legend size

(b) Legend hue

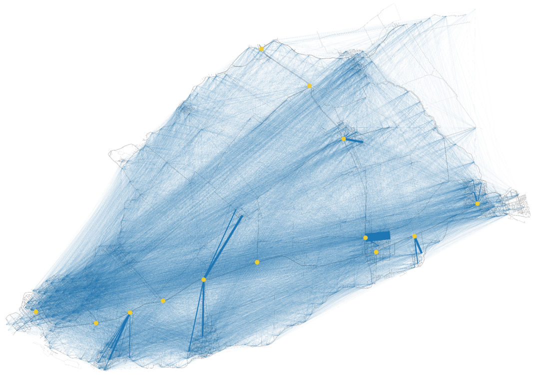
Figure 30: Usage of different modes per node

Shared bicycles are used in 58% of all simulated trips that make use of public mobility, making them the most frequently used mode. These trips can be part of a multimodal trip or a direct trip. Based on the aggregate shares, 83% of shared-bicycle trips are direct trips under two kilometre, 15% are part of a multimodal trip, and 2% are direct trips above two kilometre. This suggests that shared bicycles fulfil an access and egress role for the interlocal bus, although this is not the dominant trip type in the full sample.

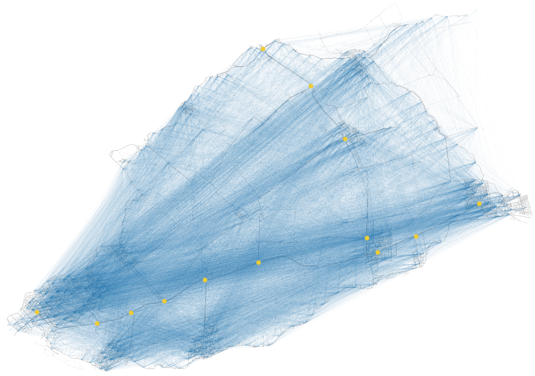
Figure 31c shows that a substantial share of short trips is undertaken in suburban regions. When suburban regions are excluded from the analysis, the shares change considerably. Across the remaining spatial typologies, the average share of shared-bicycle use increases to 78%, indicating a central role for conventional shared bicycles in overcoming the first and last mile. In this subset, direct trips under two kilometre decrease to 20%, and longer-distance direct trips decrease to 1%.

Shared bicycles are used across the entire case area, with the highest concentrations near suburban areas and villages as shown in figure 31a. Although shared bicycles can be used for direct trips, given the constraints this is not necessarily the dominant use case in low-density areas. For trips shorter than two kilometre between origin and destination as shown in figure 31a.

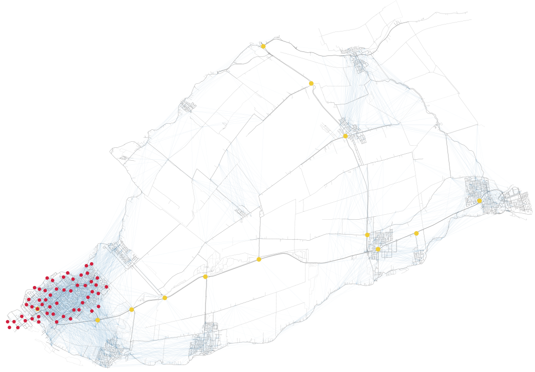
At node level, shared-bicycle usage is evident in Figure 31e. The dark hue for many nodes indicates that a high share of departing trips uses a shared bicycle. This share is lower at station nodes, where the choice set is larger because multiple modes are concentrated. At the same time, the marker radii at stations are larger than at most other nodes, indicating a large share of total trips.



