Journal of Public Transportation 27 (2025) 100143

Contents lists available at ScienceDirect

Journal of Public Transportation

journal homepage: www.journals.elsevier.com/journal-of-public-transportation

Integrating demand-responsive services into public transport networks – Results from agent-based simulation of demand-responsive transport scenarios for the city of Aachen

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A R T I C L E I N F O

Keywords:
Public transport network
Demand-responsive transport
MATSim

A B S T R A C T

Enabled by the emergence of new technologies, demand-responsive transport (DRT) offers a flexible alternative to fixed-schedule public transport. In order to improve their public transport networks, cities are attempting to integrate new DRT services into their networks without reducing fixed-schedule public transport ridership. This paper addresses the question of how DRT integration into an existing public transport network affects mobility behaviour and network load in a medium-sized city. To this end, we ran two scenarios in an agent-based model (MATSim). First, we set up a 'Feeder Scenario', where the DRT represents a feeder to a reduced fixed-schedule public transport network; second, we developed a 'Replacement Scenario' in which the DRT completely replaced fixed-schedule public transport in the whole study area. The results show that both scenarios generate extra vehicle traffic compared to the 'Status Quo' (the unchanged calibration state, before any scenario is implemented) because DRT trips replace walking and cycling trips as well as bus trips with higher capacities and the reduction in car trips does not compensate for this. Overall, our configuration of the scenarios results in the Replacement Scenario being slightly better than the Feeder Scenario in terms of replacing car trips, total motorised mileage and total vehicle load on roads in the city.

1. Introduction

Around the globe, urban public transport faces pressing challenges ranging from funding issues, to limited capacity, to the need to improve service quality in order to motivate a modal shift away from the car. One of the approaches that has been discussed in recent years is Demand-Responsive Transit (DRT), which offers a flexible alternative to traditional schedule-based public transport. On-demand services come in countless varieties and many cities are considering or experimenting with such new offers (e.g. MOIA GmbH, 2022; mobil.nrw, 2022), in some cases taking it to extremes as in the town of Innisfil in Canada, where public transport was replaced with Uber (Cecco, 2019). The accelerated evolution of information technologies, notably DRT booking and dispatching algorithms, has facilitated a substantially more efficient and adaptable operating system than was feasible two decades prior. The rapidly expanding domain of artificial intelligence, with its integration into autonomous driving systems, is poised to yield significant efficiency gains (Guo, 2024).

From a conventional transport planning point of view, replacing high-capacity vehicles that are packed in peak hours with smaller vehicles seems like a bad idea for urban areas with limited roadway capacity due to a dense and compact urban core. Increased congestion seems to be the logical consequence. However, demand-responsive services are also expected to confer substantial advantages. The need to look into this gave rise to this study, which investigates different scenarios for integrating DRT into conventional public transport. This aims at establishing a role for DRT, as part of public transport, that makes as much sense as possible from an urban planner's perspective.

By conventional public transport, we mean a high-capacity, low-flexibility, fixed-route, scheduled system. DRT, on the other hand, is a low-capacity public transport system with flexible routes and schedules, an area-based coverage, and on-demand pick-up and drop-off, providing a service based on ride sharing and trip pooling (riders who would not otherwise travel together sharing a vehicle for all or part of a trip) (Jang

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https://doi.org/10.1016/j.jpubtr.2025.100143
Received 24 July 2025; Received in revised form 13 November 2025; Accepted 13 November 2025
Available online 19 November 2025

et al. 2021).

In many cases, DRT and conventional public transport operate more or less independently from each other, or there is no systematic approach to integrating DRT into an existing public transport system (Freiberg et al. 2021). Furthermore, the mechanisms by which individuals make mode choices between PT and DRT, and the impact of diverse combinations of PT and DRT on these choices, remain to be fully elucidated. Another area of uncertainty is the effect of different DRT configurations on the urban transport system, for example in terms of vehicle load. This leads to the question of how DRT and conventional public transport should be combined in such a way as to take advantage of both systems. Will conventional public transport be redundant and can DRT completely replace existing public transport networks, or does DRT make more sense if deployed as a feeder to conventional public transport on corridors with high demand? How do these different variants of services affect mobility behaviour? Against the backdrop of these question, this paper investigates potential roles for DRT in the public transport systems of the future, and hence adds to the growing body of literature exploring the future of DRT (Ceder, 2021).

These questions were also relevant in the German city of Aachen. In Aachen, one of the approaches discussed in recent years to revitalize the city's public transport system is the idea of partially replacing conventional urban buses with smaller shuttles that operate as demand-responsive transit (DRT). This kind of an on-demand service was deemed to be more comfortable for users and thus likely to attract previous drivers to public transport. Consequently, this investigation focuses on the transport system in Aachen.

We first define and characterise DRT to distinguish it from what we understand as conventional public transport. Our literature review looks at research on the topic of integration of DRT into public transport systems, as well as DRT's influence on mode choice. The methodological part of this paper is based on a MATSim model of the city of Aachen, Germany. First, we describe the general structure of the model and its input data. Then we present two possible supply network scenarios for DRT and conventional public transport and their effects on the transport system. These scenarios have been developed with the expertise of various public transport and automotive industry stakeholders from public sector institutions and private companies (Louen et al. 2022). To conclude, the results are presented, consisting of the scenario-dependent effects on mode choice and the effects on the number of vehicles on the road network within the city.

2. Review of demand-responsive transport

2.1. Concept, service characteristics and deployment contexts

DRT systems have been defined as public transport services that adapt to specific transport needs (Ferreira et al. 2007) and for which users must book trips in advance (Diana et al. 2009). The term 'demand-responsive transport' has been theoretically investigated and experimented with since the 1970s as a different form of public transport system (Diana et al. 2009; Strobel, 1987). The primary motivation for implementing DRT systems is to serve low-demand areas and/or periods more efficiently and effectively (Coutinho et al. 2020).

The key features of DRT systems are pre-booking and on-demand operation (Lee and Savelsbergh, 2017). Current user demand determines the route and schedule, resulting in spatial and temporal flexibility (Lee and Savelsbergh, 2017; Armellini and Bieker-Walz, 2020). Demand-responsive services in public transport allow for smaller vehicles that are not tied to a fixed schedule, but which can respond to demand in real time (Higgins, 2021). In addition, passengers are usually picked up and dropped off near their desired location, rather than at fixed stops. But current research shows that there are various possibilities, how pick-up and drop-off and trip pooling can be organised to optimize operating costs while taking into account customer convenience (Vansteenwegen et al. 2022). DRT seeks to minimise the number of vehicles needed and the total distance travelled without affecting the passenger travel time, by bundling requests (Armellini and Bieker-Walz, 2020).

DRT is classified into four categories: destination-specific without trip chains; a substitute for conventional services; a feeder to conventional services; and a supplement to conventional services (Ferreira et al. 2007). Feeders in particular are one of the most common types of flexible public transport service in low-density residential areas (Chandra and Quadrifoglio, 2013; Armellini and Bieker-Walz, 2020).

Passengers welcome DRT systems because they can offer greater flexibility and a higher level of service than conventional services (Chandra and Quadrifoglio, 2013). However, several factors influence the acceptance of DRT systems (Schasché et al. 2022). These can be classified as personal factors on the user side, such as age and income, or service-related factors, such as travel costs and the need for transfers. The impact of DRT systems on costs is still unclear and depends on various factors such as vehicle size, regional conditions, and whether they are automated or human-driven (Steinrück and Küpper, 2010). These services can be much more expensive for operators than fixed-schedule public transport (Chandra and Quadrifoglio, 2013). However, if DRT is used in low-density areas or during off-peak hours, it may actually have lower operating costs (Shaheen et al. 2020).

