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SURVEY

Recent Advances in Demand Responsive Transport: Opportunities With Autonomous Bus Service–A System-of-Systems Overview

SAJID FADLELSEED[1], POURIA SARHADI[1], SOODAMANI RAMALINGAM[1], HOCK C. GAN[1], PANDELIS KOURTESSIS[1], GAV JACKMAN[2], ATZIRI GUADALUPE SANCHEZ CONTRERAS[3], JAVIER GUIMERA TENA[3], JAMES WEST[4], JACK HOLLAND[4], AND ALICE MISSLER[5]
[1]School of Physics, Engineering and Computer Science, University of Hertfordshire, AL10 9AB Hatfield, U.K.
[2]Sustainicity Ltd., GU15 1DW Camberley, U.K.
[3]Autonomous Vehicles Department, Padam Mobility, 75008 Paris, France
[4]Rail Infrastructure Department, Siemens Mobility U.K., NW1 2PL London, U.K.
[5]Integrated Transport Unit, Hertfordshire County Council, SG1 2ST Stevenage, U.K.

Corresponding author: Pouria Sarhadi (p.sarhadi@herts.ac.uk)

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ABSTRACT This study explores recent advancements in emerging technologies for Demand Responsive Transport (DRT), focusing on the potential integration of autonomous bus services. We review the historical development and current state of research, extending the discussion into the era of Connected and Automated Mobility (CAM), particularly in mass transit. Key components of modern DRT systems are categorised from multiple perspectives, including vehicle types, infrastructure, devices, simulation approaches, decision-making algorithms, and optimisation factors. Each element is discussed in detail, supported by comparative tables to help readers interpret the results effectively. Our findings highlight the growing interest and ongoing research in this promising domain. We identify common practices across studies and areas needing improvement. To support this, we propose a System-of-Systems (SoS) approach to evaluate the technological maturity of DRT solutions, in line with our ongoing project. A System Readiness Level (SRL) analysis is performed by identifying constituent systems and assessing their Technology Readiness Levels (TRLs) and Integration Readiness Levels (IRLs). The study also explores the deployment of DRT in a specific use case: the Maylands Business Park in Hertfordshire, UK. It aims to serve as a comprehensive reference for addressing various dimensions of DRT in mass transit, particularly in the context of automation. It offers insights into current progress and outlines opportunities for deploying DRT as a cost-effective, scalable solution to improve sustainability in Intelligent Transportation Systems (ITS).

INDEX TERMS Demand responsive transport (DRT), system of systems (SoS), autonomous bus, intelligent transport.

I. INTRODUCTION

DRT is an essential component of future cities, unlocking intelligent and sustainable transportation systems. It offers flexible, on-demand transport by dynamically routing and dispatching vehicles based on passenger requests. While the concept of DRT services dates back several decades, recent advances in Vehicle-to-Everything (V2X) technology, digital devices, and smarter cities are key enablers of DRT in this era. Various studies highlight the significant impact of deploying emerging DRT services in enhancing transportation efficiency through optimised costs, improved customer service, and reduced carbon footprints [1], [2], [3], [4], [5], [6]. In particular, if properly deployed, autonomous bus services can significantly improve the performance of these systems by reducing accidents caused by human error,

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optimising traffic flow to alleviate congestion, and enabling greater accessibility to transportation for all. The motivation for this paper is to explore the recent advances in mass transit DRT services using autonomous bus services and assess the current status and availability of this technology. We have conducted a comprehensive analysis of SoS progress in this area, highlighting notable advancements and research gaps. The outcome aims to draw out new research avenues in this realm and provide clear guidelines for future research.

To briefly illustrate the importance of adopting DRT services, DRT reduces environmental impacts from Greenhouse Gas (GHG) and Carbon dioxide (CO_2) emissions, as well as traffic congestion, by decreasing travelled kilometres and the number of stops. This flexibility allows passengers to experience shorter waiting and travel times, increasing passenger satisfaction and accessibility while service providers exploit DRT's adaptability to efficiently manage resources based on the real-time supply and demand. For example, a case study by Mortazavi et al. [7] replaced 11 buses with 11 to 32 12-seater vans, resulting in a 50% reduction in operational costs and a 46% decrease in travel distances and the vans consumed 8.1 litres per 100 km compared to 28.1 litres per 100 km for the buses. Diel et al. [1] found that DRT decreased CO_2 and Nitrogen oxides (NOx) emissions per passenger trip by around 60%. Another study by [2] demonstrated that taxi-based DRT models can reduce vehicle kilometres travelled by 30% and CO_2 emissions by 40%, and a conclusion drawn from [3] reveals that under DRT, vehicles produce something more than one-third of the CO_2 and consume less energy per kilometre travelled due to their smaller size and operational efficiency compared to fixed transportation.

The waiting time for a service vehicle and the number of stops per trip can be reduced significantly as seen in a case study by Melo et al. [8] where a traditional bus service was replaced by a DRT service model. The waiting time was 30-minutes for bus arrivals in the traditional bus service where each bus makes 225 stops within 2 hours and 30 minutes to cover a track length of 174 kilometres in total [8]. The new DRT service significantly reduced the number of stops to 86 and the distance travelled to 73 kilometres, with an average waiting time of less than 3 minutes. Kim et al. [9] showed that DRT reduced waiting times by 86.9% in rural areas and by 16.4% in urban areas. Similarly, Lai et al. [10] reduced waiting times by 10% and decreased vacant vehicle pick-up times by over 60%, whereas [11] reduced waiting times to 15 minutes, compared to the fixed 60 minutes in the previous fixed bus service.

A study by [12] concluded that DRT services based on semi-fixed routes provide better results in comparison to door-to-door DRT models. Another review by [13] identified key operational issues such as fleet size, scheduling, and cost optimisation, examined many real-time algorithms, and the integration of Autonomous Vehicles (AV) and considered integration with micro-mobility services like bike-sharing and scooters to enhance service efficiency and sustainability. Dauer et al. also investigate heterogeneous groups of 52 DRTs, determining their unique features in three categorised areas: rural, urban, and peri-urban [14]. A systematic review that classifies the literature based on analytical and experimental works was proposed in [15] along with a user-centred framework that improves the adoption rate of DRT in rural areas, whereas [16] provided a comprehensive taxonomy based on dynamic online, dynamic offline, and static DRT systems according to their responsiveness. Success and failure factors of DRT were analysed by [17] stating that advancements in technology (e.g., GPS, communication systems) have impacted On-demand transport services, and emphasised the potential of electric and AVs to improve both economic and environmental sustainability by optimising routes and reducing empty mileage. Deka et al. [18] highlighted that operational cost is crucial for DRT project success, with significant outcomes including a 14% reduction in travel time and a 22% reduction in pick-up estimated arrival times. Reflecting on these reviews, technological advancements, operational optimisations, and user-centred frameworks are essential for enhancing service efficiency, sustainability, and adoption, particularly with the integration of AVs and DRT.

This paper establishes a connection between the SoS concept [67], [68], [69], [70], and the CAM HertsLynx AV project, positioning the latter within this structure. Its use case focuses on a business park with over 650 businesses and 20,000 employees, located 6–7 miles from the nearest train stations and lacking direct public transport. This makes DRT a suitable solution to enhance accessibility and reduce car dependency. The resulting analysis of this paper offers clear guidance and direction for future research. The concrete contributions of this paper are as follows:

- A comprehensive overview of DRT, including its historical development, current advancements, and future prospects.
- A structured analysis and categorisation of DRT components, such as vehicles, infrastructure, decision-making algorithms, and optimisation methods.
- The introduction of SRL analysis within a SoS framework to assess technology maturity, using TRL and IRL metrics.
- An application of the proposed framework to the Maylands case study, evaluating feasibility, costs, passenger experience, and sustainability of autonomous DRT services.
- An emphasis on the environmental and operational benefits of DRT, particularly in reducing emissions and enhancing sustainability through electric and AVs.

The rest of the paper is organised as follows. Section II reviews the historical development of DRT, current research trends, and the motivation for integrating CAM technologies. Section III examines key components of DRT, including models, vehicle types and autonomy levels, simulation tools, study types, algorithms, and optimisation criteria. Section IV introduces the SRL analysis and discusses the

SoS assessment for autonomous bus-based DRT. Section V investigates the deployment of a connected AV fleet using a hybrid DRT model in the Maylands Business Park area. Finally, Section VI summarises the key findings, including service efficiency, sustainability, and automation, along with SRL insights and future challenges for technology and infrastructure integration.

II. DEMAND RESPONSIVE TRANSPORT: AN OVERVIEW

In this section, we review DRT from its historical origins to its current role in addressing modern transportation challenges. Next, we present the increasing research trends on DRT. Finally, based on these historical developments in the growing trends, we conclude this section with a discussion on the motivation, potential, and opportunities for integrating CAM and DRT.

The concept of DRT has evolved significantly with advancements in transportation needs and technologies. The Community Transport Association (CTA) [19] and the Institution of Mechanical Engineers (IMechE) [20] have highlighted the challenges of implementing DRT in both rural and urban settings. This section reviews the definitions and perspectives on DRT, drawing conclusions and identifying key components based on research and case studies from the DRT literature and reported pilot studies worldwide, with a special focus on autonomous vehicle-based DRT projects in Europe. We start by examining the historical roots of DRT terminology and concepts, including the impact of COVID-19. Next, we provide an overview of significant trend publications on DRT and present a mind map of DRT's main components. We then review each component in separate subsections, using matrix tables to connect each reference with its main findings.