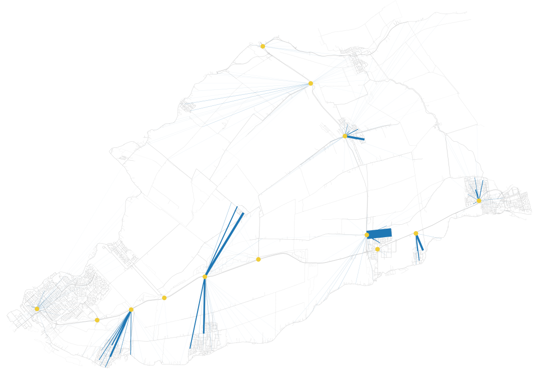
(a) All trips



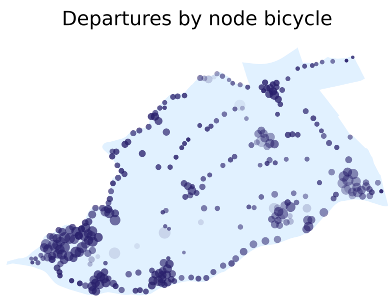
(b) Direct trips above 2km



(c) Direct trips under 2km with all suburban nodes shown in red



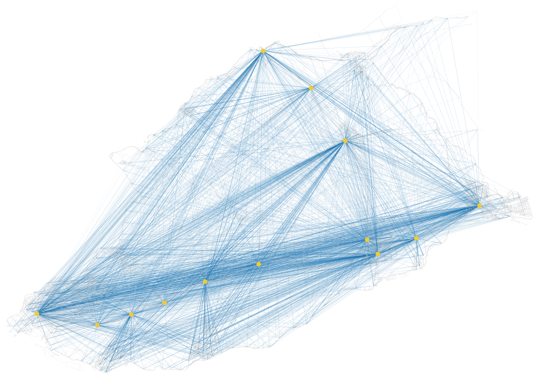
(d) Multimodal trips



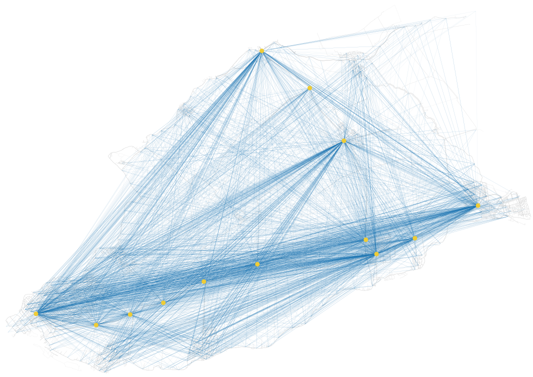
(e) Departures

Figure 31: Bicycle

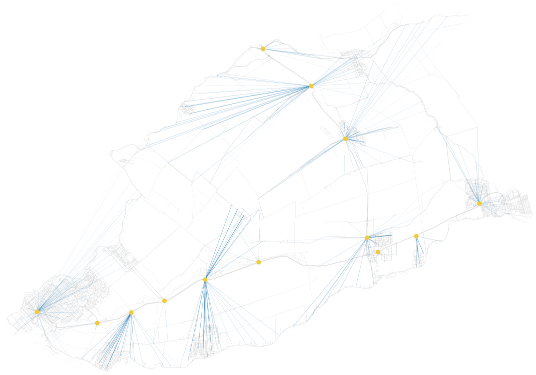
Shared electric bicycles are used in 18% of all simulated trips that make use of public mobility, making them the second most frequently used mode after shared bicycles. Due to the imposed constraints, electric bicycles are concentrated around stations, and most trips are therefore multimodal. In total, 89% of shared electric-bicycle trips are multimodal, while 11% are direct trips. Given their higher speed and ease of use, shared electric bicycles can reach further into rural areas and facilitate trips to destinations that are located farther from interlocal bus stations. At node level, shared electric bicycles are of greater importance at stations and at nodes in close proximity to stations (Figure 32). This can be explained by demand for shared electric bicycles in situations where feasible egress alternatives are absent, leading users to walk to the nearest node with an available shared electric bicycle and continue towards their destination, with an intermediate stop at the station. Under the applied constraints, this is only permitted when the station has no availability and the electric bicycle has sufficient remaining battery.