With few exceptions, evaluation studies on DRT are methodologically either real-world case studies, based on stated-preference experiments, or use traffic models such as MATSim. The subsequent subchapters present a concise synopsis of the most important findings.

2.2. Scenario design and integration strategies within PT networks

Designing public transport networks is complex but essential for efficiency and usability; several algorithms and models exist for this purpose (Schöbel, 2012). In practice, networks are often historically evolved rather than model-optimized (Schmeidler, 2008), with typologies such as radial, ring, and grid (Vallée et al. 2021). Because transfers are negatively perceived (Currie, 2005), minimizing transfers is a central design goal and can attract new customers (Badia et al. 2017; Dakic et al. 2021).

Against this backdrop, integrating DRT into public transport can add flexible capacity to otherwise fixed networks. Many established DRT systems still operate parallel to existing networks (Freiberg et al. 2021), but recent research examines integration through both theoretical models (e.g. Sun et al. 2018) and empirical case studies (e.g. Leffler et al. 2021).

A review of the literature reveals that several strategies have been proposed for the design and integration of DRT. These include the replacement of fixed PT lines with DRT, the implementation of feeder DRT services to complement existing PT networks, and other scenarios where DRT functions as an off-peak service or a paratransit service. In a peri-urban case, a bus rapid transit corridor with DRT feeders replacing a conventional bus line achieved shorter travel times, higher maximum frequency, and expanded service area. In this case, DRT is competitive with a private car's quality and comfort (Armellini and Bieker-Walz, 2020). Feeder-type flexible services are common in low-density areas (Armellini and Bieker-Walz, 2020; Chandra and Quadrifoglio, 2013). Dytckov et al. (2023) found that creating better PT accessibility through a DRT feeder service, the demand for PT can be increased. The study by Vasiutina et al. (2025) from Poland found that, dependend on the city and exisiting PT network, a DRT feeder service can significantly reduce waiting times for travelers. In Amsterdam's rural context, replacing standard bus lines with DRT reduced ridership, alongside lower costs and emissions (Coutinho et al. 2020). A comparable approach is adopted in the study by Mortazavi et al. (2024), wherein the existing local bus network is substituted with a DRT service in areas of Canberra, Australia, characterised by low demand. The study demonstrates that, despite the DRT requiring a greater number of vehicles, the DRT configuration is less expensive when demand is low and travel times are reduced. In a German rural case, adding an attractive DRT led some customers to stop using the existing fixed-route service while switching to DRT (Sörensen et al. 2021). DRT can be used as an overlay to expand coverage or as an off-peak service, potentially generating new users for both DRT and conventional public transport when well integrated (Thao et al. 2021).

Operational design choices that influence integration outcomes include vehicle size and fleet allocation (Higgins, 2021), booking windows and on-demand dispatch (Lee and Savelsbergh, 2017), pick-up/drop-off policies and pooling (Vansteenwegen et al. 2022), and whether to anchor DRT to transit stops to facilitate transfers. In modeling contexts, agent-based or optimization frameworks have compared DRT with alternative on-demand services: for instance, a model showed DRT can deliver taxi-comparable quality at lower costs, especially with dispersed demand (Liu and Ouyang, 2021). Overall, integration strategies should be tailored to network structure and demand distributions, with explicit attention to transfer coordination and customer experience.

2.3. Impacts on mobility behaviour

Much of the literature optimizes DRT operations or assesses combined DRT/public transport systems without explicit mode choice (e.g. Galarza Montenegro et al. 2021, Di Huang et al. 2020). In these models, DRT trips often replace car, taxi, or public transport trips exogenously (Leich and Bischoff, 2019; Bischoff et al. 2017). Such replacements have been shown to increase travel time while decreasing total vehicle-kilometres travelled (VKT) when car/taxi trips are replaced (Bischoff et al. 2017). When public transport is replaced with DRT, operating costs tend to be higher and travel time slightly reduced; walking times combined with DRT are reported to be lower than when combined with public transport (Bischoff et al. 2017). These findings suggest potential environmental benefits through reduced emissions due to decreased VKT, although increased travel times may pose a challenge for user satisfaction.

There are several studies examining price effects on DRT mode choice. Low DRT fares or fare-free service can induce a modal shift from walking and cycling to DRT, while car tolls are necessary to achieve a notable shift from cars (over about 10 %) to DRT (Kaddoura et al. 2020). So, Pricing strategies could be crucial in promoting DRT adoption by influencing user decisions effectively. Stated-preference (SP) studies highlight the roles of user characteristics and service attributes (Piao et al. 2016; Guo et al. 2021), and recent evidence indicates that user characteristics strongly influence preferences between regular buses and DRT (Li et al. 2023). Understanding these characteristics is vital for tailoring DRT services that meet diverse user needs. Another recent study from Vienna, Austria based on a SP experiment found that customers are willing to pay 2.30 € more for being alone in a DRT shuttle compared to sharing the shuttle with other people (Rossolov et al. 2025). Travel time is a key factor in mode choice generally. For DRT, however, its role may be less pronounced than for private car or conventional public transport. Access and egress times appear to be rated more negatively for DRT than for private cars, possibly due to limited knowledge of stops or pick-up points (Krauss et al. 2022). Thus, there is a conflict in planning between achieving the best possible accessibility with DRT and simultaneously avoiding the cannibalisation of walking trips. The role of parking availability and parking costs in the mode choice decision between car and DRT is one of the contents of the paper by Geržinič et al. (2025). They found that pricing, in particular an increase in parking prices can lead to a shift from car to DRT. Furthermore, sensitivity to price and travel time can vary by time of day (Goerguelue et al. 2025). Temporal factors affecting pricing strategies remain underexplored but could significantly impact user behaviour.

A number of personal variables have been identified as having a significant impact on the transition from other modes of transport to DRT. These include age, with older individuals being more likely to opt for DRT, and driving experience, with those with more experience being less likely to do so (Rossolov et al. 2025). This implies that people, who drive regularly for a long time period, prefer driving over DRT or public transport, indicating that in terms of mobility policy, push and pull measures to reduce car trips can also have a long-term indirect reducing effect by influencing preferences.

The role of transfers in DRT has not been thoroughly investigated. By analogy, transfers in conventional public transport can be equivalent to an in-vehicle travel time increase of 15.2–17.7 min in Spain (Garcia-Martinez et al. 2018), suggesting substantial perceived penalties. It has been demonstrated that extended trip times for alternative modes of transport exert a more significant influence on the probability of adopting DRT than do higher costs (Rossolov et al. 2025). Behavioral intentions research in Germany reports that a positive attitude toward public transport is not significantly correlated with intention to use DRT, while a positive attitude toward cars significantly reduces the intention to use DRT (König and Grippenkoven, 2020). However, it should be noted that two small samples from different operating areas were combined in this study, which may have influenced the results. Another study shows that the trip purpose matters: in Australia, individuals are more willing to switch from car to DRT or bus for commuting than for social or recreational trips, where private cars remain preferred (Saxena et al. 2020). Scenario-based studies suggest DRT can reduce private car use depending on specific measures (Schlenther et al. 2022).