The collaboration between CTA and IMechE has defined the challenges from a modern perspective in establishing DRT in rural and urban areas [19], [20]. Many definitions have been provided by these institutes and similar organisations. According to CTA, DRT is a user-oriented form of passenger transport characterised by flexible routes and relatively small vehicles operating in Shared Ride Taxi (SRT) mode between pick-up and drop-off locations based on passengers' needs. the flexibility is what distinguishes DRT from traditional public or community transport. The Society of Automotive Engineers (SAE) has two definitions for on-demand mobility, which emphasise the flexibility of on-demand mobility services but include the factor of Internet-based technologies in their definition of on-demand mobility. The first defines on-demand mobility as an Internet-based booking and payment transportation service that can operate on both dynamic and fixed routes and schedules, depending on passenger requests and driver availability. Reference [21] puts on-demand mobility as a privately or publicly operated, and technology-enabled transit service that typically uses multi-passenger/pooled shuttles or vans to provide on-demand or fixed-schedule services with either dynamic or fixed routing. The second definition shows the importance of communication links and Internet-based technologies in maintaining connectivity between service passengers and vehicles. Reference [21] also defines ridesharing as the formal or informal sharing of rides between drivers and passengers with similar origin-destination pairings. Ridesharing includes vanpooling, which consists of 7 to 15 passengers who share the cost of a van and operating expenses, and may share driving responsibility. A broader perspective on DRT is provided by Mageean and Nelson [22], which defines DRT as a type of integrated transport service that uses a fleet of vehicles that are scheduled to pick up and drop off passengers according to their needs, offering an intermediate option between traditional buses and taxis. This definition highlights the adaptability of DRT, which aggregates features from various transport modes, such as taxis and buses, into a cohesive service that offers flexible, efficient travel solutions tailored to the needs of individual users [22]. This approach emphasises the potential of DRT to transcend traditional transport boundaries, which offers flexible alternatives that can meet diverse mobility needs in both urban and rural settings. Considering the flexibility and user-oriented nature of DRT as defined by the above, DRT's inherent flexibility by enabling dynamic routing and scheduling that responds in real-time to passenger needs, as highlighted in the definitions provided by the CTA and SAE allows seamless connection between passengers and vehicles and optimises the efficiency of transport services while maintaining the personalised, shared-ride model central to DRT. The combination of CAM's technological advancements with DRT's adaptable service models creates a transport system that is not only more efficient but also capable of meeting diverse mobility needs across both urban and rural areas.

A. DRT HISTORY

DRT is a term that has had early beginnings from illegal *jitneys* to shared taxis, Dial-a-Ride services and experimental services. The historical development of DRT is presented in the following sub-sections headed by passing decades to show the trend.

DRT began in the 1910s with jitneys offering flexible or fixed routes [23], [24]. Heavy regulation had reduced their numbers by 1918 [25]. In the 1960s, flexible transport for low-demand areas emerged [26]. The 1970s introduced experimental systems with telephone and radio dispatch [27], [28], [29], [30]. Advanced routing algorithms improved efficiency in the 1980s [31]. The 1990s saw DRT integrated with public transport aided by GIS and projects like SAMPO and FAMS [22], [32], [33], [34], [35], [36], [37], [38]. In the 2000s, real-time tracking was enabled by integrating transit systems with GPS and mobile technology [4]. The European Conference of Ministers of Transport (ECMT) [39] recognised the potential of DRT in its policy on accessible transport in July 2001 [22], and the Transportation Research

Board (TRB) produced a guidebook for evaluating DRT services [40]. During the 2010s, platforms like Uber and Grab augmented DRT with advanced algorithms and automation research [41] In the 2020s, COVID-19 and climate change accelerated the adoption of electric and automated vehicles [42], [43], [44]. Blockchain and AI-enhanced DRT's accessibility, resilience, and efficiency [45], [46], [47]. The following section presents the current status of research on DRT.

B. CURRENT STATUS OF THE RESEARCH ON DRT

The evolution of DRT systems from its basic principles of niche application to supplement public transport systems with on-demand, non-routine services continues with SoS principles being inculcated so that the DRT can interwork within a much bigger framework. We see current issues taking a more prominent place in research in the form of metrics used in optimisation studies [7]. These issues include pandemics (COVID 19), cost of living issues triggered by rise in energy prices due to war, climate change, and a growing elderly population due to the baby boomer generation [48]. On top of that, there are disruptive technologies that although may not be popular could very rapidly change. These include blockchain [49], [50] and Mobility As A Service (MaaS) [51].

COVID19: In 2019, the pandemic caused a decrease in the use of public transport [52]. The after-effect is a decrease in usage due to more working from home. The decrease in revenue stops the funding for low usage routes [7] opening the opportunities for DRT which means that more DRT studies must be made for those routes to establish viability [53]. The promise of cost reduction using AVs [45] increases the prospects for the use of DRT. Central to the use of AVs where the use of AI is crucial, is the research on safety [45]; the argument is that AI eliminates human error but at the same time software errors can be critical. During a pandemic, however, the need for social distancing disadvantages DRT for small-size buses [54].

Climate change: The need to reduce greenhouse gas emissions is reflected in the DRT studies in recent times with the increased adoption of electrified vehicles charged using green electric power sources. Research into algorithms to optimise routes based on recharging requirements contributes to the success of electrification [55]. However, DRT also plays a role in the transition to a low carbon economy in the decreased consumption of fossil fuel [41]. Studies provide an indication of the carbon footprint of different DRT solutions enabling other optimisation choices to be made [56].

Ageing population: DRT has been a solution for a vulnerable demographic from the early days in countries like the UK, where dial-a-ride and community car and bus schemes have existed. Interest in using DRT as a solution in rural areas, where there is generally an older population, shows potential [41].

Congestion: A significant issue facing cities is traffic congestion. In addition to lengthy journeys, traffic congestion contributes to health issues caused by pollutants and elevated levels of greenhouse gas emissions. Living space is taken up by too many cars. The solution is seen to be better responsiveness and connectivity of the transport system. DRT can act as an efficient feeder to transport terminals, addressing the first-mile/last-mile problem. If successful, the need for private ownership of cars will decrease especially from rural areas. In the UK, observations indicate that 80% of cars in the city only have one driver [57].

Transport Connectivity: Related to the congestion problem is the inappropriate connectivity of public transport. Typically, public transport routes span radially into major cities. Although a transportation system exists in an area, getting from one point to another can take two or three times longer with public transport than a car when travelling laterally. DRT can serve to reduce the problem [58].

System of Systems: It is common for the adoption of SoS principles to occur as an evolutionary process [59]. SoS as a discipline spans multiple domains including software systems [60]. The advancement of information and communication technologies provides the means for existing standalone systems to evolve into more sophisticated services by interacting with other established standalone systems. DRT started the process off by interacting with public transport systems. Initial interactions may just be shared ticketing and scheduling which could be manually organised. Sophistication begins with the ability to extract and respond to information from the cloud. The next level of sophistication would involve software systems communicating with each other [61]. This level of integration means that obtained data does not need to be processed to retrieve the required information, where relevant information is exchanged. With GPS, data analytics and mobile apps, a DRT could be integrated into a more seamless transportation system [61]. The initial evolution could still be a provider-centric system where the transportation system is dictated by a fixed set of resources [62]. The evolution does not need to stop there as shown by the evolution of the Internet. The transportation system could become a user-led system where different transportation modes in a city are all linked together [63]. Many practical obstructions face the form of full integration. A crucial challenge beyond the technical difficulties of interfacing with legacy systems, is the need for independent organisations to share data [51].

The literature review in this study started by identifying sources through a Scopus search, which yielded 150 papers, supplemented by 37 pre-existing sources, for a total of 187. Using keywords such as "Demand Responsive Transportation" or "Demand-responsive Transportation" in titles, abstracts, and keywords, the search covered publications from 1970 to 2024 to explore the concept of DRT. After removing duplicates, 153 unique sources remained. An initial screening then excluded 12 sources, leaving 145 for eligibility assessment. Of these, 133 articles were reviewed, with 105 excluded based on relevance or methodological criteria, particularly for sources that did not directly address

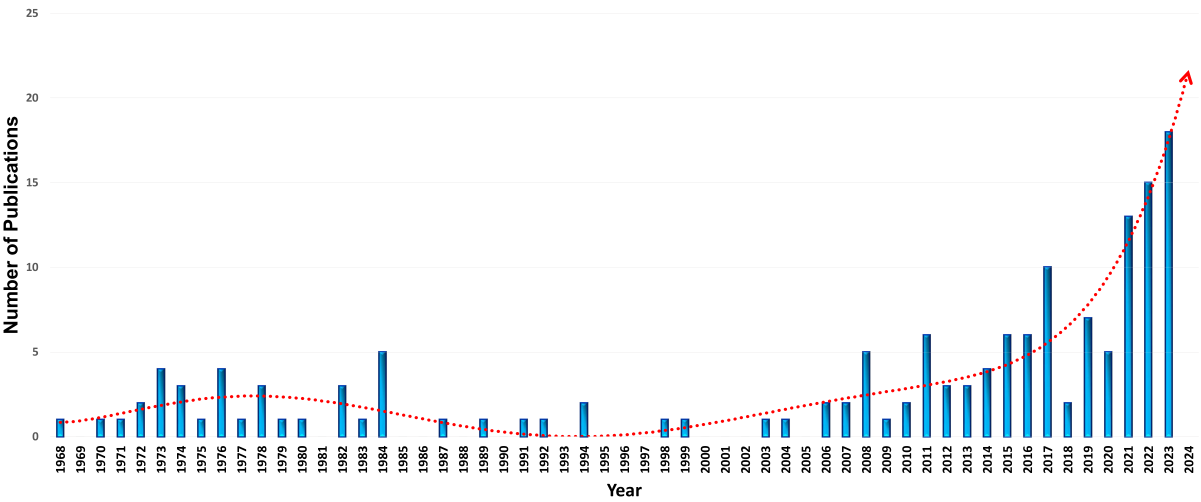

FIGURE 1. Number of yearly publications (bar chart) and their growth trend (red dashed line) in DRT research.

DRT or align with the HertsLynx Maylands use case of our project. The final sample included 40 sources that met all inclusion criteria, which required a direct focus on DRT, relevant keywords, and adherence to the time-frame. Studies were excluded if they were duplicates, lacked a focus on DRT, or did not meet research quality standards. The inclusion and exclusion criteria are based on the quality and relevance of sources related to the HertsLynx project, which excludes non-peer-reviewed sources, such as news articles and blog posts, as well as articles that do not directly relate to DRT, and the inclusion criteria requires that a source is related to CAM and DRT, based on real-world data referenced by a specific city, country, or region.

Figure 1 shows the number of yearly publications and the growth trend of DRT research from its onset, at least starting in 1968. It should be noted that this is based on available online resources, and even earlier studies may exist. This analysis is carried out using various relevant and commonly-used keywords on this topic. According to Fig. 1, DRT research was active from the beginning until 1985. This initial increase was due to the use of wired telephone technology during those decades [26], [27], [64], [65]. However, the decline in activities can be interpreted as a consequence of the limitations of wired communication technologies [66]. Nevertheless, a new era of growth is identified from post-2005, continuing with an exponential increase. This progress is owing to recent advances in the availability of post-4G communication networks, V2X opportunities, and the widespread availability of smartphones and wireless Internet infrastructure-based tools. This growth rate indicates that the topic is gaining exponentially increasing attention worldwide, with several innovative and real-world examples.

