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Redesign of public transit in low-demand areas, and integration with shared modes, based on travel preferences: A case study analysis in the province of Utrecht, the Netherlands

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ABSTRACT

Offering shared mobility options at transit stops can potentially increase the service area of a stop and consequently, possible detours in transit lines can be eliminated to decrease in-vehicle travel times for through-passengers and reduce operational costs. However, current research mostly focusses on shared mobility options and expected behaviour only, whilst not looking at this integrated transit network design problem. Additionally, most focus of current studies is on the integration of shared mobility in urban areas and/or around train stations, leaving a gap on suburban areas and transit lines with lower demand.

In order to answer our research question “what the effects are of increased route directness for low-demand transit lines in conjunction with offering shared mobility at transit stops”, we developed a mesoscopic model extension for the aggregated four-step transport model to model changes in travel behaviour as a result of straightened transit lines and the simultaneous integration of shared modes. Discrete choice models are used to accurately model first and last mile preferences of people, based on the access and egress distance, demographics and available (shared) modes. Finally, the probability of passengers cancelling their complete trip as a result of increased first and last mile distances is also explored.

This model framework was applied to nine case studies in the Netherlands. The synthesis of the case studies resulted in key factors contributing to a promising redesign of the transit network. The main factor is that through-passengers should significantly outnumber local passengers, by at least 75%-25%. Additionally, the increase in access and egress times should not be significantly larger than in-vehicle time savings of through-passengers. Moreover, it is found that the mode share of micromobility in the first and last mile is approximately 15% across the different cases, whereby the highest usage can be seen for people under the age of 25 and for distances greater than 1 km. Finally, it is concluded that the additional costs of shared mobility are on average only 10% of the savings in operational costs.

1. Introduction

1.1. Public transport network design

The design of public transport (PT) networks is an important factor in the accessibility provided by PT services (Hüsselmann et al. 2024). In order to establish an adequate coverage area, it is important to provide a sufficient number of PT stops. At the same time, the number of stops and their locations as network design parameters need to be traded off with the operational and economic feasibility of these networks (Cervantes-Sanmiguel et al. 2023). Specifically, areas with lower population density encounter distinct challenges related to their requirement for access to PT (Bronsvoort et al. 2021).

A solution approach is to improve the directness of PT routes, also known as line straightening, while providing shared mobility options to maintain PT service access. Line straightening implies speeding up transit by removing stops and/or eliminate detours (Hitrans, 2005). Consequently, PT stops situated away from the more direct routes would therefore no longer be served (Itani et al. 2024), creating longer access and egress distances (first and last mile). However, due to higher quality

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of these faster services, the catchment areas of the new stops are substantially larger (Brand et al. 2017). This design choice is referred to as the basic public transport network design dilemma, as introduced and discussed by Van Nes (2002) and Egeter (1995). Due to the emerge of new shared vehicles, the design dilemma trade-offs might have changed too. Options such as shared bicycles or shared e-scooters could provide an alternative to access PT networks, especially when stopping distances increase (Montes et al. 2023; Sun et al. 2017). From an integrated network perspective, these shared mobility options can be viewed as first and last-mile alternatives (van Marsbergen et al. 2022).

1.2. Literature on shared mobility and public transport integration

This paper is driven by the impact that enhanced PT route efficiency and shared mobility for first/last mile connectivity can have on PT users and operators, thereby investigating impacts of (re)design of PT networks. An extensive body of research is available on the design and assessment of PT networks, as set out by Farahani et al. (2013), Guihaire & Hao (2008), Iliopoulou et al. (2019), and Kepaptsoglou & Karlaftis (2009), as well as on (shared) micromobility, as for instance by Dill (2003), Li et al. (2020) and Bergantino et al. (2021).

Research on the integration of shared micromobility with public transport increasingly emphasizes its potential benefits. Shared mobility can help bridge spatial gaps in transit networks and enhance accessibility (Kosmidis & Müller-Eie, 2024; Liu et al., 2024; Oeschger et al., 2023; Spierenburg et al., 2024). It can also strengthen system resilience during both planned and unplanned disruptions, ease overcrowding (Kager & Harms, 2017), and offer seasonal, weather-related, or topographical travel alternatives (Pucher & Buehler, 2009). Moreover, integrated networks may improve the traveler experience by saving time, simplifying trips, lowering costs, and enabling more personalized journeys through better support for trip-chaining and flexible departure times (Flamm & Rivasplata, 2014; Jäppinen et al., 2013; Kager & Harms, 2017). Mbugua et al. (2025) show the related positive societal business case of the integration, by assessing all costs and benefits of the Dutch share bicycled scheme available at train stations, including accessibility and health gains.

Although attention has increased, there is only limited attention to integrated PT and shared mobility networks design and its impacts on passengers and operator. Regarding this targeted research gap, Pinto et al. (2020) concluded from their literature review that intermodality within the multimodal network design problem is only considered for some operational level decisions, yet the network topology design has not been considered. Many studies seem to focus solely on the design parameters of complementary transport services and the expected behaviour of users (see for instance Luo et al. 2023, Montes et al. 2023, Shen et al. 2018, Stiglic et al. 2018, Tang et al. 2018 and Wang et al. 2016). Additionally, *meta*-analyses show that public transportation networks and shared mobility programs in suburban and rural areas are seldomly a topic of study in comparison to their urban counterparts and systems connecting to train stations (as investigated by e.g. Mbugua et al. 2025, Torabi et al. 2022, Daisik et al. 2018,Heilig and Voβ, 2015, de Oña & de Oña 2015, Stam et al. 2021, Wu et al. 2020). This gap is also stressed by a literature review of Boting (2023), illustrated in Table 1, revealing limited attention to suburban and rural cases.

Given the interest in line straightening to improve public transport efficiency, while providing shared mobility options to maintain PT service access and given the limited attention to suburban and rural public transport and shared mobility network integration, this will be the focus of this research.

1.3 Research question and contribution

Based on the relevance and gaps discussed above, our research question is what the effects are of increased route directness for low-demand transit lines in conjunction with offering shared mobility at transit stops. In this paper, a multi-case-study approach is used to quantify the effects regarding such network designs, in order to find key factors to consider when (planning to) implement(ing). The generic aggregated four-step transport model is adapted to model behaviour of passengers when transit lines are rerouted and first and last-mile transport is offered by shared mobility (in addition to private means for the first mile). The case studies are evaluated using relevant assessment criteria on how the resulting benefits and disadvantages balance out for stakeholders. Specifically, the balance of costs and benefits for both passengers and operators concerning the proposed interventions are set out. Additional emphasis is placed on demand drop due to longer first/last mile distances (e.g. elderly) and the accessibility of the transportation system. No monetary values are calculated for this aspect though, due to unknown choices of alternative or non-travel. The synthesis of the case studies results in key factors contributing to a promising redesign of the transit network.

Table 1
Literature review on shared mobility in (sub)urban and rural areas (Boting, 2023).