Prior studies collectively indicate that DRT uptake is highly sensitive to its costs: low or fare-free DRT can cannibalize walking, cycling, and scheduled PT, whereas pricing disincentives on car use are often needed to induce a substantial car-to-DRT shift. Access / egress and waiting penalties, as well as transfers, strongly shape preferences and willingness to pool. However, much of the existing work either optimizes operations without endogenous mode choice, relies on stated-preference evidence with external validity constraints, or models exogenous replacements that underrepresent transfers, active-mode competition, and network-level feedbacks such as empty VKT and spatial redistribution of traffic. Against this backdrop, our study advances the literature by endogenizing mode choice in an agent-based framework (MATSim) and explicitly representing access/egress, transfers, waiting and travel times while holding fares constant across scenarios to isolate supply-side design effects.

2.4. Impacts on network load and operations

Integration choices and deployment contexts also manifest in network-level outcomes. Agent-based and travel demand models indicate that introducing DRT can increase total VKT within cities while slightly decreasing VKT in surrounding regions, and can raise public transport usage overall (Richter et al. 2021). When DRT substitutes for car or taxi trips, total VKT tends to decrease (Bischoff et al. 2017). In rural replacements of bus lines, lower ridership has been observed with DRT, which coincides with reduced operating costs and emissions (Coutinho et al. 2020). Conversely, adding a comfortable DRT system may induce additional trips (Sörensen et al. 2021), while well-integrated designs can generate new customers for both DRT and conventional public transport (Thao et al. 2021). Cost impacts remain context-dependent: DRT can be more expensive than fixed-route services in general (Chandra and Quadrifoglio, 2013), but may exhibit lower operating costs in low-density or off-peak applications (Shaheen et al. 2020). PT network typologies and transfer penalties interact with DRT design choices (e.g., feeder vs replacement, pooling, stop anchoring), shaping coverage, frequency, passenger travel times, and perceived service quality (Dakic et al. 2021; Badia et al. 2017; Currie, 2005; Vallée et al. 2021).

Building on these strands, our study evaluates network scenarios that combine DRT with public transport using MATSim. In contrast to many studies that either optimize operations or omit mode choice, we explicitly focus on mode choice effects across different integration scenarios. Our goal is to identify designs that attract more users to public transport and/or DRT and reduce car use and car mileage in the case study area, while acknowledging the intertwined impacts on mobility behavior and network load documented above.

3. Methodology

3.1. Case study area

For this study, the city of Aachen – Germany's westernmost city, located at the intersection of the borders of Germany, the Netherlands and Belgium – was chosen, together with its surroundings, as the case study area. Aachen has a population of approximately 250,000, and the surrounding municipalities have an additional population of approximately 300,000 (Stadt Aachen, 2022). The medieval city centre of Aachen is densely populated, with a high proportion of historic buildings and a street network characterised by narrow streets and alleys. However, the city of Aachen also comprises suburban and almost rural districts with predominantly single-family housing and a low population density, especially in the south of the city. Unusually for a German city of its size, there is no urban light rail in Aachen. Instead, public transport in Aachen consists of a bus system and a single-line local rail passenger service running east–west across the city. The bus system alone carries about 60 million passengers a year and consists of 114 lines (ASEAG, 2022). The bus network is a radial ring network with an inner ring and various radial lines connecting the city centre with the surrounding areas, that covers an area of about 770 km^2 (For a detailed network plan, see ASEAG, 2023). Aachen's key mobility statistics such as car ownership (375 cars per 1000 people (Stadt Aachen, 2021)), trip rates and modal split (see Fig. 1) are by and large similar to those of other German cities of similar size (Gruschwitz et al. 2019). A notable exception is the relatively high pedestrian modal share, probably owing to the city centre's compactness. The reconfiguration of public transport including DRT in this study was simulated only for the city of Aachen; however, the model as described below also incorporated travel demand by commuters between Aachen and its nine neighbouring municipalities as well as major source and destination locations like Cologne or Dusseldorf, including outgoing and incoming trips. The boundaries of the city of Aachen, which limit the DRT Service Area, are visible in Fig. 2.

3.2. Demand-responsive transport scenario definition

At the outset of the study, we developed plausible DRT scenarios for the city of Aachen. The focus was on a combination of conventional public transport network configuration and DRT, as well as taking into consideration the properties of these services, differentiating various service areas and times. The development of the scenarios followed a structured process that was based on scenario planning techniques (Linneman and Klein, 1979). In this paper, we provide only a brief overview over the development of the scenarios, as only the outcome of this process is relevant. More details about the development of the scenarios can be found in a project report (Louen et al. 2022) and a scientific paper (Louen et al. 2023) which describe the process in more detail.

To define the scenarios, several stakeholders from the city of Aachen, as well as transport companies and car manufacturers, participated in four consecutive expert workshops, which had to be conducted online owing to the COVID-19 pandemic. These workshops covered (a) an identification of influencing factors and parameters defining the public transport and DRT service and network configuration (e.g. routeing and network structure, operating modes, capacity) (b) an impact uncertainty analysis of all influencing factors to identify critical influencing factors (Weimer-Jehle, 2006), (c) the development of projections (possible future shapes) for each critical influencing factor and (d) a cross-impact analysis for the assessment of interdependences between each projection. Throughout the workshops, stakeholders provided feedback that we used to develop the different scenarios for public transport service configurations with autonomous DRT shuttles. The fact that the shuttles are autonomous is not further discussed in this paper because we have not modelled possible effects of an autonomous vehicle on the choice of DRT. To identify a set of consistent scenarios, we employed the software tool Scenario Wizard (Weimer-Jehle, 2018). From a pool of seven scenarios, we eventually identified two scenarios which were deemed particularly interesting by the experts and the project team, and thus selected them for further analysis. The main reason for selecting these two scenarios from the seven consistent scenarios identified was their diversity and the monetary limitations in the project context. We chose the two most distant scenarios based on a morphological scenario space that describes the design dimensions regarding the critical factors and their projections. The Feeder and the Replacement Scenario are among the most distant scenarios. We decided against modelling the fare component and the influence of fares, as our primary focus was on the configuration of the DRT and its implementation in the public transport network. Taking one or more fare scenarios into account would have further increased the complexity of the results. A comparison of two network scenarios is only possible if the fare is the same in both scenarios. In order to minimise the modelling effort, no further scenarios were included. This limitation signifies that the modelling results are only capable of providing information on these two specific scenarios. It is evident that the fare component is not a contributing factor in this matter, and the same can be said of alternative operating concepts for DRT. For more details about the scenario process and the selection of scenarios, we refer to Louen et al. (2023).

The two scenarios – the 'Replacement Scenario' and the 'Feeder

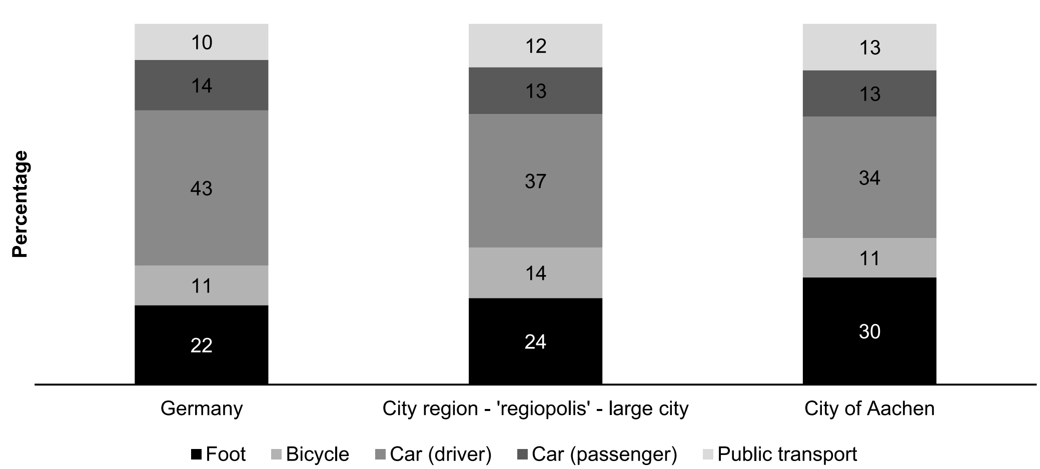

Fig. 1. Modal share of total trips in Germany, Aachen and comparable city regions in Germany (Source: Gruschwitz et al# 2019).