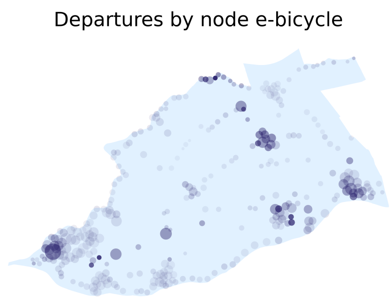
(a) All trips



(b) Direct trips



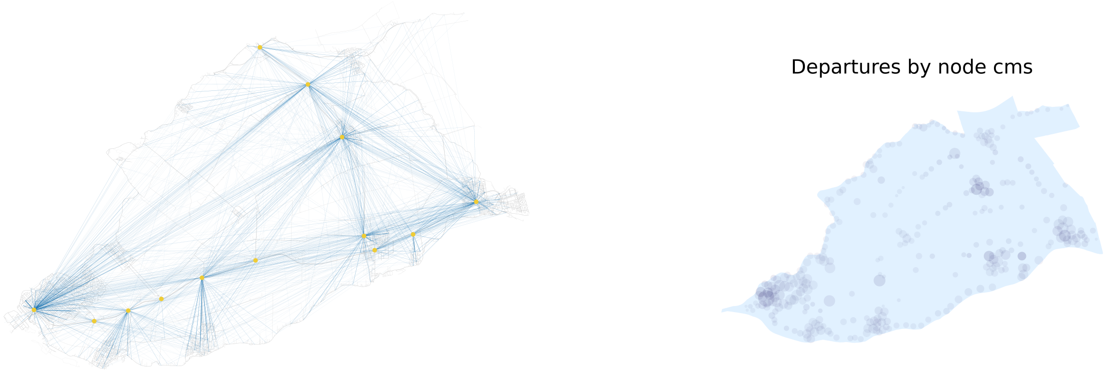
(c) Multimodal trips



(d) Departures

Figure 32: Electric bicycle

Cabin scooters are used in 3% of all trips made with public mobility. Due to their lower operating speed, cabin scooters are constrained to operate only to or from a station, which leads to a concentration around the closest station. Approximately 87% of cabin-scooter trips occur between a node and its nearest station (and vice versa) (figure 33a). In general faster alternatives are available, and the low trip share indicates that cabin scooters are selected primarily when faster modes are not feasible for a given user. Cabin scooter usage is highest during hours of darkness. This is consistent with the constraint that users are less likely to use ride-share during darkness and that, outside the operating hours of the bus and DRT, the available alternatives are more limited. During rain, cabin-scooter usage also increases. Cabin scooters are used almost exclusively in multimodal trips. During daytime, 99% of cabin-scooter trips are multimodal, and across all simulated trips approximately 96% of cabin-scooter trips are multimodal. At node level, shared cabin scooter usage is relatively uniform and does not appear to depend strongly on population size (figure 33b). In relation to the presence of travel groups O and P (table 6), a relation can be suggested; however, this is not statistically confirmed.



(a) Trips **(b)** Departures

Figure 33: Shared cabin scooter

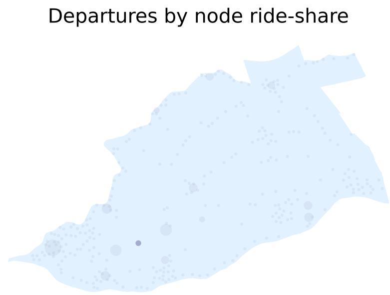
Demand responsive transportation is used in 2% of trips using public mobility. In figure 34a the operational constraints are clearly visible: DRT trips occur only between points and stations with the shortest approach duration even though the percentage of trips with DRT is little the precence of trips show many people needing this solution because it is nearly never the fastest solution.

(a) Trips **(b)** Departures

Figure 34: Demand responsive transportation

Ride-share is used in 3% of all trips that make use of public mobility. It is available at 5% of all nodes. These nodes form a corridor, with a stop at one end and a station at the other. Given this limited availability, a 3% mode share is substantial. The maximum share of departing trips from a node with ride-share is 63%, observed for the connection from the provincial road towards Ouderkerk aan den IJssel (figure 35a). This indicates the significance of ride-share where it is available. Within the model, ride-share is particularly attractive during the morning and evening peak periods, especially in the peak-flow direction, due to the higher speed of passing motorists. By contrast, in the opposite direction or during periods of low traffic density, ride-share facilitates fewer trips. At node level, stations clearly appear within the ride-share results. For example, the station “Lekkerkerk, Kerkweg,” shown as “+” in figure 22, has one of the darker hues among the nodes.