Papers	Location	Urban	Suburban	Rural
Van Marsbergen et al. (2020); Montes et al. (2023)	The Netherlands	√		
Schwinger et al. (2019)	Germany	√		
Hosseinzadeh et al. (2021); Griffin and Sener (2016); Fishman et al. (2014); Pelechrinis et al. (2017)	United States	√		
Zanotto (2014)	Canada	√		
Reck et al. (2020); Guidon et al. (2019)	Switzerland	√		
Cerutti et al. (2019); Pritchard et al. (2019)	Brazil	√		
Cherry (2007); Feng and Li (2016)	China	√		
Penati et al. (2021)	Italy	√		
Ma et al. (2020)	Delft (the Netherlands)	√	√	
Adnan et al. (2019)	Belgium	√	√	
He et al. (2019)	Park City (United States)		√	√

In Chapter 2, the methodology is covered, and the setup of the adapted four-step transport model is presented. Next, nine case studies are introduced and the model is applied to these case studies in Chapter 3. The results of the model are also presented in this chapter. Finally, in Chapter 4 a discussion of the model and the results is given, together with the conclusions and outlook of this paper.

2. Methodology

In this section, the methodology applied to model passenger behaviour as a response to straightened transit lines and the offering of first and last-mile solutions (FLMS) at stops, is presented. Additionally, the assessment methodology that is used to evaluate the effects of the proposed interventions is described. Afterwards, key factors for integrated transit networks can be derived.

The baseline scenario in all analyses is the current, non-straightened scenario. Interventions, such as eliminating detours and/or stops are analysed regarding their impact on demand and operations. Fig. 1 shows an example of a baseline scenario (before) and after interventions, being in this case the rerouting of the bus line via a faster regional road, not serving the town centre anymore.

2.1. Modelling framework

We established a framework and modelling process for assessing integrated public transport and shared mobility (PT + SM) networks by combining macroscopic and mesoscopic modelling elements. Its quintessence is based on the traditional macroscopic four-step transport

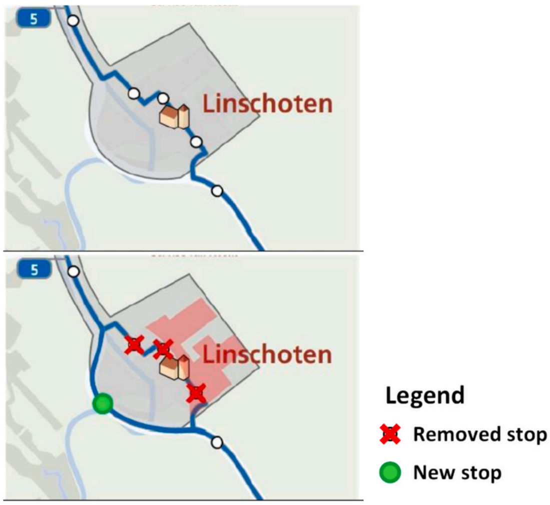

Fig. 1. Example of line straightening: Above: bus line serves town centre (white circles indicate stops) Below: Bus uses (faster) ring road.

model framework which consists of the four classical steps: trip generation, trip distribution, modal split, and traffic assignment (James, 1992).

One major limitation of macroscopic transport models is their reliance in a limited number of zonal centroids to represent the origins and destinations of transport demand (Bastarianto et al. 2023). This approach lowers the spatial resolution and diminishes the accuracy representing first/last mile impedances faced by individual travellers. Addressing these limitations is essential to produce valid outcomes in the context of the first/last mile choices.

To address these limitations, our model framework integrates the macroscopic four-step approach with a mesoscopic extension specifically designed to capture the first/last mile context, as illustrated in Fig. 2. A key enhancement of this extension is its improved spatial resolution, achieved by implementing a grid of raster cells within the case study areas. This mesoscopic model simulates transport supply and demand at a finer spatial scale, enabling detailed analysis of first/last mile re-evaluations of existing PT users. Fig. 3 outlines the modelling process including inputs, processing steps, and outputs.

The model extension has input on firstly the demand densities of particular zones in the case study area (PT Demand). Secondly, the input consists of the distance of these zones to the nearest transit stops in both the current and future scenarios and the available access and egress modes (PT + SM supply). Lastly, the behavioural preferences for FLMS and the acceptance of the first and last mile by PT passengers are incorporated into the model as input. Specifically, logistic regression parameters represent the FLMS preferences considering alternative specific travel times, the age group of the respective traveller, and the traveller's case study relationship. The latter attribute shows whether the trip is conducted by a case study resident (home-connected trip) or case study visitor (activity-connected trip). This is important as there may be discrepancies in the availability of private and shared modes of transportation.

Using the above information, the travel reconsiderations can be modelled. In particular, it can be calculated what the likelihood is of travellers using a particular mode between a PT stop and a particular zone in the future scenario. Afterwards, combining this information with the travel demand of each zone and the changed travel impedances as a result of the new PT + SM supply, the number of trips can be estimated per first and last mile mode (PT + SM demand). Also, the possibility of unfulfilled demand is explored and calculated in this step, being travellers (e.g. elderly that cannot travel anymore due to longer distances). The further monetary effects of this unsatisfied transit demand are not studied here. Individuals may opt to refrain from traveling altogether or explore alternative modes for their door-to-door journey. Opting out of travel might result in social exclusion, while a shift to car usage by passengers could contribute to additional externalities, including emissions, congestion, and increased safety risks. Nevertheless, a switch to, for instance, the (e-)bike has a positive potential.

Disaggregate demand projections d for each grid cell are calculated by using the coverage and inhabitant density within the larger area of grid cells which all have stop k as the nearest stop available. The disaggregated demand d_i is the product of the local demand density and the demand at the nearest stop. The local demand density consists of the centrality and population density. The distance between the grid cell and the nearest stop determines the spatial attractiveness s_i which is the key element for centrality. This is noted as:

$$d_i = \frac{s_i l_i}{\sum_J s_i l_i} * D_k, for i \in G^k \quad (1)$$

whereby:

- G_k: grid cells with stop k as the closest stop
- d_i: disaggregated demand of grid cell i

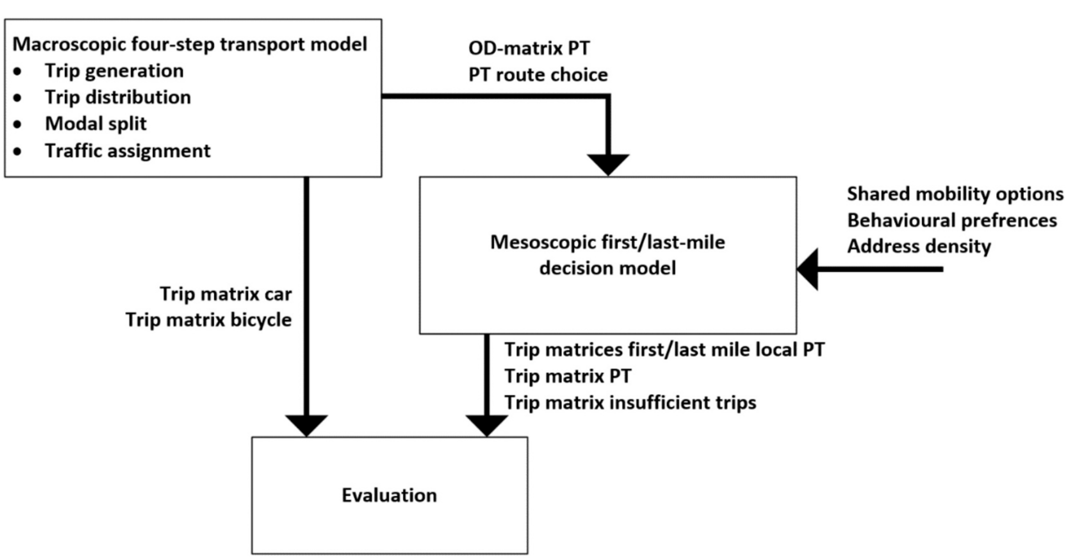

Fig. 2. Model framework combined macroscopic and mesoscopic models.