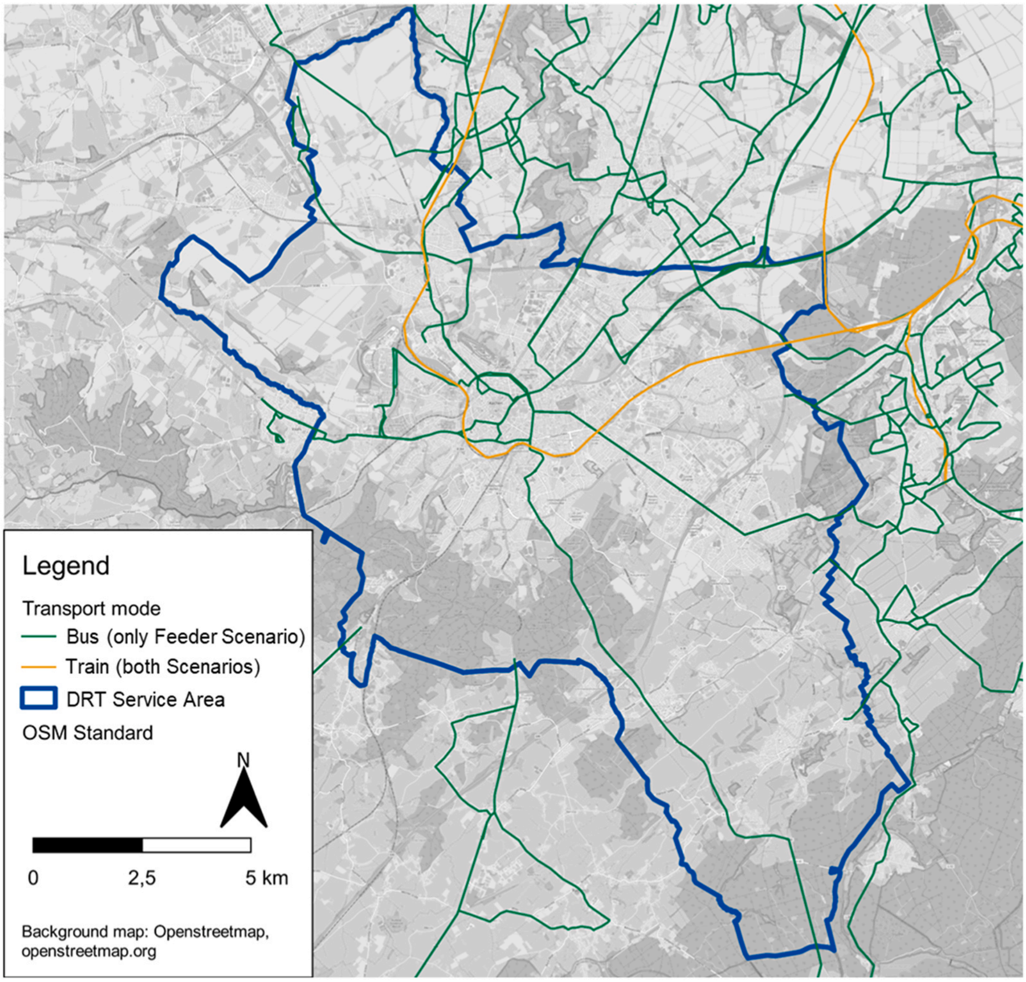

Fig. 2. DRT Service Area with Public Transport Network in both Scenarios.

Scenario' – have in common that they feature shuttles which operate on demand, thus constituting the DRT component of the scenario. The shuttles are electrically powered, and we assumed have no range restriction in order to make the results more transferable to other drivetrains and account for a future situation with drastically reduced range limitations compared to today. For both scenarios, the DRT service was implemented only in the City of Aachen, with the public transport service in the surrounding municipalities assumed to be exactly the same as in the Status Quo. For both scenarios, pick-up and drop-off times for the DRT shuttle service are assumed to be 30 seconds. Another important property of on-demand services are maximum wait times, defined as the maximum time that can elapse between ordering the vehicle and being served. As the scenarios aim for high-quality service, we have determined through iterative processes that the maximum wait time for both scenarios is ten minutes. The maximum detour time is also set to ten minutes. Aside from these common features, the two scenarios differed in relevant aspects as summarised in Table 1 and briefly described below. The appendix of this paper also contains the most important MATSim configurations and some other KPIs of the DRT system.

Table 1
Characteristics of the feeder and replacement scenarios.

Parameter	Characteristics in the Feeder Scenario	Characteristics in the Replacement Scenario
Conventional public transport	Thinning out of conventional public transport and concentration on high-demand corridors	No conventional bus transport within the city (train service remains)
Capacity of shuttles	6 persons	25 persons
Operation of shuttles	Maximum service distance: 3 km	Unlimited service distance
Parking of shuttles	Parking in street space	Parking at special hubs
Passenger pick-up and drop-off	Door-to-door	At existing bus stops

3.3. Feeder scenario

The Feeder Scenario aims at implementing a shuttle service that operates as a feeder to the public transport system. While train service in the scenario is the same as in the Status Quo, conventional fixed-route buses are assumed to be thinned out and operate only on high-demand corridors. We defined these high-demand corridors with reference to the current strategic plans of the Aachen public transport authority. The routes are selected such that there is approximately one main route in each cardinal direction. In Fig. 2, the remaining bus lines are visible, as well as the train line. Other bus lines start and end along the cities boundaries. Along the selected routes, buses run every five minutes from 05:00 to 12 at night. We modified the existing timetable so that there are no standard bus lines within the city of Aachen apart from those running on the high-demand corridors.

We added a distance constraint to the DRT service: the shuttles only serve requests up to 3 km. This constraint ensures that the shuttles serve only short or 'last-mile' trips and do not cannibalise the conventional public transport service on high-demand corridors by enforcing intermodal changes for longer trips. The shuttles have a maximum capacity of six seats and operate door-to-door, with the customer being picked up at the origin and dropped off at the destination, or at a public transport station. When not in use, the shuttles are redistributed and park on available street space, based on the best redistribution strategy ("Min-Cost-Flow") of the DRT module (Lu et al., 2021).

3.4. Replacement scenario

In the Replacement Scenario, 25-seat shuttles almost completely replace the existing public transport service in Aachen – only the train service remains in place (without changes compared to the Status Quo). Fig. 2 shows the train lines, that cover only a small proportion of the DRT Service Area. We opted for this high capacity as we anticipated a more efficient bundling of journeys.