After concluding the current stage of reviewing DRT literature, the subsequent steps will involve aligning our systematic review with the available opportunities presented by SoS and AI about DRT. Our research will investigate how SoS and AI concepts can augment the efficiency, effectiveness, and adaptability of DRT systems and insights into potential advancements and innovations within the field. These studies will be continuously integrated with other available research addressing the Maylands Business Park use case problem.

C. DRT IN THE ERA OF CONNECTED AND AUTOMATED MOBILITY CAM

The UK government aims to enable the safe and secure deployment of self-driving vehicles by 2025 through a development of a comprehensive regulatory and safety framework to ensure that technologies contribute to social, economic, and environmental benefits while maintaining public trust. The government policy and strategy document in [72], presents the government's vision, the importance of CAM, the steps necessary to ensure safety and security, the industrial and social benefits, and the needs for collaborative programs associated with government, industry, and other stakeholders to place the UK as a global leader in self-driving technology. CAM is a network of autonomous buses designed to navigate and operate without human intervention by using advanced technologies to perceive their environment and make decisions based on input from various sensors, such as Light Detection And Ranging (LiDAR) and Global Navigation Satellite System (GNSS), depending on their level of autonomy as classified by the SAE [21]. The SAE defines six levels of driving automation, ranging from Level 0, where the human driver has full control with no automation, to Level 5, where the vehicle is fully autonomous under all conditions. CAM vehicles, which are Level 4, feature high automation, where the vehicle can operate autonomously in certain conditions without human intervention, though outside these conditions, driver input may be required remotely to handle certain conditions.

Integrating CAM and DRT has the potential to significantly improve safety, efficiency, and convenience in transportation. CAM can reduce human error which is a leading cause of 80% of accidents as reported in the [73], thereby, making roads safer, where DRT services can optimise vehicle utilisation, decrease operational costs, and enhance the overall user experience by providing more personalised and reliable transport options. In general, the product of this integration represents a major step towards creating a smarter, more connected, and sustainable transportation ecosystem. After an extensive review of published research on DRT, a high-level overview is presented in the mind map in Figure 2, which highlights the key components of DRT. At the core, DRT is surrounded by six main branches: Models, Study Types and Algorithms, Vehicles, Optimisation Indices, Simulation, and Infrastructure and Devices. In this research, different models for DRT have been identified and clustered into three main categories—Full Flexible [74], Semi-Flexible, and Hybrid—to reflect the varying levels of service flexibility offered in DRT. The study has reviewed several sources from both research-based and project-based DRT studies to identify the problems or issues addressed, including the algorithms and techniques used. DRT vehicle characteristics, such as Type, Size, and Fuel, significantly impact DRT operations. Additionally, software and system platforms for Traffic and Mobility, Routing, and Single/Multi-Agent and Custom simulations are essential for testing and optimising various DRT scenarios, serving as crucial inputs for decision-making. Infrastructure and Devices, covering Communication, Mobility Platforms, and Hardware and Equipment, highlight the main technological aspects required to support DRT services.

In the following section, Section III, we review the existing literature based on DRT components, including models, vehicles, simulations, infrastructure, algorithms, and optimisation indices.

III. MAIN COMPONENTS OF DRT

In this section, we review the key components of DRT based on the findings of this study. First, we present DRT models according to their flexibility and adaptability to integrate with fixed transportation systems. Next, we discuss the types of DRT vehicles and their levels of autonomy, as observed in case studies and pilot projects across Europe. We then explore simulation and mobility software platforms used for the analysis, monitoring, and evaluation of DRT services, along with the study types and algorithms employed in existing literature. Finally, we provide a classification of optimisation indices in DRT. The section then summarises the findings in three key tables from various perspectives. Tables 1 and 2 compare the results from notable research on conventional DRT. Table 3 presents a similar comparison for autonomous DRT services.

A. DRT MODELS

Recent developments and research in DRT have provided different models with different levels of flexibility. However, there is no concrete taxonomy for DRT or a unified reference model as found in traditional fixed transportation and different names, titles, and definitions have been coined for DRT in the literature. For example, the SAE Surface Vehicle/Aerospace Recommended Practice guideline noted that between January and February 2018, the task force received feedback from members and industry stakeholders, including three presentations addressing the legal definitions and usage of the term ‘‘ridesharing’’. Based on these presentations, the task force reached a consensus that the term ‘‘ridesharing’’ should not be used to describe for-hire transportation services (such as TNCs, ridehailing/ridesourcing, and taxis), even when these services are pooled. Task Force consensus emerged around differences based on the compensatory and non-compensatory nature of pooled trips and existing legal definitions for carpooling and vanpooling.] [75]. In this paper, we categorise these models into three categories: Full Flexible (FF), Semi Flexible (SF), and hybrid models. Each category includes common models defined through research and projects. The FF model includes different forms of door-to-door service, which enables users to choose pickup and drop-off times and locations based on their needs [76]. Although these services provide high convenience, they tend to be more costly and less widespread. SF models allow adjustments to pick-up times and locations but maintain fixed arrival times and routes [29] and [65]. Hybrid DRT models integrate traditional fixed-route services with on-demand flexibility, which enhances efficiency and reduces costs by adapting to fluctuating demand throughout the day [9], [77]. Recent innovations, such as virtual stops [78] and integrated public transport systems [79], continue to refine these categories and demonstrate the growing potential of DRT systems to improve both urban and rural mobility. In the following, we detail each DRT model. The Belle-idée demonstration site by the AVENUE project was a door-to-door service which allowed users to book autonomous shuttles through an app but faced challenges in integrating with Geneva’s public transport.

Fully Flexible (FF) DRT provides a door-to-door transportation option that functions similarly to ride-sharing services. In this model, passengers determine the pickup and drop-off times and locations based on their preferences [76]. Door-to-door services, whether in transportation or delivery, allow the service provider to pick up and drop off items or passengers directly at specific locations, such as the customer’s home or desired address. Although this option offers high convenience due to its personalised nature, it often comes with higher costs. Additionally, few sources and projects in the literature specifically address or offer such services, making them less common in practice. The work by [80] analysed a project called *EcoBus* in rural Germany, which follows the FF model of DRT. This service operates with flexible routes, matching trip requests to allow travel without restrictions to specific stops or timetables. The study found that seniors expressed even greater satisfaction with the service than younger users. Another study on the EcoBus project, conducted by [81], focused on a collective DRT system. This study revealed that gift vouchers significantly

FIGURE 2. **Important components and factors of DRT.**

increased EcoBus usage by 83%, compared to a 65% increase with environmental certificates.

Early studies on DRT include those by [26] developed a computer simulation model called BUSTOP for a DRT system named DSB, aimed at assessing the feasibility of door-to-door service in urban and suburban areas. Meanwhile, [27] developed a model named Demand-Jitney (DJ) which identified the potential for a 15% shift from other transportation modes to the DJ model. However, political and social acceptance was limited, as the benefits primarily targeted a smaller segment of the population [27]. The work by [26] also studied the *many-to-many* problem, which involves the dynamic assignment of passengers to buses based on real-time demand. The many-to-many problem in transportation refers to a scenario where passengers can be picked up from and dropped off at a wide variety of locations, rather than being limited to a few fixed points [26]. The study yielded two key findings: firstly, the simulation demonstrated the significant potential of demand-based bus services to provide convenient transportation in low-density areas; secondly, it highlighted the importance of using small buses and probabilistic simulation techniques to optimise routes and reduce passenger waiting times. Additionally, SRT [64] groups passengers travelling in the same direction, offering flexibility in pickup and drop-off locations.

Semi Flexible (SF) DRT is limited pickup and drop-off times and locations while ensuring a fixed arrival time at the destination, without significant deviations from the planned route [76]. The work by [29] and [65] introduced Point Deviation Bus System (PDBS), a DRT system where the service follows a fixed schedule between checkpoints but can deviate for doorstep pickups and drop-offs upon request. Reference [82] proposed ODT services in Belleville and Milton, Canada. These services operate with limited pickup and drop-off times and locations but allow users to book trips via a single platform, commonly known in the DRT literature under the MaaS framework. This platform integrates various transportation modes (such as buses, trains, and on-demand services) into one accessible interface, often available through a smartphone app, website, or call centre. The study in [82] showed that the ODT model improved accessibility, particularly for low-income and senior populations. However, challenges such as technological barriers and concerns about data privacy were also identified. AV-based SF models incorporate what is known as virtual stops or Vstops, as examined in [78], where a system called Shared

Automated Mobility On-Demand (SAMOD) was developed. These virtual stops are dynamically designated pick-up and drop-off points that are not fixed like conventional bus stops but are determined in real time based on demand and vehicle availability — for instance, near restaurants, playgrounds, or other relevant locations. The study found that Vstops significantly enhanced the user experience by reducing uncertainty in pick-up scenarios and offering real-time information. Another related concept for virtualising transfer points to maximise service coverage was developed by [83]. This study introduced a DRT model named Dynamic Transfer Point Allocation (DTPA), which optimises on-demand services by dynamically allocating transfer points based on real-time demand. The implementation of DTPA simplified vehicle routing and increased the number of travel requests served, thus, improving operational efficiency, particularly in rural areas where demand is low and dispersed [83].

Hybrid DRT is a combination of traditional bus services and SF, operating with traditional fixed-route bus services during peak hours and switching to on-demand schedules and routes during off-peak hours. This approach leverages the strengths of both systems: during peak hours, it provides the reliability and capacity of conventional bus services, ensuring that a large number of passengers can be transported efficiently along well-established routes. However, during off-peak hours, when passenger demand is lower and more dispersed, the system transitions to a demand-responsive model. This allows for greater flexibility in service provision, as buses can be dispatched to specific locations based on real-time passenger requests rather than following a fixed route. This dual-mode operation not only maximises resource utilisation by adjusting the service to match fluctuating demand but also enhances passenger convenience by reducing waiting times and providing more direct travel options during quieter periods. Hybrid DRT is particularly effective in areas where demand varies significantly throughout the day, offering a cost-effective solution that meets the needs of both high-density urban areas and low-density suburban or rural areas.