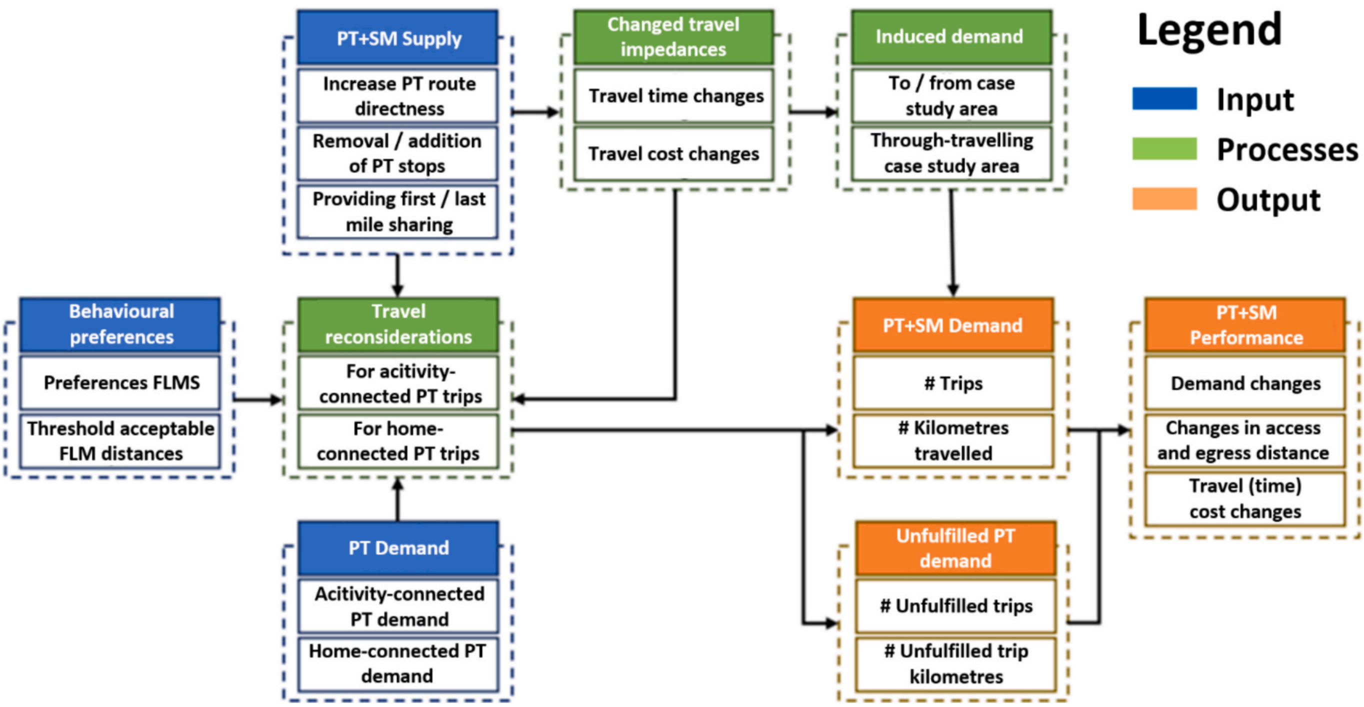

Fig. 3. Modelling process mesoscopic first/last mile model extension.

- l_i: local population in grid cell i
- s_i: spatial attractiveness of grid cell i
- D_k: ridership of transit stop k

Home connected trips.

Regarding home-connected trips, as mentioned, travellers are likely to have access to private means of transport such as private bicycles or cars. From that perspective, it is more likely that these modes will be used for the first mile as opposed to shared mobility options. We use cumulative distributions of all available private modes of transport as a function of distance in order to compute the modal split in first-mile transport, similar to the research of Brand et al. (2017).

Furthermore, the cumulative residue consists of the cumulative density function which accepts the first/last mile distance in the base scenario. Changed cumulative densities represent the demand impact as a result of changed first/last mile distance. Afterward, we can estimate the size of the demand drop effect. This effect is represented by the ratio of the changed cumulative densities and the cumulative base residue. In this study, we consider the effect as shown below in Equation (2):

$$drop(b,f) = \frac{c(f) - c(b)}{1 - c(b)} \tag{2}$$

Activity- connected trips

Moreover, regarding the activity-connected trips, in our previous study (van Kuijk et al. 2022) we estimated a discrete choice model that represents user preferences for FLMS in sub-urban activity-connected first/last mile trips. This study showed that age, and the level of cycling are important individual factors that determine FLMS preferences. Based on these conclusions, we estimated a discrete choice model that only includes the level of service of FLMS and the aforementioned individual factors.

Our discrete choice model is based on the random utility maximisation (RUM) framework. This assumes that every respondent n of each choice task t would only choose alternative i with utility U_{int}, when $U_{int} > U_{jnt}, j \neq i$. Background information on RUM models can be found in e.g. Hensher et al. (2005) and Train (2009).

We defined a utility function for each alternative according to the formulation of Equation (3). The utility value is the sum of the observed utility V_{int}, the error term ε_{int}, and the panel-effect term α_{in}. The latter is included due to earlier observed correlations between respondent's choices of multiple-choice tasks.

$$U_{int} = V_{int} + \alpha_{in} + \varepsilon_{int}, \in C_{nt} \tag{3}$$

The observed utility is the sum of the products of each included explanatory factor and its estimated parameter.

Finally, the outputs of the first/last mile model extension consist of the trip matrices for both the satisfied and unsatisfied trips, including a distinction between the different FLMS used. Besides, related output metrics such as new access and egress times can be extracted from the model processes.

2.2. Assessment process

After the behaviour of passengers as a result of the interventions is modelled, as described in Section 2.1, the results need to be assessed. Quantifiable results are extracted from the model to evaluate the effectiveness of the interventions, compared to the base line scenario as discussed in the introduction of this section. For the assessment of a particular case study, various impacts are considered. These can be split into three main categories. The first is the changes in aggregated service and journey performance metrics. The second category involves the changes in journey costs and journey time for the passengers and finally, the third category involves the changes in the revenue and costs for the operator/transit agency. All considered impacts are shown in Table 2.

Aggregate performance metrics relate to the service- and journey-based performance. The first describes the change in demand for services in the case study area. The latter describes the changes in the performance of trip-making at door-to-door level. Service-based performance is calculated based on changes in case study passenger flows according to the aggregate transport model. Journey-based performance uses the same data combined with data on changed first/last mile behaviour from the disaggregate transport model. From the latter data, also information can be retrieved on changes in average access and egress distances and times.