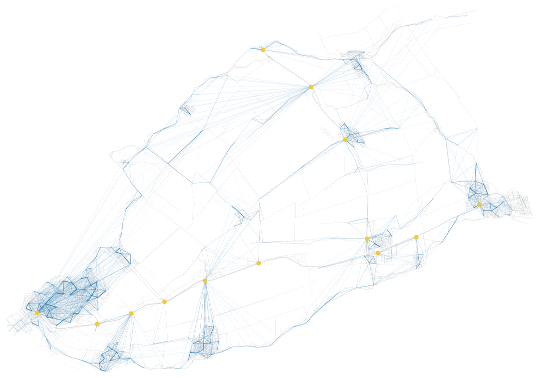
(a) Trips



(b) Departures

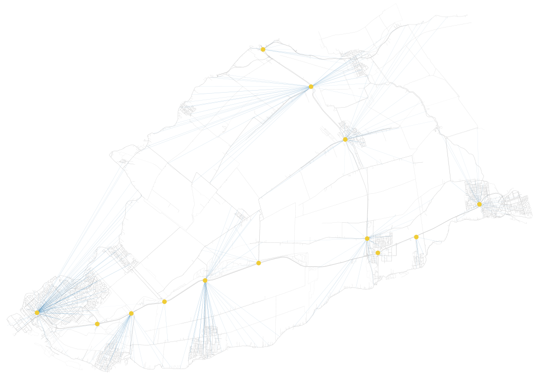
Figure 35: Ride-share

Walking is part of 65% of all trips that make use of public mobility. Most walking route-legs are undertaken to reach a node that is not the closest, but that offers better mode availability or a higher service level, accounting for 62% and 23% of walking trips, respectively (figure 36b and 36c). For these two reasons, separate maps are shown. Direct walking trips are also present and account for 15% (figure 36d) . These values indicate that modes are often not available at the closest node, requiring users to walk a short distance to a more suitable node. In 91% of cases, this walk due to unavailability is shorter than 400 metres. When interpreting public mobility as public transportation, this suggests that 91% of trips start from a sufficiently close access point. The maps also show that longer walks towards stations occur, but only rarely: only 10% of trips to a station are longer than 1 kilometre. This indicates that, when such trips occur, there are likely no feasible alternatives available, since mode choice is based on perceived travel time and walking has the lowest speed.

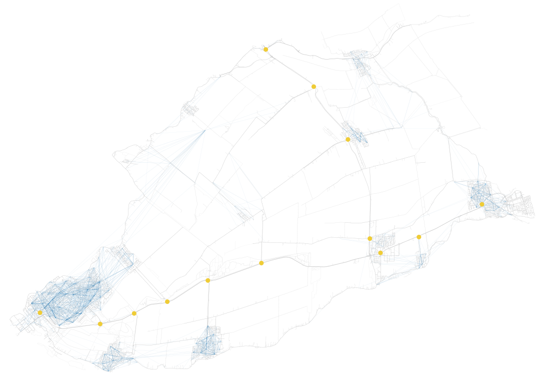


(a) All trips

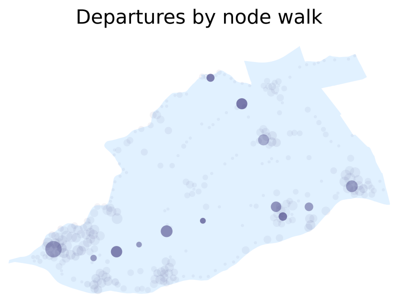
(b) All trips due to unavailability



(c) All trips to/from station



(d) All direct trips



(e) Departures

Figure 36: Walk

Cancelled trips are distributed spatially throughout the case area. No specific trips show up more as other and the amount of cancelled trips per node is in line with population density(figure 37).

(a) Trips **(b)** Departures

Figure 37: Cancelled

The results before are shown per trip and node but when aggregating data and splitting the data per spatial settlement typology in figure 38 the differences in usage of certain modes per location spatial settlement typology become clear. While the bicycle is dominating over other modes in all areas there is a immense difference, this can partly be explained by the distance to a inter local bus service, the villages on average do have a higher distance to the inter local bus service and users therefore prefer a faster mode. simultaneously due to the smaller size of the villages more trips are shorter and within walking distance. Within the dispersed settlement most walking trips are to or from a station. Multiple stations are located within dispersed settlements and when the distance between transfer location and destination are short it is normally faster to directly walk as use a egress mode. this also holds for the access side. Also multiple dispersed settlement locations are located within a very low density area resulting in less available shared vehicles. This may result in walking trips due to unavailability. Given the current commercial speed of public transportation is bellow walking speed within dispersed settlement regions, fleet compositions with a high percentage of walking will therefore never be rejected while in the suburbs this will be rejected due to a higher commercial speed.

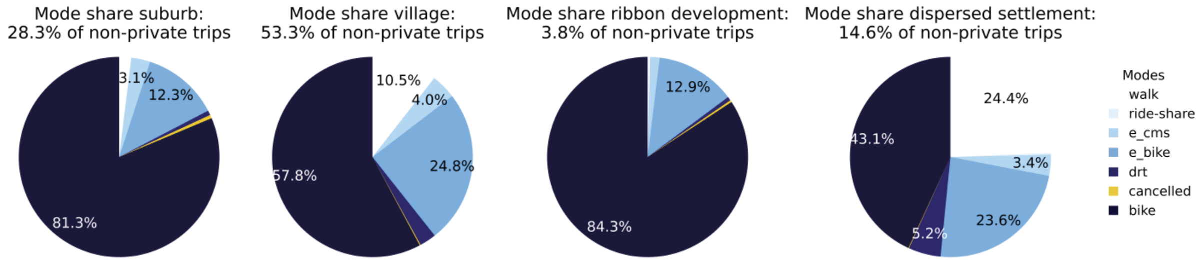


Figure 38: Usage of different modes per spatial settlement typology together with the share of trips made in a certain typology

6 Conclusions and recommendation

To answer the main question: “How should public mobility be integrated into the public transportation system to improve the public transportation system?” first the sub questions will be answered.