The authors at [77] compared Fixed-Route Transit (FRT) against a Hybrid model where DRT functions as a feeder system for existing fixed-route transit (e.g., buses and rail) in low-density areas. An analysis using simulation conducted by [9] compared the performance of DRT between rural and urban settings, referring to rural DRT as Hinterland and urban DRT as Heartland. The simulation showed that in Hinterland, using 2 vehicles handled 76 calls a day, with 57 virtual stops, whereas in Heartland, one vehicle was used, handling 41 passengers during peak hours, with 8 virtual stops. In addition, Hinterland reduced waiting times by 86%, from 70 minutes to 10 minutes, whereas Heartland, DRT reduced waiting times by 16.7% from around 7 minutes to 6 minutes. The study concluded that while Hinterland DRT shows substantial improvements in service quality due to reduced waiting times, Heartland DRT benefits are more marginal and mainly on operational efficiency. Additionally, a study on a system in Lolland, Denmark, by [3] found that Hybrid DRT is cost-efficient and produces significantly less CO_2 emissions than regular buses in rural areas. Another study in Dalian, China, by [84] Customized Bus Service (CBS) to analyse the relationship between the built environment— such as street layout, connectivity, and the design of public spaces— and the accessibility of the CBS service. The study found that local accessibility at both residential and workplace locations significantly impacts CBS use. Reference [43] studied Autonomous DRT (ADRT) through simulations where the system operates either in a door-to-door or stop-based mode. They found that current public transport could potentially be replaced by an autonomous DRT system with 300-400 AVs. The study concluded that an autonomous DRT system could reduce travel times and potentially lower operating costs compared to traditional public transport, particularly in smaller cities. Similarly, the study by [4] concluded that the DRT system could serve as an alternative to traditional buses such as a reduction in fleet size by up to 52% and significant reductions in cost per passenger. They simulated a 10 km^2 area near a subway terminal in Sao Paulo, with request rates ranging from 360 to 2,500 requests per hour and the experiments assigned vehicles to carry 3, 6, and 9 passengers. The results showed that increasing vehicle capacity from 3 to 6 passengers led to a 42% reduction in fleet size and a 56% reduction in total distance travelled and highlighted challenges in maintaining service levels during periods of lower demand. The authors suggest that future research should focus on more refined demand predictions and the optimisation of fleet idle times [4]. Another Hybrid DRT model that incorporates Machine Learning was proposed by [85] using data provided by Padam Mobility Ltd. This framework outperforms traditional optimisation methods in managing DRT systems, particularly by enhancing the acceptance rate of online requests by up to 9.5%. The authors recommend future work to further improve the robustness of the model, particularly in handling uncertainties in real-time demand.

A utility-based matching of AVs and hybrid requests for a model named Rider Demand Responsive System (RDRS) was proposed by [10]. In this Hybrid model for automatous DRT, both real-time and appointment-based requests are matched using the Bipartite Minimal-Cost Flow (BMCF) algorithm. The proposed utility-based algorithm BMCF increased the success rate for appointment-based requests while reducing rider waiting times by over 10% and pickup times for vacant vehicles by more than 60%. Another study on utility-based DRT by [86] explored the integration of utility-maximising demand with multiple pricing structures for decision-making. The study found that the decision-support tool helps the DRT operators strategically to manage their fleet and revenue, and to improve overall operational efficiency. Stochastic approaches for the Hybrid model in balancing the flexibility and demand of DRT services by considering multiple potential routes, or *multi-graph*, were introduced by [87]. A multi-graph represents different routes or paths between the same origin and destination, with each path having its own characteristics, such as cost, time, or environmental impact [87]. The authors demonstrated that by controlling stochastic factors such as travel time uncertainty and user satisfaction parameters within the multi-graph framework, user satisfaction improved and operational costs were reduced. The proposed algorithm outperformed existing methods in addressing both operational efficiency and user comfort [87].

A model for integrating DRT and public transport was developed by [79] named Integrated On-Demand Bus Routing Problem (I-ODBRP) which is a combination of DRT and traditional fixed-line public transport network. Reference [79] found that I-ODBRP improved service rates and reduced average user ride times compared to systems using pure DRT on-demand buses, the study includes a case analysis in Lisbon, Portugal, where the integrated model showed potential for enhancing urban mobility by decreasing travel times and increasing system efficiency. Integrating rural public transportation with e-commerce delivery services was studied in China by [88] using a model named Rural Bus Integration Transportation Services (RBITS) that combines traditional bus services with logistics operations. RBITS integrates rural public transportation with e-commerce delivery services by optimising bus routing and scheduling to serve both passengers and parcel delivery requests. Reference [88] model achieved significant cost savings of around £95,000 in annual operational costs and 66,000 km in annual mileage savings. A different case study in Canberra, Australia, for the integration between DRT and traditional transportation services named Integrated-Demand Responsive Transport (I-DRT) was studied by [7] which serves both as a feeder service and provides local transport. Feeder service is a type of transportation that connects passengers from local areas or neighbourhoods to a main public transportation system bus route, train station, or subway line [7]. The authors used a multi-objective model to optimise operational cost, environmental impact, passengers' travel time, and equity. The I-DRT system proved more cost-effective and environmentally friendly, reducing operational costs by up to 50% and fuel consumption by 80% compared to traditional bus services, it also improved passenger travel time by 15-36% and provided a more equitable travel experience by reducing the variability in travel times across passengers. Reference [89] has addressed DRTT (Deep Route Traversal Time) prediction for PT (public transport) buses in London, developing a GAT-LSTM (Graph Attention Network – Long Short-Term Memory) model to capture spatial-temporal traffic patterns. The problem under study was urban complexity and variability. The obtained results report up to 9.5% improvement in RMSE (Root Mean Squared Error) of travel time predictions during peak hours, indicating better accuracy and robustness.

B. DRT VEHICLES

DRT is experiencing a significant shift from traditional Internal Combustion Engine Vehicles (ICEVs) to more innovative and sustainable modes of transport. Integrating DRT models by replacing traditional vehicles with autonomous ones necessitates a thorough review of existing research. The following text presents the progression from classic petrol and diesel-powered vehicles to modern Electric Vehicles (EVs) and AVs. By reviewing a range of studies, it highlights the comparative advantages of these emerging technologies, particularly in terms of efficiency, cost-effectiveness, and environmental impact. Additionally, it explores the implementation and challenges of these advanced transport systems across different regions, providing a comprehensive overview of the future of mobility.

In the study by [26], it was found that using small buses resulted in wait times ranging from two to three minutes and travel times between three to four minutes, with each bus carrying five passengers. Reference [64] conducted a study in Davenport, USA, using 20 cabs and found that SRT served 750 to 1,530 passengers per weekday, compared to buses, which carried 2,500 to 3,000 passengers. The study concluded that SRT was more effective in serving widely scattered origins and destinations, particularly during off-peak hours, compared to buses. Additionally, [29] used 21-passenger Flexible Flxettes in their study and observed a significant increase in ridership to an average of 288-weekday trips, which was more than double the combined rider-ship of the previous taxi and school bus services. The simulation model by [90] was tested with various configurations, including different numbers of vehicles (10 to 40) of 11-seat buses. The study evaluates the most efficient number of vehicles needed to provide service while minimising costs and ensuring a certain level of service for passengers.

A study by [91] simulated 1 to 5 vehicles (each with 9 seats) and found that increasing the number of vehicles and the level of demand improved the system's performance, and reduced the average waiting time for passengers. Reference [77] simulated 38 demand-responsive vehicles, one for each sector around a rail station, using Network-Inspired Transportation System (NITS). In some suburban areas, NITS performed better than the traditional system, which reduced travel times by up to 35%. However, in other areas with a grid street layout, traditional transit was more efficient. Reference [80] used minibuses with features such as low entries and wheelchair mounts to enhance accessibility for older passengers. A case study in Brazil [4] found that increasing vehicle capacity from 3 to 6 passengers led to significant improvements in cost-efficiency which decreased the required fleet size by 52% and the total travelled distance by 56%. Another study analysed the replacement of traditional public transport buses with DRT in Denmark and compared operational costs, CO_2 emissions, and service quality between DRT and regular public transport. The new DRT system required an average of 28.6 eight-seat minibuses to replace the existing system of 16 traditional buses and showed that during peak hours in the morning, CO_2 emissions dropped to 75.87% of baseline values under one scenario and 64.60% under another and around midday emissions were reduced between 66% and 60%, By evening emissions were reduced between 74% and 68%.

Battery Electric Vehicles (BEVs) are powered entirely by rechargeable batteries. More than 10 electric vehicles were used in the MK Connect service project in collaboration with Padam Mobility Ltd in Milton Keynes, which replaced traditional bus routes with a DRT system. The initial fleet included 13 electric vehicles and 5 wheelchair-accessible diesel vehicles. Due to increasing demand, the fleet was expanded by adding 2 more diesel vehicles and ordering 6 additional electric vehicles. The shift to DRT resulted in a cost reduction of £1.9 million from £2.8 million. A simulation study proposed by [82] explored a combination of Electric Scooters (e-scooters) and Automated Vehicles, showing their potential to reduce carbon emissions and improve sustainability in urban transportation networks. Reference [88] discussed the use of rural electric buses as part of an integrated system.

AVs are equipped with advanced sensors and AI capabilities and capable of navigating and operating with/out human intervention and are categorised according to their autonomy level [21]. A study by [43] in the Cottbus project in Germany simulated and evaluated the potential of replacing traditional public transport systems with a fleet of Shared Autonomous Vehicles (SAVs). The simulation showed that between 300 and 400 AVs would be needed to replace the existing public transport system effectively and that AVs are less expensive to operate, particularly because fewer staff members are required. Another study by [10] introduced a new algorithm for autonomous DRT which minimised rider waiting times by over 10.4% and decreased vehicle pickup times by more than 60.9%. Reference [85] developed a machine learning algorithm that, when compared to traditional methods, showed a 9.5% improvement in handling dynamic demands. The study used data from real-world instances provided by Padam Mobility and demonstrated that the proposed method could optimise the use of AVs in a DRT system, which reduces operational costs and improves service quality. This was followed by a simulation by [92], where the authors proposed an optimisation method that improved the insertion rate of online requests by 11% compared to traditional planning methods. they used 25 real-world instances with up to 30 agents, handling 100 offline and 200 online requests. The initial routes were 17% longer on average, and the final routes were only 7% longer, which indicates overall efficiency in managing dynamic demands. Another study by [78] introduced the integration of autonomous DRT with virtual stops.