Table 2
The considered impacts studied for the assessment of a case study.

Impact Category	Metric Description	Variable Being Assessed
Changes in service and journey performance	The change in the number of passengers compared to the baseline scenario.	Number of passengers
	The change in average door-to-door travel time compared to the baseline.	Door-to-door travel time
	The change in average access and egress distance compared to the baseline.	Access and egress distance
	The change in average access and egress time compared to the baseline.	Access and egress time
Changes in costs and benefits for passengers	The change in fares and shared mobility costs compared to the baseline.	Costs (fares and shared mobility)
	The change in total travel time costs for passengers compared to the baseline.	Travel time costs
Changes in costs and benefits for the operator/transit agency	The change in operational costs compared to the baseline scenario.	Operational costs
	The change in costs of offering shared mobility compared to the baseline.	Costs of shared mobility
	The change in revenue generated from shared mobility usage compared to the baseline.	Revenue from shared mobility
	The change in revenue generated from fares compared to the baseline.	Fare revenue

The costs and benefits for passengers can be categorised into three groups. Firstly, there are alterations in expenses necessary for travel. These encompass both the added costs associated with shared mobility use and adjustments in fares based on the length of the transit journey. Secondly, there are the changes in perceived travel costs. As a trip becomes quicker or slower, passengers endure either additional or fewer costs. These costs are monetised using the Value of Time (VoT) (Athira et al. 2016). Finally, there are costs endured if a person chooses not to travel anymore due to the increased (journey time) costs. These latter costs are not quantitatively included in this paper as it is not modelled what people will do instead; namely if they do not travel anymore, change their transport mode, or even choose another destination for their trip.

At last, the costs and benefits for the operator/transit agency can be split into the changes in operational costs, the added revenue and costs connected to offering shared mobility, and finally the changes in revenue due to the differences in ridership. Operational costs change as increased route directness decreases the need for driving personnel and rolling stock. The costs for the operator/transit agency, the expenses for passengers, and the perceived travel time changes can be computed for a case study using relevant cost parameters and output of both the aggregated as well as the disaggregated model.

2.3. Data requirements

The proposed method requires data that is part of a standard four step model, regarding zonal characteristics, public transport supply and passenger flows (James, 1992). Typical input consists of census data, behavioural parameters and smart card data (see e.g. Van Oort et al. 2015). All these sources will be illustrated in the next chapter.

In summary, this section presents a methodology to model passenger behaviour in response to straightened transit lines together with FLMS being offered. The framework combines macroscopic and mesoscopic elements, addressing spatial resolution limitations. Logistic regression captures FLMS preferences. The assessment framework evaluates impacts on aggregated performance, operator costs, and passenger costs. The model framework is utilised in Chapter 3 to showcase the application possibilities through multiple case studies.

3. Application of the method in Utrecht, the Netherlands

To demonstrate the model framework exhibited in Chapter 2 and assess the effects of straightening transit lines in conjunction with offering shared mobility, nine case studies are performed in the province of Utrecht, The Netherlands. These cases and their results give insights into the actual challenges of the proposed interventions. The synthesis of the case studies results in key factors contributing to a promising redesign of the transit network. All individual case study details can be found in De Ridder et al. (2024).

3.1. Case studies description

The Utrecht province is a strongly urbanised area located in the middle of The Netherlands. Given its geography, which varies from larger cities and multiple post-modern urban expansion areas to small settlements and farmlands, it shows a wide variety in population density. Our analysis covers nine cases which are all located in rural or suburban areas within the Utrecht province. The location of each of these cases is depicted in Fig. 4. These areas are chosen as the goal of this study is to find the effectiveness of straitening low-demand transit lines in combination with the offering of shared mobility. All of these cases currently have a detour in a particular area to increase the service area of the line, instead of taking the more direct route. This detour is removed in the intervention scenarios together with the stops along this detour.

In order to provide a basic understanding of its local contexts and to show the variety of cases, we have set out the most important attributes of each case study in Table 3. These are demand (local and through-travelling), service frequency, age distribution among PT users, and the time that is saved with the proposed intervention. In order to learn most from the cases, we aimed to identify a large variety of case studies in terms of passenger numbers and differences in first/last mile distances. Local passenger numbers on an average workday vary between 66 and 938 with a case study origin/destination, while through-travelling passenger numbers vary between 76 and 1170.

3.2. Case studies Implementation

The model framework as described in Chapter 2 is applied to the case studies presented in Section 3.1. For all case studies, the same steps are undertaken. The Province of Utrecht already disposes of an aggregated macroscopic four-step transport model, which is adapted with the aforementioned mesoscopic extension for modelling the first/last mile context. The aggregated model is able to compute transit ridership to, from, and through the case study area, after which the first/last mile behaviour is modelled for the proposed intervention using the described model framework. Both the current transit network, as well as the transit network after the intervention are incorporated to assess and compare results.

In the case studies, data from smartcards are utilised to calibrate transit ridership in the four-step transport model. The smartcard data consists of tap-in and tap-out records from November 2019, whereby an average weekday is considered. For the data description, van Oort et al. (2015) can be consulted. Besides, for travel distances and travel costs the values are used as incorporated in the provincial transport model. Additionally, socio-economic data from Statistics Netherlands (2020) are incorporated to extract essential information regarding population density in specific areas of the case studies. This data is used to model first/last mile behaviour in the case study area.

For the modelling of home-connected and activity-connected trips, the models as described in Section 2.1 are used. For the home-connected

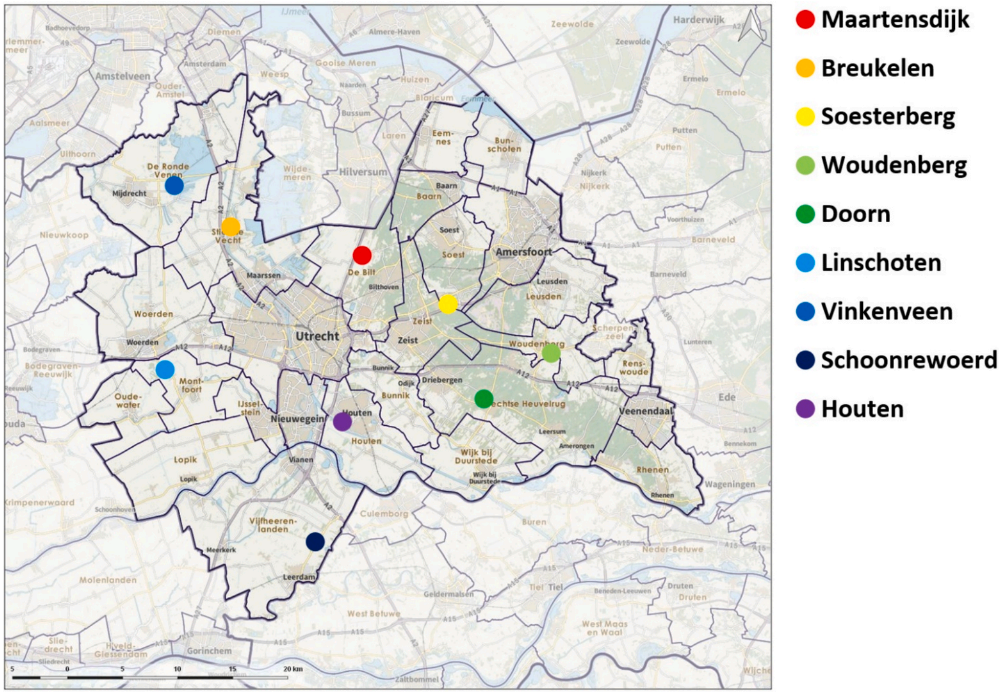

Fig. 4. Researched case studies in the province of Utrecht.