6.1 Answers to sub questions

The first sub question: “Which node configurations exist elsewhere for different public mobility aspects and which are best applied in rural regions according to literature?” is answered in detail within section 2.2. Most node configurations depend on the number of different public mobility services available at that node. Because trip densities are lower in rural regions, it is desirable to bundle modes at nodes to improve mode at node availability. Different service levels are applicable because nodes serve different functions. A point, node without facilities, is typically the nearest node for the user and should be widely available. Because distances in rural regions are larger, more points are required to ensure accessibility across the entire region, and especial nodes close to the destination as people are less likely to walk longer distances near the destination. Therefore, a very simple design is preferred, to be easily implemented in many and different locations. A point should include an area where modes can be parked and should be clearly recognisable through signage. Preferably, this area is physically separated discouraging parking outside the point by shared mobility users, this is preferred by surrounding residents and can keep local acceptance to the system high. Nodes that include a ride-share option, stops, are less common and because they involve (longer) waiting times, require more comfort. Therefore, a bench should be provided. Ideally, a shelter is available so travellers can take cover from the rain while waiting. Nodes with a transfer option to a inter local bus, stations, are least abundant in the area and can therefore be of high quality. Travellers will encounter waiting time at a station therefore a station must have a bench, waiting shed and dynamic route information. The distances between modes should be as short as possible to reduce transfer time.

The second sub question: “Which public mobility configurations are most promising to improve reachability within rural regions according to literature?” is answered in detail within section 2.4. A public mobility system should consist out out of multiple aspects, depending on the user or desired trip a different aspect may be more useful or preferable. Given the rural setting distances are large and battery powered shared modes often need a battery switch or charging station. It is too expensive to operate battery powered shared mobility on a many-to-many tactic and should therefore be restricted to frequently pass by a charging location. Therefore battery powered shared mode trips will be restricted to have the origin or destination always at a station where battery swaps and charging can be concentrated. 25km/h scooters are competing with electric bicycles and offering multiple modes with the same target group only reduces certainty of availability at nodes. Given the higher potential of electric bicycles as a shared mobility aspects in the rural region 25km/h scooters should not be considered. Microcars are to slow for a bigger vehicle to merge with normal traffic on rural roads and are not allowed on the bicycle path reducing shortcuts. The speed difference between microcar and traffic creates unsafe situations combined with the width of the vehicle overtaking is more dangerous compared to smaller vehicles on narrow roads. Therefore microcars should be avoided. This results in a limited set of public mobility aspects which seem potential: a DRT service professionally operated in vans with specific meeting nodes. A ride-sharing system which has limited nodes and shared mobility containing 45km/h scooters, Cabin scooters e-bicycles and conventional bicycles of which only the conventional bicycles are allowed to operate a many-to-many tactic while all battery powered modes must operate few-to-many and if present in the region the neighbourhood bus could full fill a important role. This list is displayed in more detail in figure 16.

The third sub question: “Which scenarios for fleet composition of public mobility aspects should be considered to model a public mobility given the geospatial indicators of the case area?” is answered in chapter 3.5. Due to limited computational power not every possible fleet composition will be tested however with steps a set of fleet compositions will be tested. To determine the set first the maximum possible fleetsize is determined by simulating a single public mobility aspect fleet composition. A set of ten different fleetsizes per mode is determined with equal steps between zero and the maximum fleet size of the specific mode with integer values. All possible combinations are created with the set of different fleet sizes per node resulting in 240,000 fleet compositions which will be tested.

The fourth sub question: “To what extent can integrating public mobility into the public transportation system improve reachability within rural regions?” is answered in chapter 5. Reachability can be improved in multiple manners, by improving commercial speed more locations become reachable, better availability makes it possible possible to reach a destination at more moments. When less trips are cancelled more people reach their destination and when the given set of trips reduces average trip duration people will tend to go travel further, increasing reachability. Depending on the fleet composition this is answered differently. For the selected fleet composition that may be the best fleet composition. This question is unanswered with 99% certainty that the Average trip duration will decrease with 13.4%, the amount of cancelled trips reduce with 7%, the service availability improves with 31.9%, and the commercial speed improves with 7% The biggest gain is for the slowest 1%trips, The new set of slowest trips will be at least 57.9% faster.