The European Union's Horizon 2020 research and innovation program funded project Autonomous Vehicles to Evolve to a New Urban Experience (AVENUE) [6], [93], and the European Commission funded project Advancing Sustainable User-centric Long-term Transportation with Intelligent Mobility and Operations (ULTIMO) [94]. As shown in Table 3, 12 projects spanning 8 countries in the field of AV-driven are presented. The Avenue projects cover various implementations in cities like Lyon, Meyrin, and Oslo, and the Ultimo projects implementations in North Rhine-Westphalia and Oslo. In Luxembourg projects, automated minibuses in the Pfaffenthal Valley, as part of the AVENUE project, provided a first and last-mile mobility service, that integrates different parts of Luxembourg City with existing public transport and urban infrastructure [95]. The project used two automated minibuses operating on a fixed 1.2 km speed of 30 km/h on public roads and 40 km/h in a controlled environment with energy consumption of 0.58 kWh per hour and 0.51 kWh per km. The route had four stops: Panorama Lift, Funiculaire-Gare, Sichenhaff, and Funiculaire, and other key areas within the Pfaffenthal Valley, including a multimodal station and a public elevator. Between September 2018 and March 2020, the two minibuses collectively covered 9,000 kilometres and served approximately 25,060 passengers. The project faced challenges such as incorrectly parked vehicles, construction work, heavy rainfall, snowfall, and instances of vandalism (resulting in broken windows on two occasions) [93]. The project report did not specify the vehicle brand or model, but they could potentially be NAVYA [96] or EasyMile [97]. The Contern trial operated on a 2.3 km fixed route within the industrial zone of Contern, with three fixed stops: Campus Contern, Gare Sandweiler-Contern, and another stop within the industrial area using one NAVYA autonomous minibus [95]. The trial successfully served around 850 passengers with a total of 4,040 kilometres during its operational periods between September 2018 and December 2022, but the cost per vehicle kilometre was higher than expected due to the limited service duration and challenges with route extensions [95]. Autonomous minibuses used in Esch-sur-Alzette are NAVYA shuttles. The project initially operated one NAVYA autonomous minibus. However, due to operational needs, a second shuttle from Pfaffenthal was added to handle the on-demand service during the evening hours and to ensure continuous operation during battery recharging periods. The minibuses operated on a 1 km fixed route along Rue de l'Alzette, the main pedestrian shopping street in Esch-sur-Alzette. The route includes six fixed stops and an additional four virtual stops for the on-demand service and collectively travelled around 4,700 kilometres from September 2021 to October 2022, which served around 12,000 passengers. The project suffered problems such as pedestrians testing the shuttle's reactions, technical problems with doors, GNSS connection, and software compatibility with the on-demand system. The on-demand service was introduced in September 2022 which required extending the service hours and the incorporation of virtual stops. This feature was popular, with more than 100 requests in the first 1.5 months of operation.

In France, a pilot study by AVENUE in Lyon operated two NAVYA autonomous minibus, where the minibus operated on a 2.6 km fixed route between the Decines Grand Large tramway station and the Groupama Stadium, with a speed limit of 30 km/h [93]. The route included mixed traffic, roundabouts, and traffic lights, which travelled around 6,400 km during the first phase before the COVID-19 pandemic and an additional 4,750 km after the service resumed again. Before the pandemic, the service transported 4,000 passengers with an average of 1.13 passengers per journey. Post-pandemic, the shuttle carried 1,639 passengers with 0.3 passengers per journey. It was noted that the shuttles faced several problems, including GNSS signal losses, hardware malfunctions, and difficulties in maintaining service reliability due to the experimental nature of the vehicles. In Switzerland, two pilot areas, Meyrin and Belle-idée, were selected for the deployment of the AVENUE project. In Meyrin, the project initially used a traditional minibus, which was later replaced by an AV after a few months due to delays in obtaining the necessary federal authorisations for the AV. The route, which connects Meyrin-Village with Meyrin-Gare train station, was integrated into the existing public transportation network. The traditional vehicle made 1,048 trips covering 1,100 km, while the AV made 1,657 trips covering 1,743 km. The only issue encountered was the initial delay in authorisation for the AV. Belle-Idée hosted the two projects, AVENUE and ULTIMO. The ULTIMO project in Belle-Idée is a Door-to-Door DRT service that started in 2023 and is planned to run until 2026. The initial deployment began with three NAVYA vehicles, but it is expected to expand to 15 fully autonomous vehicles. However, due to the limited availability of suitable Level 4 vehicles, partly because of the bankruptcies of key suppliers like NAVYA, there have been delays. Regulatory challenges and public acceptance of the service have also been noted. The three NAVYA autonomous shuttles currently in use are capable of self-driving on 99% of the routes within the Belle-Idée estate. The service includes five shared bus stops, 70 virtual stop points, and a track length of 9.2 km, with a maximum speed of 25 km/h. The vehicles are monitored remotely. The AVENUE project started in 2018 and was planned to run for several years and used more than one NAVYA autonomous minibus, though the exact number was not reported. The project faced challenges with the mixed-traffic environment both pedestrians and other vehicles. Few deliverables were found for this project by AVENUE in Belle-Idee.

In Ormoya Island, Oslo, Norway, the city hosted both the AVENUE and ULTIMO projects, which operated sequentially, and based on the earlier efforts of the AVENUE project, the ULTIMO project continued and expanded upon these findings [98] and [99]. The AVENUE project deployed a 1.6 km track that connected six bus stops across the island, using three autonomous NAVYA minibuses with an average driving speed of 10 km/h. The total distance travelled was 22,984 km, serving 6,637 passengers, with 93.8% of the driving in autonomous mode and only 6.8% in manual mode. Reported issues included 1,786 instances of parked cars blocking the route, overhanging branches, difficulties in obstacle detection due to snow, and an incident where the operator fell inside the shuttle because of overtaking by other vehicles. In Copenhagen, Denmark, two areas, Nordhavn and Slagelse, were selected for the deployment of the AVENUE project [100]. The Nordhavn area, Århusgadekvarteret, operated a circular loop with six bus stops over a 1.6 km route and served around 1,579 passengers using two autonomous NAVYA minibuses. The minibuses travelled around 2,417 km, with 82.6% of the distance driven in autonomous mode and 17.4% in manual mode due to obstacles like parked cars. Reported issues included parked cars, roadworks, and a complete shutdown of the service due to construction work [100]. In Slagelse Hospital, using one autonomous minibus, the track length was 770 meters through 5 parking areas and stops at different entrances within the hospital [100]. Distances between different departments and parking areas within the hospital were too long for many patients, visitors, and staff to walk comfortably [100]. Some insightful analysis about these projects can be found in [6] and [101].

As the transition towards more advanced modes of transportation continues, integrating CAM into DRT systems has shown significant progress and benefits, including cost reductions and increased operational efficiencies. The subsequent section reviews simulation approaches and tools used to analyse and optimise these DRT systems, which present both proprietary and open-source software libraries. These tools are critical in evaluating the performance and impact of new transport technologies, such as MATSim, SUMO, and custom solutions like BUSTOP and Padam Mobility software, which have been employed in studies to model and improve DRT services.

C. SIMULATION APPROACHES FOR DRT ANALYSIS

In this section, we list several closed and open-source simulation software libraries and applications used in the existing literature on DRT. Some of these applications and libraries are designed specifically for simulating transportation services for commercial purposes, while others are custom applications built specifically for the studies in the underlying literature.

D. SIMULATION APPROACHES FOR DRT ANALYSIS

This section presents various closed and open-source simulation software libraries and applications that have been employed in the existing literature on DRT. Some of these tools are designed for commercial transportation modelling and optimisation, while others are custom-built for academic or institutional research. The following items briefly describe some of the most prominent simulation and optimisation platforms used in DRT-related studies:

Multi-agent Transport Simulation (MATSim): An open-source, multi-agent-based transport simulation platform used for modelling and analysing DRT systems in dynamic environments. It has been applied in studies such as [43] to simulate autonomous DRT services and estimate the cost of replacing public transport systems.

Simulation of Urban MObility (SUMO): An open-source traffic simulation package capable of handling large-scale road networks. It is commonly used for traffic planning and management, particularly in urban areas [102], [103].

BUSTOP: A custom simulation program designed for studying door-to-door DRT services. Developed using the SPURT simulation language, it was originally implemented on CDC 3400 systems [26].

Aimsun: A commercial, agent-based traffic modelling software used for simulating complex transport networks and conducting strategic and operational planning [104], [105].

OpenTripPlanner: An open-source suite used for passenger information services and transportation network analysis [3], [106], [107].

jsprit: A Java-based open-source toolkit for solving vehicle routing and travelling salesman problems [108].

Open Source Routing Machine (OSRM): A high-performance routing engine for OpenStreetMap data, focused on efficient route calculation and navigation [109].

MobilityDR: Scheduling software based on the Dial-A-Ride Problem (DARP), developed by the Regional Transportation District for managing DRT services [110], [111].

Padam Mobility Software: A commercial solution developed to optimise and manage demand-responsive transport operations. It was used in [85] to handle dynamic ride request assignments.

Microscopic Mobility Simulation for Corporate (Simba): Developed by Swiss Federal Railways (SBB), this tool supports simulation of specific DRT operations [112].

mbH Mobility Software: Developed by the Max Planck Society in Germany, this software supports the simulation of mobility systems and user behaviours [80].

Gurobi: A commercial optimisation solver used for addressing complex mathematical programming models. For example, it was applied in [88] to optimise rural bus service routing integrated with e-commerce logistics.

NetLogo: A multi-agent simulation environment developed by Northwestern University, commonly used to model social, economic, and technological systems [9], [113].

PASSI ToolKit: A UML-based design framework for building multi-agent systems composed of autonomous entities [114], [115].

TomTom Webfleet: A commercial software platform for vehicle tracking and geolocation, typically used for fleet management.