Table 3
Information on the researched case studies in the province of Utrecht. Ridership of an average workday in November 2019 is taken and socio-economic data from the same year (Statistics Netherlands, 2020).

	Case study	Local passengers workday	Through-passengers workday	Age distribution			Frequency per direction	Time savings of new route
		Aggregated Trips	Aggregated Trips	Young	Middle	Old	Buses/hour	Minutes
1	Maartensdijk [line 58]	146	89	58 %	35 %	7 %	1	3
2	Breukelen [line 120]	452	372	53 %	41 %	6 %	4	3
3	Soesterberg [line 56]	200	597	38 %	58 %	4 %	4	4
4	Woudenberg [line 80]	165	650	64 %	33 %	3 %	4	1
5	Doorn [line 56]	425	340	47 %	49 %	4 %	2	3
6	Linschoten [line 5]	66	76	58 %	36 %	6 %	1	2
7	Vinkeveen [lines 126 & 130]	938	1170	61 %	35 %	4 %	4	4
8	Schoonrewoerd [line 85]	120	893	58 %	40 %	2 %	2	1
9	Houten [line 48]	478	134	22 %	76 %	2 %	4	5

first/last mile we assume that these will only be conducted on foot or by private bicycle, given the high level of bicycle ownership in the Netherlands. We use the results of Brand et al. (2017) which are based on empirical data for walking and cycling in the home-connected first/last mile of conventional and express bus services (BRT) in the Netherlands. They described this data by means of cumulative distributions as a function of first/last mile distance *d*. Based on this data, we estimate the demand drop and the first/last mile mode choices as a result of changed first/last mile distances and improved route directness.

Furthermore, we use a polygon raster grid of 100x100 metres cells in the data frame for the disaggregate representation of the case study areas. We excluded all grid cells located over 3,100 m away from the nearest stop in the base scenario. This reflects the empirically determined coverage area of a stop (Brand et al. 2017). Besides, for the cross-referencing of sociodemographic information with our grid cells, we use similar-sized polygon cells from the Dutch census.

For the remaining demand, we need to estimate the modal split between walking and private bicycle in the first/last mile. Based on the data we found that the discrete modal split distribution shown in Table 4 provides a sufficient representation (Brand et al. 2017).

Furthermore, for the activity-connected trips it is determined that at all stops in the case study area there are both shared bicycles as well as shared e-scooters available to use. Other shared mobility options are not further researched in the analysed case studies. Table 5 shows the estimated parameters for the discrete choice model, which was presented in Section 2.1. These parameters were estimated using a stated choice model in the Province of Utrecht for rural bus lines (van Kuijk et al. 2022).

3.3. Detailed case studies results

For the case study results, the first two different cases are presented with varying impacts as a result of the new PT + SM offering. The cases that are presented here in more detail are the cases of Breukelen and

Table 4
Estimated modal splits between walking and cycling for home-connected trips.

Modal split for home-connected trips	Distance from stop in meters < 300	300—1100	1100—1500	1500—1900	1900—3100
Walking	100 %	78 %	56 %	36 %	0 %
Cycling	0 %	22 %	44 %	64 %	100 %

Table 5
Estimated parameters for the utility of activity-connected trips.

Parameter	Shared bicycle Coef.	T-test	Shared e-scooter Coef.	T-test	Walking[a] Coef.	T-test
Alternative-specific factors						
$\beta_{Constant}$	−1.16	−3.70**	−1.14	−2.00**		
$\beta_{Travel\ time}$	−0.08	−4.43**	−0.03	−0.99	−0.08	−5.68**
$\beta^2_{Travel\ costs}$	−0.67	−9.37**	−0.67	−9.37**		
Individual factors (represented as binaries)						
$\beta_{Age\ young}$			1.01	3.44**		
$\beta_{Age\ old}$	−1.83	−6.47**	−1.61	−5.69**		
$\beta_{Cycling}$	0.69	3.87**	0.37	1.76*		

[a] *reference alternative,* [2] *generic cost parameter, ** – significant on a 95 % confidence level, * = significant on a 90 % confidence level.*

Schoonrewoerd. The case of Breukelen shows a relatively high drop in the number of passengers, whilst the Schoonrewoerd case is picked as the net effect on ridership is almost zero. Afterwards, the results of all case studies are presented to enable a synthesis.

Case 1: Breukelen.

First of all, the case of Breukelen is presented. Line 120 is a bus route that traverses through Breukelen, a town of approximately 11,000 people (Van Oort et al. 2015). The bus line runs from Utrecht Central Station to Amsterdam Bijlmer ArenA Station, however, the bus is considerably slower than the train between these two stations and primarily serves as a local connection between the many villages along the route. It also acts as a link between these villages and one of the four train stations where this bus makes stops. Coming from Amsterdam, the bus takes a detour through Breukelen-Noord before heading towards Breukelen Station, as presented in Fig. 5. Breukelen-Noord consists mainly of residences with a few shops and public buildings near the stops. In this case study, there is a substantial number of both through and local passengers, with the latter group being the majority.

By straightening Line 120 along the Straatweg on the east side of the neighbourhood, a net loss of two stops occurs. This change results in longer access and egress distances, particularly on the west side of the neighbourhood, while the east side experiences minimal differences in both first and last mile transportation. However, in the future situation, all addresses on the north side of the village will still have a bus stop within a distance of less than 600 m.

Fig. 5. Straightening of line 120 in the northern part of Breukelen.

As can be seen in Table 6, a relatively small increase in the average access and egress distances results in nearly 18 % of travellers choosing not to take this bus in the future scenario. They might stay home or use alternative modes of transport. Both could lead to unwanted impacts, such as social exclusion (stay home) or additional emissions (shift to car).

The use of shared mobility is also limited in the future situation, as shown in Fig. 6, with the shared bicycle being utilised slightly more than the shared e-scooter. Interestingly, the door-to-door time for local travellers slightly decreases since many local travellers can benefit from a faster bus service. However, the perceived travel time increases as first and last mile transportation is perceived as less pleasant than time spent on the bus. Furthermore, through-passengers can benefit from a journey that is 3 min faster. Despite the improved operating speed, which accounts for almost a 5 % reduction in door-to-door time, the number of through-passengers increases by just over 1 %.

Finally, the operational costs significantly decrease due to the reduced number of staff and rolling stock required to operate the desired schedule. This saving more than compensates for the income loss resulting from the more than 9 % decrease in the number of passengers.

Case 2: Schoonrewoerd.