There is no distance constraint on the shuttle service, in other words shuttles can serve trips irrespective of their origin and destination within the city of Aachen. In this scenario, the shuttles pick up and drop off passengers at the existing public transport stops in Aachen, meaning that passengers walk to the closest stop from their origin to access the shuttle service and disembark at the closest stop to their destination. The existing park-and-ride locations in Aachen serve as dedicated parking spaces for the shuttles.

3.5. Scenario implementation in MATSim

The simulation experiments conducted in this study use MATSim (Horni et al. 2022), an agent-based simulation tool that simulates travel demand at a microscopic scale. In the following we provide only a brief overview of MATSim in order to enable a basic understanding of our simulation. For more detail we refer the reader to Horni et al. (2022). We also briefly introduce our pre-existing MATSim model of Aachen (Louen et al. 2022), while the focus of the remainder of this section is on how MATSim was adapted in order to implement the scenarios described above. The general process of the MATSim modelling in our project is shown in Fig. 3.

A synthetic population, consisting of individual agents (simulated individuals each assigned a daily plan which includes in particular the way they interact with the transport network) and mirroring distributions within the real population, forms the basis of the MATSim simulation. The synthetic population created for this model is based on mobility data from Mobility in Germany (MiD 2017) (Follmer and Gruschwitz, 2019) combined with census population data. Each agent performs a series of daily activities and uses the available means of transport to move from one activity location to another. The agents' movement profiles are then simulated and evaluated in terms of their travel time, composed of waiting time, walking time, transfer time and in-vehicle travel time, and the cost required for the route using the selected mode. We used the standard Charypar-Nagel scoring in the model (Horni et al. 2022), which consists of the sum of all activity utilities ($S_{act,q}$) and the sum of all travel (dis)utilities ($S_{trav,mode(q)}$) (Formula 1).

$$S_{plan} = \sum_{q=0}^{N-1} S_{act,q} + \sum_{q=0}^{N-1} S_{trav,mode(q)}, \quad N = number\ of\ activites \tag{1}$$

The utility of an activity q is calculated with the following formula 2, taking into account the utility of performing the activity ($S_{dur,q}$), the waiting time for the activity ($S_{wait,q}$), possible late arrival ($S_{late.ar,q}$), possible early departure ($S_{early.dp,q}$) and a penalty for a too short activity ($S_{short.dur,q}$).

$$S_{act,q} = S_{dur,q} + S_{wait,q} + S_{late.ar,q} + S_{early.dp,q} + S_{short.dur,q} \tag{2}$$

The travel disutility formula (Formula 3) consists of a mode-specific constant (Cmode(q)), the direct marginal utility of time spent traveling by mode, multiplied with the travel time between travel locations ($\beta_{trav,mode(q)} * t_{trav,q}$). Furthermore, the fixed monetary costs for a mode (tolls, fixed fares) ($\beta_m * \Delta m_q$) is considered as well as the costs per distance ($(\beta_{dist,mode(q)} + \beta_m * \gamma_{dist,mode(q)}) * d_{trav,q}$). Finally, penalties for public transport transfers ($\beta_{transfer} * X_{transfer,q}$) are included in the travel (dis) utility function.

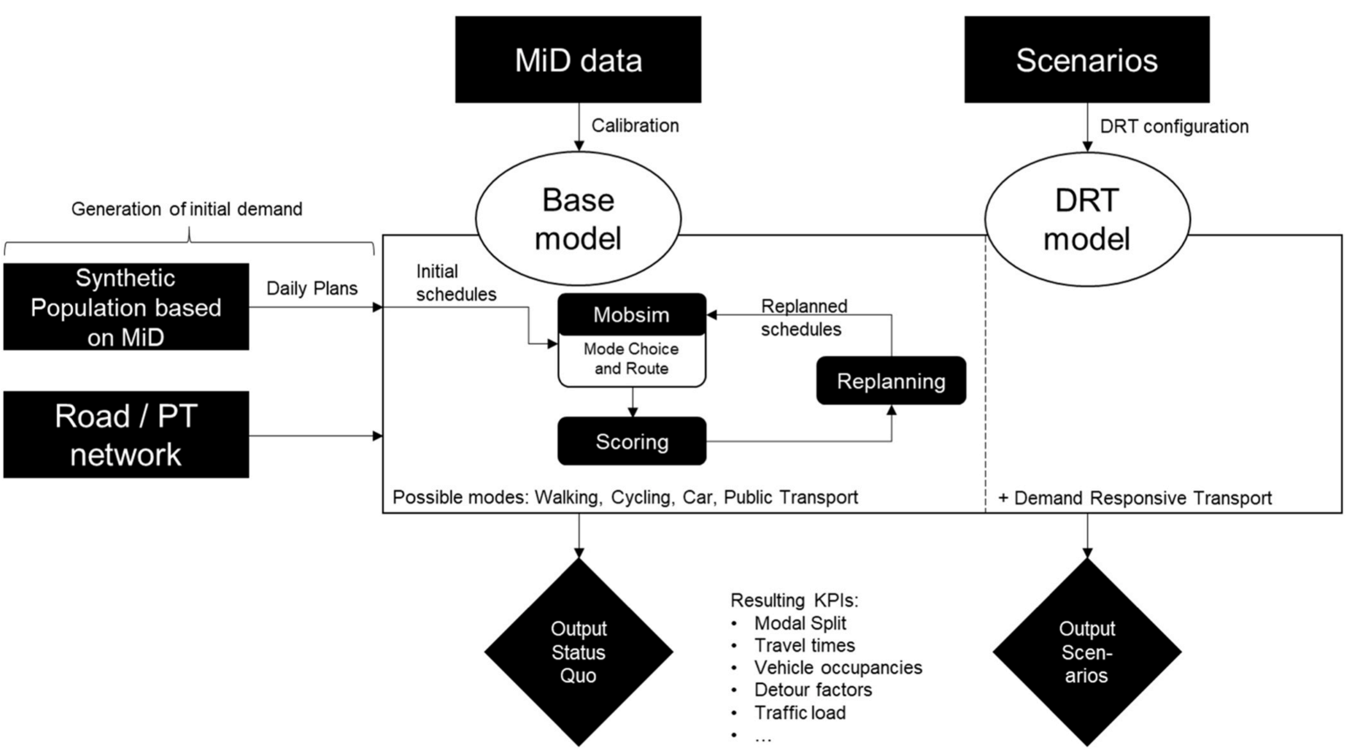

Fig. 3. Flow chart of the MATSim workflow.

$$S_{trav,q} = C_{mode(q)} + \beta_{trav,mode(q)} * t_{trav,q} + \beta_m * \Delta m_q + \left(\beta_{dist,mode(q)} + \beta_m * \gamma_{dist,mode(q)}\right) * d_{trav,q} + \beta_{transfer} * X_{transfer,q} \quad (3)$$

For further details about the Charypar-Nagel scoring, we refer to Horni et al. (2022). In our model, each of five different agent groups has three scoring parameters for each mode (See the Appendix for further details.). The scoring is based on alternative-specific constants (ASC) as well as the travel times and the costs, depending on the mode of transport. Transfer times in public transport or from public transport to DRT are part of the travel times. Waiting times – e.g. due to early arrivals at activity locations - are also included, but not scored negatively, since long waiting times usually do not occur due to the agent's plans and waiting times also reduce activity times that increase the score. However, late arrivals for activities lead to a high negative score. MATSim specialises in its co-evolutionary algorithm that optimises the agent's plan in successive iterations. The program does not evaluate aspects such as comfort which might vary between standard public transport and shuttles.