6.2 Answer to the main question

The main question: “How should public mobility be integrated into the public transportation system to improve the public transportation system?” is answered in this section. The first two paragraphs focus on the Krimpenerwaard, and the third paragraph focusses on rural regions in general.

The performance of public mobility is better, compared to the currently existing public transportation within Krimpenerwaard. This holds on average and also for most spatial settlement typologies. This is however not true for the suburb region of Krimpen aan den IJsel. This both confirms the existing quality of public transportation within the different spatial settlement typologies and the limited capability of public mobility within more trip dense areas. Therefore it is not recommanded to implement public mobility as a replacement within suburb locations. Within all different spatial settlement typologies there is a improvement, the less trip dense the area the higher the improvements. Due to trip density variations during the day rush hour bus services within the spatial settlement typology of villages operating at more trip dense time windows are also irreplaceable with public mobility.

For the specific composition multiple considerations should be made. A key finding concerns the role of e-scooters in a rural context. Within the model constraints, all battery-powered modes must start or end at a station-level node. Under these conditions, e-scooters become a strong competitor to the interlocal bus service itself, because of their relatively high speed and the directness. This competition leads to two undesirable dynamics: demand concentrates heavily on e-scooters, while the interlocal bus occupation rate lowers. This increases total system costs, and because the e-scooter fleet size is limited due to the system cost constraints, the system also becomes unreliable due to a too low availability when many users simultaneously prefer e-scooters. Consequently, e-scooters are not suited for a robust rural public mobility system. In contrast, cabin scooters emerge as a functional and robust mode for the rural region. The model results indicate that the cabin scooter is used throughout the day, consistent with the assumption of higher perceived social safety, also when DRT is outside operating hours. The lower speed of a cabin scooter naturally positions it as an access/egress mode rather than a replacement for longer interlocal trips. This reduces direct competition with the interlocal bus, supports high interlocal bus utilisation rates, and helps maintain system robustness while still providing essential coverage for users who need a safe and accessible option. Finally, the trip patterns show a clear division of usage between bicycles. Conventional bicycles are used abundantly across the entire area, predominantly for short trips but also for a small share of longer trips. However, most longer single mode public-mobility journeys are made by electric bicycles, indicating that battery powered modes are particularly effective for extending the viable single mode trip, access/egress, length in rural settings without undermining the function of the interlocal bus. It creates the possibility to reach a (transfer)station that is en route instead of reaching only the closest station. Together, the modelled results suggest that a robust rural public mobility system is best structured around strong accessibility coverage, as seen in the vision to increase rider ship as much as possible. It is clear this is only possible when increasing the availability. Bicycles are the best solution for local circulation, and electric bicycles for longer connections, while eliminating e-scooters to avoid costly and reliability-reducing competition with the interlocal bus network.

Therefore the best integration of public mobility is by using a fast and frequent inter local bus service as the core of the system integrated with a mix of demand responsive transportation, ride-share and shared mobility. The demand responsive transportation (DRT) should operate at any node, it however must reduce trips as much as possible and therefore only connect to/from the nearest interlocal bus service stop. The ride-share should only be focused on a few corridors between villages further away from the interlocal bus service and the interlocal bus service station located most logically for car drivers to pass by. Shared mobility should consist of conventional bicycles, electric bicycles and electric cabin scooters. for which the electric modes should operate as a many-to-few (or node-to-interlocal bus station) tactic creating charging opportunities at the few interlocal bus service stations while conventional bicycles may drive any-to-any node. The exact amount of modes is case specific and can not explicitly stated for general rural regions.

6.3 Recommendations

It is recommended to introduce public mobility next to the existing public transportation system within the Krimpenerwaard, with a primary focus on the dispersed settlements, ribbon developments and villages. Given the current frequency of public transportation, a public mobility system is expected to generate a much higher performance. The least resident dense areas, not served by the interlocal bus service, in the Krimpenerwaard are currently not or only a few times a day reachable with the existing public transportation system. These areas will therefore have a big improvement of reachability. In these areas the biggest gain can be achieved by implementing shared mobility consisting of conventional bicycles, electric bicycles and cabin scooters next to the existing public transportation infrastructure. Conventional bicycles and electric bicycles offer the biggest improvement. Cabin scooters make the system inclusive and better weather resistant. Ride-sharing is infeasible in these areas due to the low density and it is therefore not recommanded to promote besides existing acquaintance based ride-sharing. Introducing a DRT within this area is urged if the existing local busline is to be discontinued. Otherwise the DRT is optional to offer more frequent trip options complementing the existing public transportation system. For success, public mobility should be implemented as a network, as low availability and few reachable destinations will result in failure. If a stepwise introduction is desired, first nodes must be created in dispersed settlements and ribbon developments, supplemented with nodes at key facilities to support access and egress together with additional desired nodes proposed by the community to generated a positive public perception. In case of step wise introduction the villages will be the next step Benefits are lower within villages but will create more equality between trips.