Secondly, the case results of Schoonrewoerd are presented. Bus line 85 operates from Leerdam to Utrecht Central Station, passing through the small village of Schoonrewoerd just north of Leerdam. Schoonrewoerd has a population of approximately 1,600 (Van Oort et al. 2015). One distinctive feature of this route segment is the significant number of through-passengers traveling to or from Leerdam. The ratio of through to local passengers is notably higher for this case compared to the other cases. In this intervention, line 85 will follow highway N484 located directly west of the village, and make a stop there, as shown in Fig. 7.

In the current situation, the access and egress distances in Schoonrewoerd are relatively short. Although these distances double as a result of relocating the bus line, the average distance to the stop stands at 500 m after the rerouting of line 85. As a result, the bus attracts approximately 12 % fewer passengers at the Schoonrewoerd stop, and the number of users of shared bicycles and e-scooters is relatively low in the future scenario, as is presented in Fig. 8.

Moreover, as there are relatively many through-passengers, a

Table 6
Results of the case study in Breukelen. All values are for an average workday.

Aggregated performance metric	Local	Through
Difference number of passengers	−80 (−17.7 %)	5 (+1.3 %)
Difference average door-to-door time (min)	−0.1 (−0.2 %)	−3 (−5.4 %)
Difference average access and egress distance (m)	150 (+60 %)	
Difference average access and egress time (min)	1.4 (+45.9 %)	
Costs and benefits passengers		**Monetised**
Total costs savings fares and shared mobility		€ −31.9
Total costs savings with regards to travel time savings		€ 96.8
Costs and benefits operator/transit agency	**Metric**	**Monetised**
Operational cost saving (timetable hour)	3.6	€ 432
€ 120 per timetable hour		
Costs shared mobility	20	€ −51.4
€ 2.20—3.00 per trip		
Passenger revenue shared mobility	20	€ 26.3
€ 0.75—2.00 per trip		
New fare revenue		€ −186.5
Balance costs and benefits for passengers (excluding unsatisfied trips)		**€ 70.2**
Balance costs and benefits operator/transit agency		**€ 236.8**

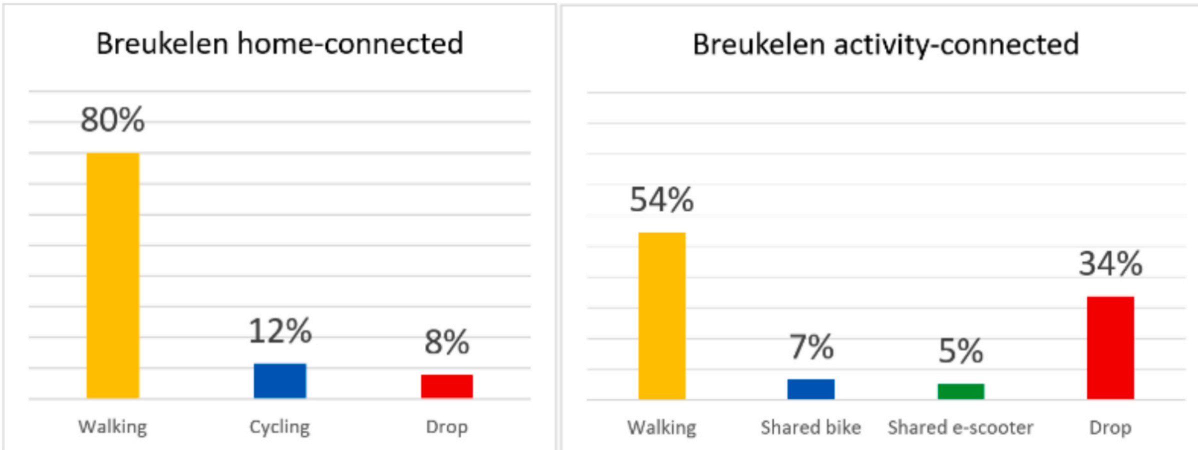

Fig. 6. First and last mile mode share in Breukelen of current PT users for both the home-connected and the activity-connected trips after the proposed intervention.

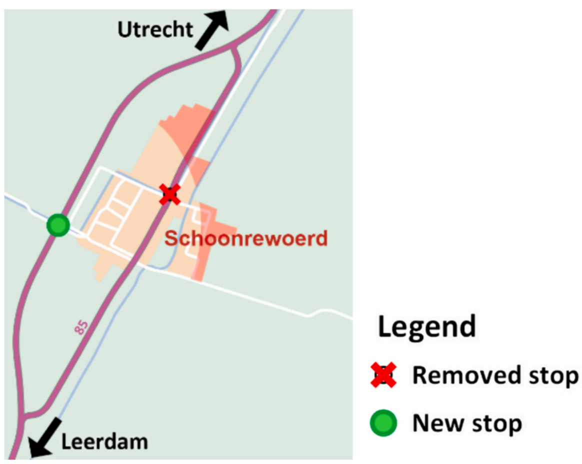

Fig. 7. Rerouting of line 85 around Schoonrewoerd.

significant number of passengers benefit from the slight time save of 1 min for bus line 85. It is even the case that almost all passengers lost in Schoonrewoerd are recaptured in through-passengers, as is exhibited in Table 7.

Finally, the operator/transit agency experiences monetary benefits from the sped-up service. Although the saving in operational costs may be low due to the limited travel time savings of the new route, it is still significant considering that this is a relatively small intervention compared to other cases. In conclusion, this intervention seems to have more societal benefits than costs. However, it is important to note that the benefits and costs are not evenly distributed among all parties. Especially passengers from the eastern part of Schoonrewoerd may have to travel an extra 400 m at times to reach the bus stop.

3.4. Synthesis on case studies results

The cases of Breukelen and Schoonrewoerd showed both different and similar conclusions. Compared to the other eight cases, the case of Breukelen shows a moderate increase in access and egress distances, but a significant reduction in passenger numbers. Schoonrewoerd on the other hand scores relatively well in overall transit ridership compared to the other cases that are assessed.

The most important results from the different case studies are presented and compared in Fig. 9. This is done in order to establish in which cases, if in any, the proposed interventions make the most sense, both from a monetary and a societal standpoint. A synthesis of these case studies resulted in key factors contributing to a promising redesign of the transit network.

To start, all nine analysed cases show a decrease in the number of local passengers and an increase in the number of through-passengers. The decline in local passengers ranges from 6 % (Woudenberg) to 25 % (Vinkeveen), while the increase for through-passengers ranges only from 1.1 % (Maartensdijk) to 2.9 % (Vinkeveen). This results in all cases in a net loss of up to 11 % of passengers on a section of the route, except for Woudenberg where there is a net increase of 1 % due to the straightening of the bus line.