The optimisation, which leads to a final mode choice of the agents, consists of two phases. In the first phase, called the 'innovation phase', agents can choose between different modes, change their activity departure times, and change their route. Each agent creates a new plan with a different mode, departure time and route. This plan is then simulated, evaluated and saved as a plan set with a score based on the Scoring function. Each agent starts with a single set of plans, and successive iterations generate optimised new sets of plans with different transport modes with different scores that are then added to the existing set. Each agent stores its five best plans (Five highest scores) at the end of the first phase.

After the agents have tried all their options, the second phase, called the 'non-innovation phase', begins. In this phase, MATSim does not create new sets of plans, but instead reruns and re-evaluates the five existing sets (replanning). The rationale behind this approach is that the first phase of the simulation reaches a local or agent-level optimum, and the second phase reaches a model-wide optimum. We verified a stable model-wide optimum by comparing the mode choice changes after simulation runs with a different number of iterations. For further details about the model see Burla and Schrömbges (2019). The last selected plan among the available plans for each agent gives the best mode, route and departure time for each agent. We call this the 'calibrated state' (and also refer to it as the Status Quo), since it is calibrated with the MiD (Mobilität in Deutschland[1]) modal share for regions of the same region type as Aachen. As DRT is considered an integral component of the public transport system, the model was not newly calibrated to specific parameters for DRT. Instead, DRT was treated as an extension of public transport. Accordingly, the same scoring parameters that were used to calibrate public transport in the 'calibrated state' (Status Quo) were also applied to the scenarios.

The simulation framework uses the existing intermodal public transport router (routeing algorithm implementation) 'Swiss Rail Raptor' developed by Rieser et al. 2018. This router allows users to define access and egress modes to public transport facilities. The access and egress mode to each facility is limited to walking in the Status Quo. For both scenarios, DRT is added to the access and egress choice set along with walk. With this extension, the following trip chains are possible:

- walk → public transport → walk;
- shuttle → public transport → walk;
- walk → public transport → shuttle; and
- shuttle → public transport → shuttle

For this study, we modified our pre-existing Aachen travel demand model (Louen et al. 2022) to implement the two selected DRT scenarios. The model was updated using the April 2021 General Transit Feed Specification (GTFS) data and mapped onto the new road and rail network using the April 2021 from OpenStreetMap data. The agent plan file containing the intended out-of-home activities of the agents in the study area is based on a dataset from urban areas comparable to Aachen from the German MiD 2017 data. The agent plan file for the Aachen synthetic population contains a total of 250,000 agents out of which 220,000 perform out-of-home activities on the simulation day, totalling 800,000 trips. Because the simulation of such a large total number of agents is very time consuming, we created samples of 5 %, 10 %, 25 % and 50 % of the population to reduce simulation runtimes, a common approach for large models (Kagho et al. 2022). Depending on the model, it is recommended not to scale down below a percentage of 5 % or 25 % (Llorca and Moeckel, 2019). It has been demonstrated that a downscaling ratio greater than 25 % enables consistent and reliable results, irrespective of the population sample (Ben-Dor et al. 2021). The fleet size of DRT varies in a linear way between the different population samples, with 100 vehicles for 5 %, 200 vehicles for 10 %, 500 vehicles for 25 %, and 1000 vehicles for 50 %. The fleet size was determined by identifying a local optimum of various KPIs, such as the total number of DRT rides, average occupancy, or the ratio of empty distance to total distance, using the 10 % sample. After checking the results of all sample sizes, we decided to use the 50 % sample with 1000 DRT vehicles for the further analyses. To maintain simplicity in the scenario setting, the fleet size was scaled linearly.

The simulation of on-demand service in this study focuses on the contributions of the work of others on dynamic vehicle routeing problems (Maciejewski, 2016; Maciejewski et al., 2017) and DRT (Bischoff et al., 2017). The DRT module developed by Maciejewski et al. (2017) allows trips to be bundled into a single vehicle while considering various constraints such as capacity and maximum waiting time. As explained earlier, the switching of modes – which agents do to maximise the utility of their daily plan – takes place during replanning (non-innovation phase). The DRT module specifically interacts with this mode switching: once an agent decides to take a shuttle, the dispatching algorithm checks to see if a shuttle in the fleet can accept the request. If not, this means that the dispatcher has rejected the request based on a set of constraints. The constraints are the shuttle's operating time and capacity, the agent's maximum waiting time and the agent's maximum allowed travel time. We have decided to implement a Demand-Responsive Transport (DRT) service with a high level of service, which includes a low maximum waiting time and a low detour factor. The decision is supported by our iterative process of analysing results which indicated that a low level of service results in significantly longer travel times compared to other modes of transport.

4. Results

As laid out in the very beginning of the paper, as regards the implications of the DRT scenarios we were interested specifically in the trade-off between the modal shift on the one hand and the possibly increased vehicle mileage and congestion on the other. Therefore, the following presentation of results focuses on modal split, vehicle mileage and traffic distribution in the Aachen road network, though MATSim generally enables analysis of many more indicators for a given scenario. Nevertheless, the DRT vehicle occupancy is an important KPI for interpreting the results. It should be noted that the feeder scenario can accommodate up to 6 people in a shuttle, whereas in the replacement scenario a shuttle carries a maximum of 15 passengers. Thus, a capacity of 25 seems to be excessively high. Typically, the vehicle occupancy fluctuates between 1.5 and 2 passengers, depending on the time of day.

A key indicator for evaluating the impact of the scenarios on traffic in

[1] "Mobilität in Deutschland" ("Mobility in Germany") is a nationwide survey of households on their everyday transport behaviour commissioned by the German Federal Ministry of Transport and Digital Infrastructure.

Aachen is the modal shift. To consider the modal split, the calibrated state of the model was compared with the modal split of the two simulated scenarios. Fig. 4 shows the modal share of the number of trips made by all agents living in Aachen and the modal share of passenger-kilometres for the Status Quo (calibrated state) and the two scenarios. The results demonstrate a shift towards public transport (including DRT) in both scenarios. In the modelled Status Quo, the modal share of car (for number of trips) is 50 %, conventional public transport comes in at 14 % of the trips, 28 % of the trips are walking trips and 7 % of the trips are by bicycle. The Status Quo of passenger-kilometres shows that the modal shares of walking and cycling are lower here, as these are generally used for short trips. Both are at 4 %. The modal share of car-kilometres is 76 %, and the modal share of conventional public transport is 16 %. However, comparing the two scenarios with the Status Quo gives a similar picture of change to that seen in the trip-based modal splits. Returning to the lens of number of trips, the Feeder Scenario shows a modal shift in favour of DRT and the combination of conventional public transport and DRT. In contrast, the modal shares of car, bicycle and walking decrease. However, this also shows the low share of trips that are combinations of conventional public transport and DRT. Only 2 % of the trips have this pattern. Therefore, the scenario does not achieve the desired result of configuring a situation that promotes this combination of modes.

The Replacement Scenario shifts more trips from traditional modes to DRT than the Feeder Scenario. The share of DRT trips in the Replacement Scenario is 29 %, while the share of car trips decreases to 36 %. In addition, the share of cycling decreases from 7 % in the Status Quo to 3 % in the Replacement Scenario, while the share of walking trips remains stable (even slightly increasing on the status quo). The modal share of the combination of conventional public transport and DRT is even lower in the Replacement Scenario than in the Feeder Scenario, because in this scenario only the train is available as conventional public transport, and conventional public transport virtually disappears for the same reason. Here, the share of trips for each of these modes of travel is only 1 %.