Implementation should always consist of a mix of modes which must be adapted to local spatial conditions and distance to frequent interlocal bus services, resulting in different emphasizes in mixes of modes per location as shown in figure 38. For Krimpen aan de Lek and Ouderkerk aan den IJssel, the recommended emphasises is on conventional bicycles due to the short distance to a more frequent bus service, electric bicycles remain relevant, particularly for destinations and facilities in Krimpen aan den IJssel. For Gouderak and Lekkerkerk, which are located further from the interlocal bus service, the recommended mix shifts towards electric bicycles while conventional bicycles remain important. In Lekkerkerk the relatively high trip density is incompatible with public mobility. Bus services (during rush hour) are better compared to public mobility. In Bergambacht, Haastrecht, Schoonhoven and Stolwijk, public mobility is less used due to short access and egress distances to the interlocal bus service, though it remains useful for trips reaching outside of a interlocal bus service station its service area. Ride-share is most relevant as a corridor solution, with potential between the village core of Ouderkerk aan den IJsel and station ”Lekkerkerk, Kerkweg”, and between the core of Krimpen aan de Lek and ”Krimpen aan de Lek, De Viersprong”, where it can improve access to the more frequent interlocal bus service. In all areas, a cabin scooter serves great importance for inclusivity and becomes crucial if a bus may be to disappear.

Within South-Holland at multiple locations demand responsive transportation (DRT) is present. DRT should be monitored and implemented with caution. It is strongly recommanded to create cheaper alternatives to demand responsive transportation at locations DRT operate. Any other mode besides a conventional bus with a average occupation bellow 1.4 is a cheaper alternative. Offering a conventional bicycle as alternative is already financially beneficial if the bicycle is replacing a DRT trip at least once a month. This cost containment is however only possible if people are aware of all options available at a certain node. Therefore communication is important.

DRT vehicles themselves should be used as a primary channel for behavioural nudging and user education. Passengers using DRT are already engaged with flexible mobility and are therefore a key target group. Placing clear in-vehicle information about available alternatives, can increase user awareness of alternatives and reduce DRT consumed financial capacity. Simultaneously most DRT users arrive by interlocal bus, where onboard information screens also provide an effective channel to communicate transfer options. This approach is already applied in other concession regions, figure 39 provides an example from Zeeland, where passengers are informed about onward DRT options during the interlocal bus trip. While figure 39 only shows DRT, if more options are available it should include all options. Besides providing information about DRT alternatives information on last mile solution at nodes must also be clear. Although shared bicycles are available at many locations in South Holland, their presence is often not noted by many people and should be better communicated. Also the DRT itself is not always clear where it is operating. the DRT-symbol is not (consistently) present on the bus stop sign.

Figure 39: Information on egress options in Zeeland, provided by Conexxion (Waaij, 2025).

Second, communication and marketing efforts of the province should prioritise the mobility platform rather than individual modes or operators. Current campaigns in South Holland often highlight specific mobility providers, while platforms that enable access to multiple operators are unheard of. This contributes to a fragmented user experience and increases dependence on individual companies. If an operator exits the market or is replaced, users may need to adopt new applications and routines, which can create a barrier to continued use. In contrast, when users are accustomed to a platform that aggregates multiple suppliers, switching between operators becomes less disruptive. To support this, it is recommended to strengthen requirements for interoperability, ensuring that operators integrate with platform(s) that provide access to the full available fleet rather than only a subset.

7 Discussion

Given the literature study multiple operation constraints are introduced. These constraints are mostly based on literature investigating a single part of the public mobility spectrum. If different hypothesis are formulated for the operating constraints the results of the study will also differ.

The used OD-matrix may not be a perfect representation of the area. The OD-matrix is realised under the assumption that no external imbalance is present and everyone will be at the same place at the end of the week as the beginning. Even though for the duration of a week this is likely it is not always true for everyone. Also the assumption that the residual of the OD-matrix minus the car, bicycle and walking trips yields the public transportation trips is acceptable but given the issue with a missing bus link in the model people may be choosing different when this link is present influencing all other OD-matrixes too.