The significant drop in local passengers is attributed to the longer distances in the access and egress phases, which double on average for

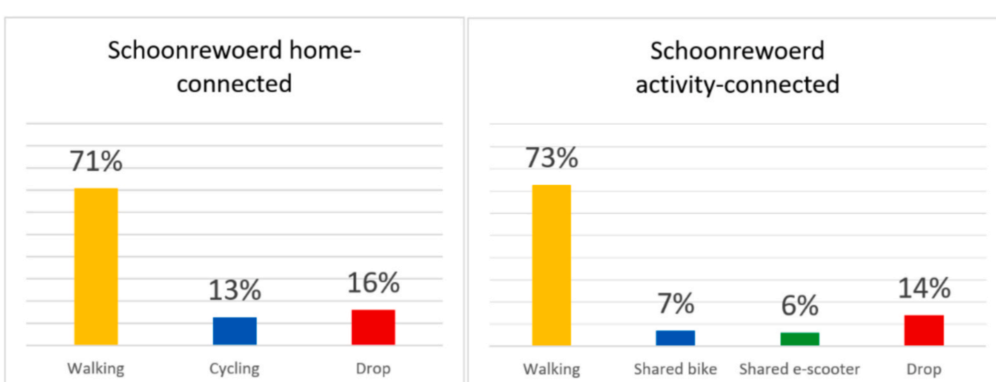

Fig. 8. First and last mile mode share in Schoonrewoerd of current PT users for both the home-connected and the activity-connected trips after the proposed intervention.

Table 7
Results of the case study in Schoonrewoerd. All values are for an average workday.

Aggregated performance metric	Local	Through
Difference number of passengers	−14 (−11.7 %)	12 (+1.3 %)
Difference average door-to-door time (min)	0.9 (+1.3 %)	−1 (−1.7 %)
Difference average access and egress distance (m)	200 (+80 %)	
Difference average access and egress time (min)	2.5 (+83.8 %)	
Costs and benefits passengers		**Monetised**
Total costs savings fares and shared mobility		€ −5.6
Total costs savings with regards to travel time savings		€ 79.7
Costs and benefits operator/transit agency	**Metric**	**Monetised**
Operational cost saving (timetable hour) € 120 per timetable hour	1.5	€ 180
Costs shared mobility € 2.20—3.00 per trip	6	€ −14.4
Passenger revenue shared mobility € 0.75—2.00 per trip	6	€ 7.4
New fare revenue		€ −13.1
Balance costs and benefits passengers (excluding unsatisfied trips)		**€ 78.5**
Balance costs and benefits operator/transit agency		**€ 160.3**

local passengers. However, there are substantial differences between cases; in Woudenberg and Houten these distances increase by 50 %, while in Vinkeveen the distances to the stops almost triple. As a consequence, more people opt for cycling at the home end or shared mobility at the activity end. In these cases, 9 % to 18 % of home-connected trips will involve cycling. The bicycle is mainly used for distances longer than 1.1 km, and its usage is logically higher in case studies where the distances to the bus stops are higher in the future scenario. Shared mobility is used by 10 % to 16 % of passengers at the activity end. Due to the increased distances and the use of (shared) bicycles and scooters, the average access and egress times increased by 80 %. However, there are still significant variations; for instance, the time required for access and egress in Woudenberg increases by 30 %, while it more than doubles in Vinkeveen.

Naturally, there are significant differences in cost-benefit balances for passengers, as shown in Fig. 9. Illustrating the major indicators for all 9 case studies. While travel time gains (using the VoT) of passengers in Soesterberg are approximately 280 euros per day due to travel time reduction, passengers in Vinkeveen experience an average loss of about 80 euros per day. This is without taking into account the significant drop in demand in many cases, which also leads to additional (perceived) costs. For example, in the case of bus lines around Vinkeveen, 9 % of the number of passengers will be lost. However, these monetary costs are not explicitly included in this study. In reality, there are likely few cases where the net result is positive for the group of passengers. Moreover, there are significant differences between groups that benefit and those that lose out. Through-passengers always benefit, but some local passengers also do so if a stop is closer or if the in-vehicle time save is larger than the additional access and egress time. Yet, some passengers have to travel more than a kilometre further to reach the nearest stop in the future scenario.

Nevertheless, when looking at the costs and benefits for the transport operator, in all cases, the savings in operational costs are significantly greater than the costs endured for offering shared transportation and the forgone revenues from passengers who no longer use public transportation. Naturally, these savings are greater when more travel time gains can be achieved and when the frequency on a bus line is higher. For instance, the savings in Linschoten for the transport operator are the lowest at approximately 130 euros per day, while it is the highest in Vinkeveen at 910 euros per day, as shown in Fig. 9.

The straightening of bus lines seems most promising in Soesterberg, Woudenberg, and Schoonrewoerd. Not only do these cases have a relatively more positive cost-benefit balance for passengers compared to other cases, but in these three instances, demand loss remains limited to less than 3 %, and there is even an increase in passengers in the case of Woudenberg. What these three cases have in common is that the proportion of local passengers is below 25 %, whereas in all other cases, it is above 40 %. This means there are relatively many through-passengers benefiting from the intervention and the related in-vehicle time save, but as mentioned earlier, the burdens are not distributed equally.

Cases that perform relatively poorly are Doorn and Vinkeveen. Not only do these cases have many local passengers, but future stops will also be relatively far from their current locations. Consequently, large areas will lose their nearby bus lines. As mentioned, placing stops further away results in a significant demand decline and substantial increases in access and egress times, partly because at least four out of five passengers still choose to walk to the stop.

The fact that the total mode share of (shared) bicycles and electric scooters in the first and last mile is less than 20 % for all cases is noteworthy. Especially among people over the age of 45, relatively few people abandon walking to a stop in favour of using a micromobility, even for distances over a kilometre long. As a result, the effects of shared mobility on access and egress times and the overall cost picture are not substantial. Most effects are experienced in the reduction of operational

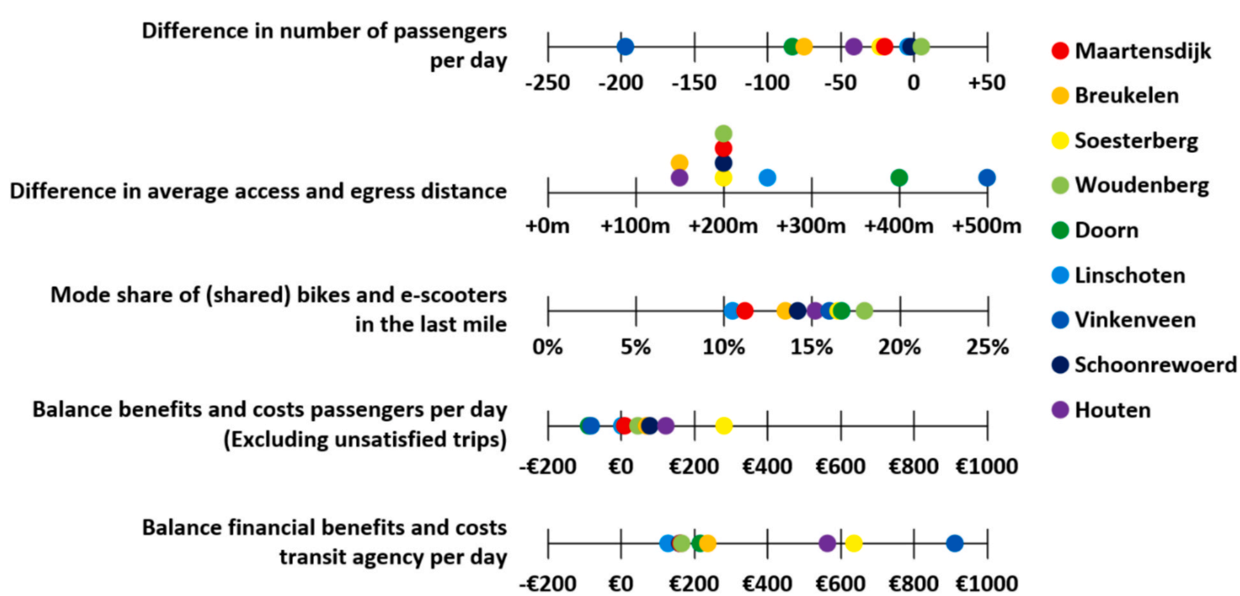

Fig. 9. Results of the proposed interventions for all the case studies.