HOLO Dashboard: A monitoring platform used to oversee key aspects of DRT systems such as driving mode (autonomous or manual), battery status, and trip coordination. It was utilised in the Slagelse Hospital project by the AVENUE initiative [93].

LOKI: An on-demand transport solution offering dynamic mission planning and route optimisation.

Stata: A proprietary statistical analysis tool used in transport research. For instance, [5] employed it to explore factors influencing public acceptance of DRT systems.

Custom Simulators: Several studies have used bespoke simulation tools developed for specific case studies or systems. These simulators are tailored to reflect unique service characteristics, operational environments, or research objectives [4], [15], [26], [27], [31], [90], [107], [116], [117].

It should be noted that there may be other project-specific or proprietary software that are used in practice but not reported in the literature. These simulation tools provide essential capabilities for modelling, analysing, and optimising DRT systems across a range of operational contexts. Their applications have supported both theoretical research and practical implementations, contributing to more efficient and adaptive [118] mobility solutions.

E. DRT INFRASTRUCTURE AND DEVICES

DRT service providers allow users to book their trips through telephones, smartphones, mobile apps, and web or desktop applications. Early applications of DRT enabled passengers to book their trip using telephones where they call human dispatchers [26], [27] or radio dispatchers [29], who then pass the details on to the service vehicles such as taxis or bus drivers. The radio dispatcher may be located inside the vehicle, with the driver or a hired operator maintaining communication [29]. Passengers can make calls from their home telephones, either in advance or in real-time [31], or from specific telephones installed within the service area [90]. The dispatcher is responsible for receiving passenger requests and confirming the availability of a vehicle and driver for the requested time [65]. The service logs or databases accumulated from these calls provide detailed information about the DRT service, which is used for analysing, evaluating, and improving service request times, locations, and passenger details [27], [64].

A study by [5] introduced a mobile application that demonstrates video and allows passengers to interact with the DRT system. Reference [78] used a mobile application to connect passengers to 70 virtual stops, or ’vStops’, through a Human-Machine Interface (HMI). In [82], passengers book and pay for trips using mobiles, websites, or call centres through a single platform as part of the MaaS. Reference [87] implemented mobile applications with a multigraph that accounts for stochastic travel times. The mobile application in [81] reported 38,472 successful bookings, and Cost et al. in [4] highlighted similar achievements. The EcoBus service accepted bookings through a mobile application, website, or call centre [80]. In the MKconnect project [119], passengers could book a trip via a mobile application, web portal, or by phoning the contact centre. The mobile application, along with the automated algorithm, improved the booking and scheduling processes [10], [11], [85], [119]. In the AVENUE project, the Esch-sur-Alzette test site, which began on September 12th, 2022, required users to book the shuttle via an app. However, during the trial period, no one used the app, and all bookings were made via telephone [95] where 12,000 passengers were served in the period between September 17, 2021, and October 31, 2022, and the travelled number was 4,700 km [95].

In traditional or classic DRT, communication technologies include long-range network technologies, Global Positioning Systems (GPS), General Packet Radio Service (GPRS), Universal Mobile Telecommunication System (UMTS), Mobile Data Terminals (MDTs), Private Radio Networks (PRN), and cloud-based networks [31], [62], [120]. Reference [62] introduced a DRT model that utilises cloud networks to facilitate communication between service vehicles, the cloud platform, sensors for tracking passenger occupancy rates on buses, smart card readers, and mobile and web applications. Reference [77] introduced a telecommunications-based DRT network model, NITS, where the demand-responsive subnet operates similarly to a LAN in data communication. They conducted a simulation in a fictional city with a 100 × 100 square block grid, dividing the city into 36 subnets. The results showed that the NITS system, with passenger request rates of 3, 6, and 12 requests per minute, improved average trip times by 21%, 17%, and 14% over walking, respectively. Reference [31] discussed the use of Geographic Information Systems (GIS), Mobile Data Terminals (MDTs), Automatic Vehicle Location (AVL), and Intelligent Transportation Systems (ITS) technologies. In an early study from the 1970s, Flusberg et al. demonstrated the use of mobile telephones in the Merrill-Go-Round system, employing radio transmitters as a communication method to manage passenger requests and coordinate with bus drivers [29]. Similarly, [26] discussed the use of telephone-based communication for receiving passenger requests, combined with radio communication to coordinate bus operations in real-time.

In autonomous vehicle-based DRT projects, advanced communication technologies are employed, including LIDAR, GNSS, 3D Video Cameras (3DVC), Odometry Sensors (OS), 4G/5G communication, On-Board Units (OBU) V2X YoGoKo, and Roadside Units (RSUs) V2X FARECO [93], [94], [95], [98], [121]. These projects also utilise advanced hardware components for operation and communication, such as NVIDIA Jetson Orin (NJO), Intel Realsense D435 (IRD), PROPHESEE Metavision (PMV), VIVOTEK FE9180-H (VFH), and Texas Instruments AWR6843 [98], [121]. High-definition cameras on the vehicle provide a 360-degree image of the surrounding. NVIDIA Jetson Orin serves as an AI computer for autonomous operations, while Intel Realsense D435 functions as a sensor for RGB and depth maps. PROPHESEE Metavision is an event-based vision sensor, VIVOTEK FE9180-H is a panoramic fisheye camera, and Texas Instruments AWR6843 is an automotive radar sensor [94], [98], and [121]. At the Pfaffenthal test site, the [95] project equipped automated minibuses with LIDAR sensors to detect obstacles and installed GNSS base antennas to ensure precise navigation and safe operation along designated routes. However, the study highlighted the limitations of LIDAR sensors, particularly in terms of resolution and range, which impacted the shuttles' operational speed and reaction time.

F. STUDY TYPES AND ALGORITHMS

This subsection presents the study types and algorithms used in this research and highlights the methods used to optimise routes, reduce operational costs, and enhance overall service efficiency.

Melis et al. reduced the User Ride Time (URT) by applying a Mixed Integer Programming (MIP) and an Insertion-based Heuristic algorithm to improve the selection of optimal routes for passenger transfers [79]. MIP is an optimisation technique that identifies the best solution from a set of integer variables under certain constraints [122]. The Insertion-based Heuristic method incrementally inserts new elements, such as requests or tasks, into an existing partial solution to maximise overall utility [123]. A case study by Mortazavi et al. in Australia found that using 12-seater vans reduced operational costs by up to 50%, minimised unnecessary travel distances by 46%, and replaced 11 buses with 11 to 32 vans. Each van consumed 8.1 litres per 100 km, compared to 28.1 litres per 100 km for buses [7].

In another study, [88] minimised operational costs using the Multi-Trip Vehicle Routing Problem (MTVRP) along with an integrated approach combining Adaptive Large Neighborhood Search (ALNS) and Tabu Search (TS). Reference [3] employed a VRP algorithm solver enhanced with an insertion-heuristic. Reference [87] demonstrated that their ALNS algorithm outperformed reference algorithms by 32.67%. Reference [81] examined the effects of vouchers and certificates on the number of EcoBus trips over time, revealing significant impacts on user behaviour. Reference [92] utilised a ML algorithm for guided optimisation to manage dynamic demand in collaboration with Padam Mobility Ltd. Reference [85] introduced the Machine Learning Guided Optimisation (MLGO) framework, which improved DRT trip scheduling using the Padam Mobility simulator. This simulator models how the DRT service operates throughout the day, including the behaviour of virtual users when presented with various trip options. Building on this, [119] developed an integrated model of the MLGO framework to further enhance DRT systems. Additionally, [10] designed a vehicle-rider matching problem by modelling it as a minimal-cost flow problem on a bipartite graph, where vertices are divided into two distinct sets, ensuring no two vertices within the same set are adjacent.

Autonomous DRT systems rely on advanced hardware and algorithms such as GNSS for precise positioning and obstacle detection to avoid obstacles like parked cars along the route [94], [95], [124]. The FRPD algorithms are employed to identify and verify passengers by analysing their facial features and presence in the vehicle. This technology enables continuous tracking, providing parents or caregivers with real-time information about minors or disabled individuals onboard, and also detects smoking and e-cigarette use. OD algorithms are utilised to identify data points that significantly deviate from expected patterns or distributions within the dataset. This real-time monitoring and evaluation compare the empirical behaviour of the autonomous system against previously expected behaviour, using techniques such as Vector Regression Analysis, Mahalanobis Distance-Based Techniques, and Kernel Density Probability Estimates. Lastly, AGDM algorithms are designed to detect and mitigate interference in wireless communication. These algorithms identify the location of jamming sources and apply mitigation techniques to avoid such interference, ensuring safe telecommunications between DRT personnel, passengers, and electronic devices, and protecting the normal operation of intra/intercommunication in AVs.

G. OPTIMISATION INDICES

In this section, we categorise DRT optimisation indices into four categories Environmental Impact (EI), Passenger Satisfaction (PS), Operational Cost (OC), and Operational Planning (OP). As presented in Figure 3, sources discussed EI in the context of reducing Greenhouse Gas (GHG) emissions, improving Energy Efficiency (EE), reducing traffic congestion TC, maintaining sustainable urban mobility (SUM), and noise pollution (NP). Early studies on DRT [26], [27], [29], [64], [65], [90] have discussed that DRT has the potential to improve SUM and TC, as other subcategories under EI were not discussed during that time except the study by Arad et al. [90] introduced a model named FORCAST to enhance the EE and reduces the TC of the DRT model in the study. Later studies in the 1990s by [31] show that EE can be improved by minimising the idle time of DRT vehicles. The work by [91] showed that minimising DRT can reduce EI, the simulation in this study of TC considered delays due to congestion as a factor impacting the performance of DRTS. The paper [77] introduced the Network-Inspired Transportation System (NITS) framework, which integrates demand-responsive transit with static routes. The study discussed EE by minimising Vehicle Miles Traveled (VMT). Simulations showed that for a small number of passengers, the on-demand vehicle reduced VMT compared to static routes, with an average VMT as low as 10.64 units for 5 passengers. Another study by [43] indicates that improving EI can be achieved using a stop-based DRT system. The study found that a stop-based system with 300 vehicles required less energy in terms of VMT (60,381 km daily) compared to a door-to-door system with 400 vehicles (65,306 km daily). This suggests that the stop-based system is more energy-efficient than a door-to-door DRT service. Coutinho et al. [11] studied the replacement of a fixed bus service with a DRT bus service, including Combi-DRT and Electric-DRT. Combi-DRT uses Compressed Natural Gas (CNG), while the e-Crafter DRT is an electric van. This replacement resulted in a significant reduction in GHG emissions, dropping from 5.4 kg of CO_2 per passenger for the fixed bus line to 2.1 kg of CO_2 per passenger for the Combi-DRT, and further to 1.0 kg of CO_2 per passenger for the e-Crafter DRT.