The modal share of DRT trips shows that the Replacement Scenario offers users a more attractive DRT service. Significantly more people in the model switched from the classic modes of transport to DRT. The combination of conventional public transport and DRT attracts modal shares of passenger-kilometres of 6 % and 7 % in the two scenarios respectively, which is a significantly higher proportion than seen in the trip-based modal split. This is due mainly to the combination of DRT with rail transport, which usually covers long distances.

In order to find out whether the selected scenarios lead to a reduction of motorised traffic, we looked at the total car traffic mileage in the planning area. For this purpose, we calculated the VKT of conventional public transport, cars and DRT shuttle in the scenarios and for the Status Quo. To achieve this, the VKT of the different population samples (see “Scenario implementation in MATSim” in Chapter 3) were scaled up to 100 % with a negative quadratic function (see Fig. 5). It is important to note that due to the MATSim configuration with fixed daily plans, induced trips are not possible. A comparison of the total VKT shows that it changes only slightly between the Status Quo and the two scenarios. However, the VKT does increase in both scenarios, even though DRT trips replace car trips. The increase is 2.4 % in the Feeder Scenario and 1.2 % in the Replacement Scenario. It can thus be seen that the expected decrease in VKT owing to the bundling of car trips with DRT did not occur. The reason is that DRT also replaces conventional public transport, walking and cycling trips, thus increasing the total distance travelled by motorised vehicles. The replacement of conventional public transport trips leads to a lower bundling of trips and consequently to more VKT. Therefore, it is not possible to achieve, in the scenarios, an effective (from a traffic planning point of view) bundling of trips by the DRT service and thus any reduction of the overall traffic volume.

In addition to the summarised VKT, the distribution of traffic within the network is also relevant. The peak hours in particular should be considered. Fig. 6 shows the change in traffic volume (car plus DRT). The Feeder Scenario is characterised by an overall increase in vehicle-kilometres travelled throughout the network, with increases on almost every road segment. It is also noticeable that increases can be observed on almost all residential and access roads. The main reason for that is that the access to the remaining bus lines is more attractive by DRT if the access distance to be covered on foot is too great. During periods of high demand for public transport, particularly during peak hours, DRT vehicles are often seen on access and residential roads, transporting passengers to the available bus lines. Only parts of the middle ring road and the highway show a decrease in traffic. One reason for the higher load on residential and access roads is the DRT configuration in this scenario: it runs as a door-to-door service, meaning that there is no bundling of trips from bus stops as in the Replacement Scenario.

The change in traffic volumes in the Replacement Scenario differs from that in the Feeder Scenario. There are significantly more road sections with a decrease in traffic volumes. This is especially the case for the residential and distributor roads and is due to the configuration of

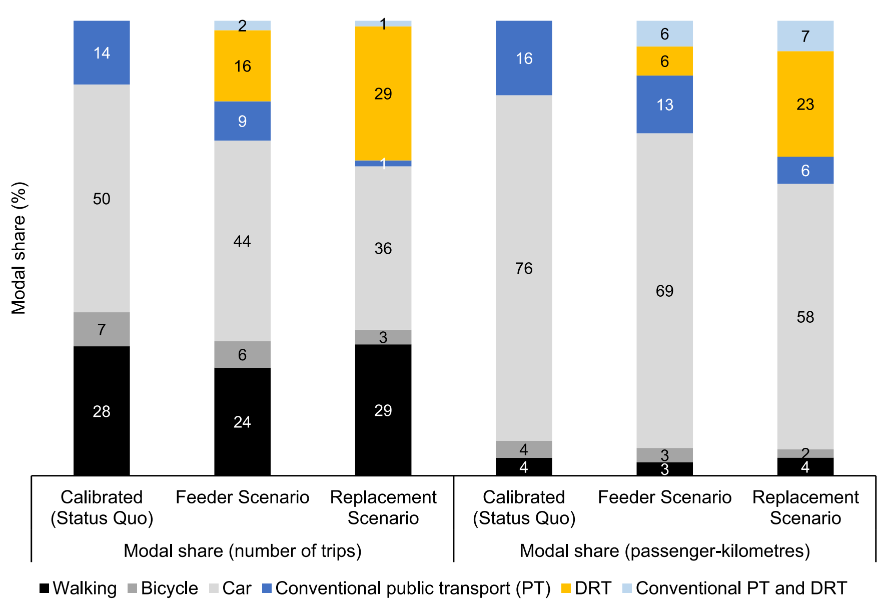

Fig. 4. Scenario-based modal share of passenger-kilometres and number of trips.

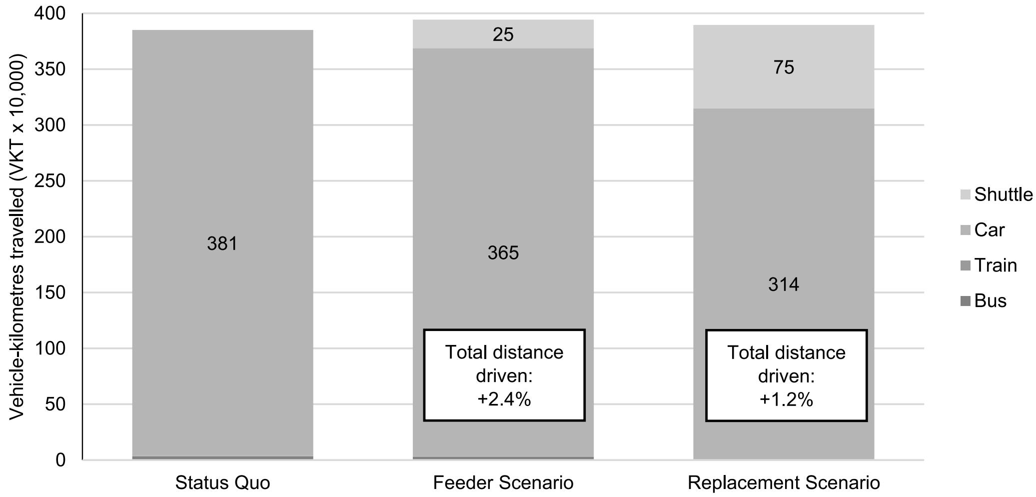

Fig. 5. Calibrated extrapolated total motorised mileage showing change in each scenario.

DRT in this scenario, where the shuttles stop only at existing bus stops. This leads to a concentration of trips on the arterials, and people are not taken to their doors via the residential streets.

In summary, both scenarios show an increase in traffic on many road segments during the morning peak. However, in the Feeder Scenario, this increase is more evenly distributed. As a result, several road segments experience a significant increase in traffic. In the Replacement Scenario, the increase in traffic is more pronounced on certain sections of the network, with the main roads especially affected.

5. Discussion and conclusions

5.1. Summary of results

Against the backdrop of vehicle automation, the concept of DRT opens the way for completely new possibilities for organising public transport services. However, the design of these services can have very different effects on traffic from one city to another (see Chapter 2). In order to promote the use of sustainable transport, implementations are needed in which DRT has the effect of supporting public transport instead of competing with it. The focus of this study is to evaluate the modal shift and traffic distribution effects of different designs for the integration of DRT with public transport in such a way that people are encouraged to use public transport more often. For this purpose, we developed two scenarios and analysed the effects on mode choice using transport simulations. The Feeder Scenario focuses on DRT as a means of access (with strong distance regulation) to conventional public transport. In the Replacement Scenario, all conventional public transport lines in the city are replaced by DRT. Both scenarios show a modal shift from car to public transport, but also an overall increase in motorised transport. This is because the provision of DRT causes shifts not only of car trips, but of also conventional public transport trips, as well as attracting trips away from walking and cycling trips. In addition, the Feeder Scenario shows that the idea of using DRT as a feeder to high-capacity public transport is not an attractive alternative for users: at least in our case study area, Aachen, with its generally short distances between origin and destination (possibly because of the number of transfers involved in a trip which includes a DRT feeder), only a relatively small number of users choose this option. The spatial distribution of the traffic increase in the network differs between the two scenarios – depending mainly on the start and end points of the shuttles (door-to-door vs bus stops). Overall, the Replacement Scenario has a higher impact on modal shift to public transport under the given conditions.