costs, shorter bus travel times, and longer walking times to the stops. Therefore, it is expected that the cases of Soesterberg, Woudenberg, and Schoonrewoerd would still score relatively high compared to other cases even without the availability of shared mobility. Nevertheless, with the assumed operating costs for shared mobility, it costs the operator/transit agency relatively little to offer this service. Yet, shared transportation can bring significant benefits to the small group of people who do use it because this group reaches their destination notably more quickly.

3.5. Key take aways from case studies results

The previous synthesis of the case studies revealed key factors contributing to a promising (re)design of a transit network. One of the main success factors is e.g. that through-passengers should significantly outnumber local passengers. This proved to be if less than 25 % of passengers on a line segment see their closest transit stop move elsewhere due to the proposed intervention. Hence, more than 75 % of passengers (all through-passengers) see their door-to-door travel time become shorter by design. The cases which score best are those where there is the highest percentage of through-passengers, hence the in-vehicle travel time reduction is experienced by most people. Additionally, the increase in access and egress times should not be significantly larger than in-vehicle time savings of through-passengers. Moreover, it is found that the mode share of micromobility in the first and last mile is approximately 15 % across the different cases, whereby the highest usage can be seen for people under the age of 25 and for distances greater than 1 km. Finally, it was found that the transit operator/transit agency is in all researched case studies better off from a pure financial point of view with the proposed straightening of the bus line. The additional costs for shared mobility, typically being 0 to 200 euros per day, are only a fraction of the potential savings in operational costs, being between 150 and 1500 euros per day for the studied cases. Low-demand bus lines often have relatively high operational costs compared to fare revenue. However, one of the reasons why costs of running a shared mobility scheme at stops is low, is because the usage of first/last mile options remains limited for activity-connected trips. Also, the private bicycle is only used in one-fourth of home-connected trips. These modes are mainly used by people under the age of 25 for distances longer than 1.1 km, whilst people older than the age of 45 walk to and from the transit stop in the majority of cases. Walking share is on average still 85 % while shared mobility options are offered at stops.

4. Conclusions and future research

Given the relevance but yet limited attention to suburban and rural public transport and shared mobility network integration, this paper investigated what the effects are of increased route directness for low-demand transit lines in conjunction with offering shared mobility at transit stops. In order to do so this paper presented the development of a four-step transport model adapted for assessing public transport redesign and simultaneous integration with shared modes. The model provides valuable insights into the key interactions between transit routes, shared mobility at stops, usage, and operations in a variety of regional and suburban cases. The model and approach presented in this study integrated mesoscopic first/last mile behaviour within an aggregated transport model. Preferences for alternative first/last mile solutions are modelled considering alternative-specific costs, travel times, and sociodemographic attributes. The approach enabled a multi-case study of which the synthesis resulted in key factors contributing to a promising redesign of the transit network. The results demonstrate the conditions and potential for decreasing door-to-door travel times while achieving operational cost savings.

Most importantly, it is concluded that the straightening of low-demand transit lines has the most potential in the case that there are notably more through-passengers than local passengers. Nevertheless, also some of the local passengers do benefit from the rerouting of the transit line. There are instances where the added access and egress time is much less than the shorter in-vehicle travel times. In the case of Woudenberg, there will even be more passengers in the future scenario with the new route of the bus line due to the overall savings in door-to-door travel times.

However, as can be expected, the costs and benefits of passengers are not equally distributed. As a consequence, there might be equity concerns. In the case of Vinkeveen, some people have to travel up to a kilometre more to the closest transit stop and in this case study, even 9 % of passengers choose to not take the bus anymore. This comes at additional costs which are not explicitly considered in this study. In future studies, additional research can be done into the behaviour of unsatisfied public transit trips. People might choose not to travel anymore, which could lead to exclusion. Alternatively, there can be a shift to micromobility as the mode for an entire trip, or a shift to the car, the latter creating more negative externalities like emissions, congestion and increased safety risks. If the effects of these unsatisfied transit trips can be monetised, a more comprehensive cost-benefit balance can be computed. Consequently, this balance can be better compared to the cost-benefit balance of the operator.

As the case studies where all performed in a Dutch context, and the Netherlands is generally known for its high bicycle usage, the low usage of micromobility is remarkable. It may be that similar case studies in other countries show even lower usage of first/last miles solutions. This weakens the business case for offering shared mobility at stops. However, if results are different for cases where, for instance, personal ownership and overall usage of micromobility is lower, this must be investigated in another study. Nevertheless, the people who will make use of shared mobility can often experience significant time savings over a scenario when no such service is offered. Finally, it is concluded that the additional costs of shared mobility are on average 10 % of the savings in operational costs.

What must be noted is that in this research only the shared bicycles and e-scooters at bus stops were considered as first and last-mile solutions. These modes were found in a previous study to show the most potential for low-demand transit lines in a Dutch context (van Kuijk et al. 2022). Nevertheless, in the same study it was found that although overall usage of other shared modes such as shared LEVs, shared cars, and taxi-like services was low, they were highly preferred by elderly people. As this sociodemographic group is in the majority of case studies the group which experiences the biggest disadvantages of the new integrated transport network, it might be beneficial from an equity perspective to offer these services, nonetheless. However, this hypothesis must be confirmed in a further study on the matter.

Additionally, in the applied model passengers could not use alternative transit lines to access their destination. A further developed model could improve on this by not only considering first/last mile reconsiderations and the possibilities of unsatisfied trips but also itinerary alterations. This change would also allow the model to be applied in a wider range of cases. For instance, this makes the evaluation of similar integrated transit networks in more built-up environments more accurate, as line density in these areas is often higher and thus itinerary reconsiderations are more likely.

Nonetheless, the conclusions drawn from the case studies conducted in this research can be extended to other transit networks. This paper identified key factors for which cases the integration of shared mobility with the redesigning of a transit line shows the most potential. The most important factors are the share of local passengers compared to the number of through-passengers, and the time saved for through-passengers compared to the average increase in access and egress time. For the province of Utrecht, the recommendation is to identify specific sections of bus lines where buses take detours to include additional stops. The key consideration is that, on these particular sections, only 25 % of passengers utilise these additional stops. In such cases, it is advisable to evaluate the feasibility of straightening the bus line, essentially eliminating these detours. The same recommendations are also valid for other transit agencies. Yet, for their cases, it must first be determined if the expected first/last mile behaviour of passengers is similar to the Utrecht case. However, since there are often many case-dependent aspects, it remains important to model the local context and evaluate results before making decisions on what is best from a policy perspective.

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