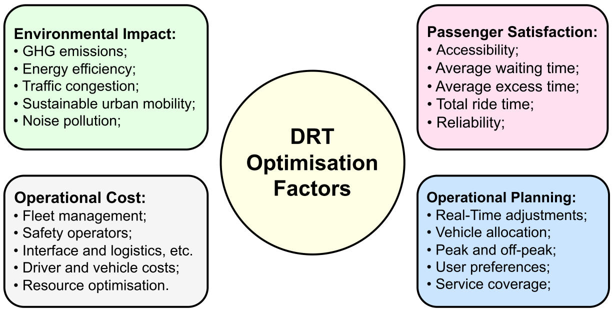

FIGURE 3. **Optimisation factors in DRT.**

We categorised findings from this review regarding Passenger Satisfaction (PS) into five subcategories: Accessibility, Reliability, Average Waiting Time (AWT), Average Excess Time (AET), Total Ride Time (TRT). The study [7] reported passenger satisfaction increased by 80% with their I-DRT model as the accessibility to public transport hubs increased by 65%, and the reduced AWT by 8 minutes, where AET was between 3 to 5 minutes, due to the dynamic multiple passenger pickups. Reference [119] case study quantified the reliability of the service by ensuring that 95% of journeys are picked up within 10 minutes of the scheduled time. In the AVENUE project, the service in Luxembourg was offered free of charge, which improved accessibility. It was available online via the website `mobiliteit.lu` and supported by a dedicated intervention team. In Geneva, 59.77% of scheduled trips were completed on time. In Copenhagen, safety incidents were recorded, including 15 passenger falls and frequent operational disruptions caused by parked vehicles. Reference [86] included user preferences and demographics into the pricing model of the DRT service they simulated which improved the accessibility to the service for groups with different socio-economic backgrounds, and reduced AWT, AET, and TR for 30 requests - AWT from 150 minutes to 119 minutes, AET reduced from 180 minutes to 151.94 minutes, where TRT was 30 minutes and reduced to 24 minutes. Adjusting the fleet sizes reduced AWT in [10] from 30 minutes to 22 minutes and TRT was reduced from 60 minutes to 45 minutes, and the SR remained high at 95%, [85] remained 98%, by ensuring that most trips were completed without cancellations. A recent study with deeper insight into DRT service satisfaction is performed in [125]. Authors discovered that 90.65% of participants believe extensive driving experience reduces willingness to use demand-responsive transport (DRT). Furthermore, a 100% rise in parking fees could increase the likelihood of choosing DRT by up to 1.25 percentage points, while users showed greater sensitivity to travel time than to costs in mode choices.

Operational Cost is categorised into five subcategories: Fleet Management (FM), Safety Operators (SO), Interface and Logistics (IL), Driver and Vehicle Costs (DVC), and Route Optimisation (RO). Reference [92] reduced the operational cost by decreasing the total fleet required by 12%, [81] reported a 5% reduction in driver and vehicle costs where [31] used real-time scheduling to adjust vehicle routes dynamically, which improved fleet efficiency and reduced waiting times by 10%, and operational costs by 12% [91] decreased operational cost by 15%, [87] decreased operational costs by 20% by refining vehicle dispatching processes, which led to a 20% reduction in fleet size. Reference [81] used environmental incentives to increase ridership by 9%, which reduced idle vehicle time and reduced driver and vehicle costs by 5%. Reference [117] found that AVs can potentially slash driving costs by 25%. They could also potentially reduce the operational costs by adaptive fare pricing strategies, which improved vehicle utilisation by 15%, and it was validated using New York City taxi trip data and a 0.17% increase in overall profits.

ULTIMO projects in Germany, Norway, and Switzerland, showed that the deployment of SAE Level 4 AVs reduced operational costs by 30%, while the fleet utilisation improved by 25%. In Luxembourg use case by AVENUE showed that the capital expenditure (CAPEX) for a single shuttle was €346,250, with a total fleet cost of €626,950. The operational expenditure (OPEX) for a single shuttle amounted to €123,685, bringing the total fleet's operational costs to €242,070. Key performance indicators (KPIs) for this site showed a cost of €0.90 per passenger per kilometre and €13.45 per shuttle per kilometre. In Contern, the CAPEX for a single shuttle was also €346,250, and operational costs were €123,685. Due to the challenges during the project, the actual operational costs per passenger was €2.23, which is higher than what was planned (€0.86), and the cost per shuttle per km was €33.43, more than double what was planned (€12.95). In the city of Esch, the CAPEX for a single shuttle was also €346,250, while OPEX was higher at €137,185. The cost per passenger per km was €1.83, and the cost per shuttle per km was €27.44, which was due to the difficulties in operating in a pedestrian zone. For all pilot sites in the AVENUE project (Lyon, Geneva, Copenhagen, and Luxembourg) a safety operator for each autonomous shuttle was allocated [6]. Even though shuttles are autonomous, French regulations require a safety driver to monitor the shuttle's operations. Each safety operator was equipped with a tablet-based application to log incidents, report technical issues, and track ridership data. They played an essential role in troubleshooting and ensuring the smooth operation of the shuttle fleet and the total cost of safety operators was €72,552. The logistics for passenger reservations and shuttle dispatch were provisioned using the Padam Mobility Platform, despite efforts to automate the service, limitations in the API integration between Padam and NAVYA software added complexity to the logistics [6]. The Maintenance costs for the AV were high due to reliance on NAVYA for technical support, and around €9,000 was spent on remapping the area and €9,900 was allocated for developing the safety operator application.

Operational planning is categorised into five subcategories: Real-Time adjustments, Vehicle allocation, Peak and off-peak hours, User preferences, and Service coverage. A decision-support tool proposed by [86], which guided DRT operators on which users to serve based on geographical coverage (e.g., zone-based fare structures). In terms of real-time adjustments, the Keolis Lyon project [93] described how traffic lights are adjusted in real-time when a shuttle is approaching to give the shuttle priority at intersections and ensure safe navigation through high-traffic areas. In addition, the AV shuttle departs from a stop at off-peak hours every 15 minutes and 10 minutes during peak hours. Another critical item considered in the literature is decision-making in rejecting non-essential DRT requests [126]. A recent study in Berlin shows that actively declining ride requests with viable alternative travel options can optimise fleet capacity, resulting in improved service quality and ensuring that resources are prioritised for passengers who truly need DRT services.

In the next section, Section IV, we present the System Maturity Level analysis approach and discuss the SRL assessment for the Autonomous Bus DRT service.

IV. SYSTEM OF SYSTEMS AND TECHNOLOGY READINESS LEVEL IN DRT WITH AUTONOMOUS BUS SERVICE

A DRT service that involves autonomous buses is a highly complex system composed of various subsystems, each with enough complexity and independence to be considered a system in its own right. Consequently, the integrated system can be regarded as a System of Systems. Figure 4 schematically illustrates the diverse systems that engage with this SoS. The diagram includes an automated bus connected to existing (or potentially new) transportation systems, V2X communications, interactions with devices and humans, fleet management systems, networks, payment systems, and other vehicles.

ISO 21839 [127] and INCOSE Systems Engineering Handbook [128], drawing on Maier's work [129], outline five characteristics for constituent systems of a SoS:

- Operational independence of component systems;
- Managerial independence of component systems;
- Geographical distribution;
- Emergent behavior;
- Evolutionary development processes;

which all the above characteristics are relevant to a DRT SoS. Some references categorise research categorises SoS based on complexity and scope into three spectra: technical systems (involving engineered systems), socio-technical systems (including people, technology, and organisations), and enterprise (encompassing a wide variety of systems, organisations, policies, and competing efforts) [59], [67]. The integration of an automated bus in DRT can be readily categorised at the socio-technical level or higher. Consequently, it is advisable to employ systems engineering tools to support its design and analysis.

TABLE 1. Summary of research on conventional DRT (continued 1/2).

Ref.	Year	DRT-model	Vehicle type	Study type	Algorithm(s)	Simulation/ Mobility Platform	Infrastructure/ devices	Optimisation indices	Region
[26]	1968	DSB	Up to 5 Small Bus	Stochastic	Call/Bus assignment	BUSTOP	Telephone	PS - OC - OP	Not Specified
[27]	1971	DJ	Small Bus	Empirical	Queueing	Not Specified	Telephone	PS - OC - OP	100 U.S. cities
[64]	1976	SRT	20 Cabs - 30 Cars	Comparative	Not-specified	Not-specified	Not-specified	PS - OC	USA
[29]	1976	PDBS	21-passenger Flexible Flxettes.	Empirical	Route/Point Deviation	Not-Specified	Telephone	PS - OC - OP	USA
[90]	1978	Hybrid	10 to 40 Bus each with 11-Seat	Planning	Best Route Selection	Residential simulation	Telephone	PS - OC - OP	Israel
[65]	1982	PDBS	12-passenger vans	Empirical	FORCAST	Not-specified	Not-specified	EI - PS - OC - OP	USA
[31]	1998	Hybrid	Many	Empirical	Heuristic		MDTs, GPS	EI - PS - OC - OP	USA
[74]	2006	Full-flexible	Not-specified	Analytical Model	TWC	Not-specified	Mobile App	PS - OC - OP	Not-specified
[91]	2011	Hybrid	1 to 5 vehicles each with 9 seats	Emprical	DARP, HGA	Not-specified	Not-specified	EI - PS - OC - OP	Italy
[77]	2012	FRT	38 Buses	Empirical	DARP, HGA	Not-specified	Not-specified	EI - PS - OC - OP	USA
[43]	2019	ADRT	SAVs	Empirical	K-Means Clustering	MATSim	Mobile App	EI - PS - OC - OP	Switzerland
[11]	2020	Hybrid	1 to 5 Buses each with 9 seats	Case Study	Not-specified	Mokumflex project	Not-specified	EI - PS - OC - OP	Netherlands
[10]	2020	RDRS	SAVs	Case Study	BMCF	Not-specified	Mobile App	EI - PS - OC	China
[85]	2021	Hybrid	SAVs	Case Study	MLGO, RBFN, GPR, FNN,CNN ALNS	Padam Mobility Platform	Mobile App	EI - PS - OC	Not-specified
[119]	2021	Hybrid	19 Electric Vehicles and 5 Diesel Vehicles	Case Study	ALNS	Not-specified	Mobile App	EI - PS - OC	UK
[80]	2021	Hybrid	Minibuses	Case Study	DARP	EcoBus	Mobile App	EI - PS - OC	Germany
[5]	2023	Hybrid	SAVs	survey of 1,168 participants	SEM - UTAUT - ITM	Not-specified	Mobile App	EI - PS	Korea
[118]	2023	MRT	Not-specified	Simulation	Continuous Approximation	SimMobility	Mobile App	EI - PS - OC - OP	France

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TABLE 2. Summary of research on conventional DRT (continued 2/2).