Too use the MNL heat parameters must be selected. These are calibrated to the OD-matrices. Given the OD-matrices may have a slight imperfection this calibration will enlarge the imperfection. This can be reduced by investigating the travel behaviour within the area and determining the heat parameters from this study. Given the MNL is only based on a perceived time function while more parameters influence mode decision a additional study should be conducted within this area to have a more realistic generalised cost function including all different available modes. With this study the generalised costs become more realistic and the heat parameters can also be determined more arcuately.

All fleet composition simulations are run with three different runs, this is too little to have a significant result. To have a more certain selection of the truly best fleet compositions more runs should be conducted. Within the current study the potential best solutions are the only fleet compositions with more runs improving the certainty of the achieved KPIs for that fleet composition but this does not improve the certainty this is actually the set of best fleet compositions.

Within the model the shared modes are only rebalanced if a DRT vehicle is available and only if the stock at a station closes zero or if a point contains more as 5 same mode vehicles. If different assumptions are made for recirculating shared mobility the amount of vehicles may reduce and the composition of cost per fleet composition will differ.

7.1 further research

Further research is needed to address several gaps identified in the current work.

First, better input for the OD matrix is needed. The existing mobility models for the Krimpenerwaard are incomplete and should be supplemented to encompass all relevant links for cars, public transport, cycling, and walking. Alternatively, the workaround used in this research, using a gravity model, requires improved calibration and sensitivity testing, particularly regarding how heat or impedance parameters affect trip distribution outcomes.

Second, the vehicle preference assumptions should be strengthened using empirical choice data. Capturing a better heterogeneity across user groups, trip purposes, and constraints—to better represent how travellers substitute between vehicles and modes.

Third, the evidence base for cabin scooters remains limited. Additional studies should better quantify their operational potential, user benefits, and constraints relative to other modes.

Fourth, alternative node sets should be explored to assess how spatial aggregation choices change model outcome and policy conclusions. Simultaneously the analysis should be replicated across different locations to test transferability and identify context-specific effects driven geospatial structure.

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For this report AI is used to improve modelling code when errors occurred, improving model calculation speed, plotting data into visuals and writhing improvement suggestions.

A Societal impact

This thesis will give an alternative framework to structure public transportation into public mobility for low-density rural regions. This evolution will have an impact on the users, operators and administrators, both positive and negative.

The conventional solution to create mobility in rural regions is implementing enough scheduled based local bus services. In previous years however, the interpretation of enough is seemingly changing. local bus services have declining passenger numbers and it is very expensive to sustain previous service levels(CROW 2024). With new concessions it is visible that local bus-services service levels are lowering, less frequent, smaller buses, more winding route to merge multiple loss-making services into a single bus service or completely disappearing(CROW 2024). This result in a cost reduction for operators which may lead to a higher profit, or competitiveness in tendering for concessions for the administrators, mostly political entities like provinces, this can be good as a cost reduction or bad as a decline of service level, depending on the political background. For the user, this is generally a negative phenomenon.

By making a framework how to evolve public transportation into public mobility, areas in which local bus services are obliterated will have an improvement in accessibility because all locations which first saw a local bus line and lost it, will again be incorporated in a system of public mobility (Bastiaanssen and Breedijk 2022). This will improve the mobility within the area. For the operator this will be a way to make interlocal bus services more profitable while reducing less profitable routes into demand responsive services, which may be expensive per passenger but are less expansive as local bus services with little to no ridership. For the administrator, this is very positive, returning mobility without returning to previous cost ineffective measures.(CROW 2024)

While taking the benefits into account, it should be noted that in areas where current local bus services are still running with high service levels, a replacement with public mobility may be regarded as a loss to current users (Bastiaanssen and Breedijk 2022). In general, schedule based buses have a better accessibility. However, when looking at a longer timeframe, replacing public transportation with public mobility will result in a system which is more adapted to the low demand high diverse routing of rural regions, creating a durable mobility solution (CROW 2024).

Accessibility is the Achilles heel of public mobility. Public mobility has a responsive nature, people need to notify about their desire for mobility. In most systems, this happens by digital application on the spot or in advance, depending on which aspect of public mobility is used. This system may pose additional complications for the more vulnerable people, especially digital illiterate people (Bastiaanssen and Breedijk 2022). Digital illiteracy tend to have a higher presence under older people, who also form a bigger part in the demographics of rural areas compared to urban centres (CBS 2023). Contradictively, most elderly and physical impaired mobility solutions have a responsive nature, indicating a implementation can also be made inclusive for these groups. When it is decided public mobility should be implemented, additional care should be given to the inclusiveness to prevent the most vulnerable people from our society get more dependent and only the more autonomous do benefit (Bastiaanssen and Breedijk 2022).