5.2. Implications for practice

These findings carry several implications for practice. In dense, well-served urban corridors, DRT should be positioned to complement rather than compete with scheduled PT, focusing on coverage gaps (e.g., off-peak periods, peripheral areas) and first- last-mile connections where scheduled service quality is low. Eligibility rules or booking constraints can limit DRT availability on origin - destination pairs already well served by high-quality PT, reducing cannibalisation of scheduled services and active modes. There are various service designs that promote pooling while lowering the share of empty rides:

- Stop-to-stop operation where feasible
- Short access - egress walking distances
- Bounded maximum trip distances
- Given time windows that facilitate rider grouping

Integrated fare policies are essential. A DRT fare structure should be calibrated to discourage substitution away from walking, cycling, and. Strengthening multimodal integration with seamless transfers to PT and modes like micromobility (e.g. bikesharing) can help channel DRT demand toward complementary use cases. Finally, operational levers such as fleet size, rebalancing strategies, dispatch and matching algorithms, and coordinated information and transfer times should be tuned to minimise perceived transfer penalties and improve pooling.

5.3. Limitations recommendations for future research

Study limitations qualify the interpretation and transferability of our results. First, the scope of the analysis is restricted to two stylised scenarios (Feeder and Replacement) and specific parameter choices that do not exhaust the design space. Assumptions such as the routes and frequencies of scheduled PT lines, the cap of 3 km on shuttle access and egress in the Feeder Scenario, and chosen fleet and dispatch settings shape outcomes and should not be read as optimal. Second, the MATSim-based simulation environment imposes simplifications that affect behavioural realism and perceived service quality: comfort, reliability, and crowding are not explicitly represented; fares for DRT were not charged, so price effects are absent; and the perception of waiting time is simplified and does not differentiate waiting at home from waiting at stops. Transfer penalties and in-vehicle time in shared shuttles may also be valued differently than in scheduled PT, but empirical data to parameterise such differences were unavailable. Third, the findings reflect the specificity of the Aachen case study, a compact city with short trip distances and comparatively good scheduled PT, and may not

Fig. 6. Scenario-based change in traffic volumes (car and DRT).

generalise to lower-density or rural settings where DRT can be more constructive. Fourth, the analysis focuses on short-run behavioural responses captured by daily mode and route choices; long-term adaptations such as changes in car ownership, season-ticket uptake, residential or workplace relocation, and habit formation are excluded, yet these dynamics can materially reshape modal shares and mobility patterns over time. Finally, it was beyond the scope of this study to compare autonomous versus human-driven operations.

These limitations naturally point to directions for future research. Broadening the scenario space to include hybrid concepts (e.g. corridor-based or zone-based DRT, peak-only replacements, dynamic service radii, and time-window settings) would help identify designs that better balance ridership gains with network efficiency. Improving behavioural realism through empirical estimation of distinct valuations for waiting at home versus at stops, in-vehicle time in shared shuttles versus scheduled PT, transfer penalties, reliability, comfort, and crowding as well as integrating fares, subscriptions, discounts, and dynamic pricing would strengthen model fidelity. Extending the analysis to long-term dynamics regarding car ownership, PT subscription decisions or residential and workplace relocation would capture structural shifts that emerge from sustained DRT deployment. Finally, expanding the evaluation framework to include emissions, energy use, noise, safety, accessibility, and distributional equity is critical for comprehensive policy appraisal.

In sum, under the conditions studied, DRT can strengthen the attractiveness of public transport but is not, by itself, a reliable lever for reducing motorised traffic in dense urban settings. Realising societal goals like shifting trips from cars without undermining active modes and scheduled PT requires a careful design of DRT.

CRediT authorship contribution statement

Pradeep Burla: Writing – original draft, Software, Methodology, Formal analysis. **Conny Louen:** Writing – original draft, Supervision, Project administration. **Carina Böhnen:** Writing – original draft, Formal analysis. **Tobias Kuhnimhof:** Supervision, Resources, Project administration, Funding acquisition. **Niklas Höing:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Acknowledgements

This research has been developed in the context of the project NAIXTransit, which has been funded by the Federal Ministry for Digital and Transport in Germany.

Appendix. MATSim configurations and DRT KPIs

MATSim model configurations and DRT KPIs		
MATSim model configurations:		
Scoring function		Standard Charypar-Nagel scoring
Number of iterations		200 (with 160 iterations in the innovation phase)
Number of DRT vehicles (based on population sample)		100 (5 % sample), 200 (10 % sample), 500 (25 % sample), 1000 (50 % sample)
Redistribution interval of DRT vehicles		30 min
Redistribution (Rebalancing) strategy of DRT vehicles		“Min-Cost-Flow” rebalancing strategy
Maximum waiting time for DRT		10 min
Maximum travel time parameters		$traveltime_{\max} = \alpha * traveltime_{expected} + \beta$ $with \alpha = 1.0, \beta\,(absolute\ detour\ time) = 10$
DRT Pickup- and Dropoff time		30 sec
MATSim scoring parameters:		Distance costs: PT/DRT: 13 cents/km; Car: 35 cents/km Travel time disutility ASC
DRT KPIs:		
Average DRT vehicle occupancy		1.5–2.0, depending on the time of the day
Average occupancy		1.09 passengers per kilometre (feeder scenario), 1.30 passengers per kilometre (replacement scenario)
Maximum vehicle occupancy (based on scenario)		6 (feeder scenario), 15 (replacement scenario)
Average travel speed (DRT trips) in km/h		14 (feeder scenario), 18 (replacement scenario)
Average travel speed (combined PT-DRT trips) in km/h		29 (feeder scenario), 40 (replacement scenario)
Share of DRT kilometres without passengers		15 % (feeder scenario), 10 % (replacement scenario)
Share of waiting time for DRT in relation to the total travel time		29 % (feeder scenario), 23 % (replacement scenario)
Average DRT waiting time		4 min (feeder scenario), 5 min (replacement scenario)
Average DRT trip length		2581 m (feeder scenario), 5480 m (replacement scenario)
Mode Shift Status Quo - Scenarios		
Feeder Scenario:		
Mode Status Quo	**Mode Sequence Scenario**	**Number of trips**
Walk	PT-DRT	64
PT	DRT	2959
Car	DRT	1066
PT	PT-DRT	1379
Walk	DRT	4401
Bike	PT-DRT	290
Car	PT-DRT	1024
Bike	DRT	2662
Replacement Scenario:		
Mode Status Quo	**Mode Sequence Scenario**	**Number of trips**
Bike	PT-DRT	115
Car	PT-DRT	629
PT	DRT	4641
Walk	PT-DRT	22
Car	DRT	5923
PT	PT-DRT	2127
Walk	DRT	2042
Bike	DRT	3306

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