Ref.	Year	DRT-model	Vehicle type	Study type	Algorithm(s)	Simulation/ Mobility Platform	Infrastructure/ devices	Optimisation indices	Region
[4]	2021	Hybrid	Up to 9 Passengers Vans	Case Study	DARP	Not-specified	Not-specified	EI - PS - OC	São Paulo, Brazil
[92]	2022	Hybrid	Not-specified	Case Study	DARP, ML, Adaptive Large Neighborhood Search (ALNS)	Numerical benchmarks	Not-specified	EI - PS - OC - OP	Mauritius Island
[86]	2022	CC-DARP	Not-specified	Case Study	MILP, Local Search Heuristic	case study	Not-specified	EI - PS - OC	USA
[81]	2022	Hybrid	EcoBus	Case Study	DiD	EcoBus project	Telephone, mobile app, website	EI - PS - OC	Germany
[87]	2022	SDARP-MGUS		Miniubs	Case Study	ALNS	Mobile App	EI - PS - OC	China
[9]	2022	Hybrid	Minibus	Case Study	Not-specified	NetLogo	Not-specified	EI - PS - OC	Korea
[3]	2022	Hybrid	Average of 28.6 minibuses	Case Study	Vehicle Routing	OTP, OSRM, jsprit	Not-specified	EI - PS - OC	Denmark
[82]	2022	MaaS	SAVs and Electric Scooters	Case Study	Not-specified	Not-specified	IoT - Mobile App	EI - PS - OC	Canada
[84]	2023	CBS	Not-specified	Case Study	GBDT	Not-specified	Not-specified	EI - PS - OC	China
[78]	2023	SAMOD	SAVs	Evaluation Study	Not-specified	Not-specified	HMI, Mobile App, vStops	EI - PS - OC	Germany
[15]	2023	DTPA	Vans	Case Study	GA, MDVRP	Custom simulation	Not-specified	EI - PS - OC	Spain
[88]	2023	RBITS	Electrical Vehicles	Case Study	MTVRP, ALNS, TS	Gurobi	Not-specified	EI - PS - OC	Case study 78 villages in China
[7]	2024	I-DRT	between 11 and 32 vans each with 12 seats	Case Study	LDDA	Not-specified	Not-specified	EI - PS - OC	Australia
[79]	2024	I-ODBRP	Not-specified	Case Study	MIP, Insertion-based Heuristic	Not-specified	Not-specified	EI - PS - OC	Not-specified

TABLE 3. Overview of projects on DRT systems with AV service.

Ref.	Year	DRT-model	Vehicle type	Study type	Algorithm(s)	Simulation/ Mobility Platform	Infrastructure/ devices	Optimisation indices	Region
Pfaffental [95]	2018	Fixed	2 Navya	European Union's Horizon 2020 - AVENUE	FRPD, OD, AGDM	TomTom, HOLO	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - OC - OP	Luxembourg
Contern [95]	2018	Fixed	1 Navya	European Union's Horizon 2020 - AVENUE	FRPD, OD, AGDM	TomTom, HOLO	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - TC - OP	Luxembourg
Esch [95]	2018	Semi-Flexible	1 Navya	European Union's Horizon 2020 - AVENUE	FRPD, OD, AGDM	TomTom, HOLO	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - OC - OP	Luxembourg
Lyon [95]	2019	Fixed	2 Navya	European Union's Horizon 2020 - AVENUE	FRPD, OD, AGDM	Padam	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - OC - OP	France
Meyrin [95]	2019	Fixed	1 Navya	European Union's Horizon 2020 - AVENUE	FRPD, OD, AGDM	TomTom, HOLO	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - OC - OP	Switzerland
Belle-idée - AVENUE [94]	2019	Semi-Flexible	Not-specified	European Union's Horizon 2020 - AVENUE	FRPD, OD, AGDM	TomTom, HOLO	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - OC - OP	Switzerland
Nordhavenn	2017	LetsHolo	2 Navya	European Union's Horizon 2020	FRPD, OD, AGDM	TomTom, HOLO	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - OC - OP	Denmark
Belle-idée -ULTIMO	2018	Semi-Flexible	3 NAVYA SAE level 4	European Commission - ULTIMO	FRPD, OD, AGDM	TomTom, HOLO	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - OC - OP	Switzerland
Slagelse [95]	2017	LetsHolo	1 Navya	European Commission - ULTIMO	FRPD, OD, AGDM	TomTom, HOLO	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - OC - OP	Denmark
Oslo [95]	2017	LetsHolo	3 Navya	European Commission - ULTIMO	FRPD, OD, AGDM	TomTom, HOLO	LIDAR, Sonar, GNSS , 3DVC, OS	EI - PS - OC - OP	Denmark
North Rhine-Westphalia [121]	2022	DB Regio Bus	Navya	European Commission - ULTIMO	FRPD, OD, AGDM	Loki	NJO, IRD, PMV, IRD, VFH, TIA	EI - PS - OC - OP	Germany
Oslo [98]	2019	Ruter	Nio ES8	EU-funded Project	FRPD, OD, AGDM	Loki	NJO, IRD, PMV, IRD, VFH, TIA	EI - PS - OC - OP	Norway

FIGURE 4. **The SoS concept for integrating an automated bus DRT service into smart cities (icons from flaticon.com).**

In this paper, we have performed a maturity level analysis to assess the current state of the system. This includes identifying the main constituent systems and conducting an SRL analysis using TRL and IRL evaluations. This approach will offer insights into the system's current status and identify areas for potential improvements.

A. SYSTEM MATURITY LEVEL ANALYSIS APPROACH

The analysis of technology and system maturity levels is essential for informed decision-making during the early stages of project acquisition. Amongst the most recognised metrics for this purpose is the TRL, which originated from NASA's efforts in the 1980s to establish a consistent framework for evaluating technology integration in flight systems [130]. This scale was later adopted by the US Department of Defense (DoD) to encompass a broader range of systems, thereby, enhancing its applicability across various sectors, including defence and aerospace [131]. The TRL scale has gained widespread acceptance, serving as a common language for stakeholders to assess the maturity of individual technologies within complex systems [132], [133].

An important extension of the TRL metric is the SRL, which evaluates the overall maturity of a system considering the integration readiness level (IRL) of its constituent technologies [134], [135]. This approach recognises that while individual technologies may be mature, their successful integration is critical for system performance. Sauser and colleagues have extensively researched SRL, proposing methodologies for its assessment and emphasising its role in initial system evaluations to gauge overall feasibility before development and integration [134], [135], [136], [137], [138]. Furthermore, [139] recommends applying SRL for SoS evaluations to evaluate overall feasibility before development and integration.

Details on the calculation and evolution of TRL, IRL, and SRL are available in [130], [131], [132], and [134]. However, we provide a brief overview to facilitate the use of these metrics. TRL measures the maturity of technology through nine levels, ranging from basic principles to proven systems through successful mission operations (see Table 4). To address TRL's limitations in capturing the interactions between compatible technologies within a system, the Integration Readiness Level (IRL) metric is also defined in nine levels, similar to TRL. Various IRL levels are summarised in Table 4.

To calculate the SRL for a System of Systems (SoS), one must first define the constituent System of systems the SoS. Next, the TRL for each system and the corresponding IRL between these systems should be determined. For an SoS comprising n constituent systems, a vector of TRL values can be established for the overall system as follows:

$$[TRL]_{n\times 1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ \vdots \\ TRL_n \end{bmatrix}. \tag{1}$$

where TRL_i corresponds to the TRL for the i^{th} technology. The next step is to define the IRL matrix, where each element represents the $[IRL]$ level between system i and system j out of n. This $n \times n$ matrix can be written in the following form:

$$[IRL]_{n\times n} = \begin{bmatrix} IRL_{11} & IRL_{12} & \ldots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \ldots & IRL_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ IRL_{n1} & IRL_{n2} & \ldots & IRL_{nn} \end{bmatrix} \tag{2}$$

It should be noted that for the IRL values representing the system itself (diagonal elements, IRL_i) and between technologies not intended for integration, the corresponding IRL value is set to nine [136]. Moreover, it is suggested to normalise the TRL numbers from the range $(1, 9)$ to $(0, 1)$ to simplify the analysis [136]. The $[SRL]$ matrix can then be calculated as the product of the $[IRL]$ matrix and the TRL vector as follows:

$$[SRL]_{n\times 1} = [IRL]_{n\times n} \times [TRL]_{n\times 1}. \tag{3}$$

The resultant SRL matrix can be written as follows, where each SRL_i quantifies the readiness level of a specific system with respect to every other system in the SoS:

$$[SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \vdots \\ SRL_n \end{bmatrix} = \begin{bmatrix} IRL_{11}\,TRL_1 + IRL_{12}\,TRL_2 + \cdots + IRL_{1n}\,TRL_n \\ IRL_{21}\,TRL_1 + IRL_{22}\,TRL_2 + \cdots + IRL_{2n}\,TRL_n \\ \vdots \\ IRL_{n1}\,TRL_1 + IRL_{n2}\,TRL_2 + \cdots + IRL_{nn}\,TRL_n \end{bmatrix}. \tag{4}$$

Each SRL_i yields a number within $(0, n)$, which can be normalised to $(0, 1)$ by dividing by n. This normalisation allows each element of the SRL matrix to be used in decision-making to identify the strengths or weaknesses of particular technologies. Finally, the overall SRL of the system

TABLE 4. The definition of TRL [131] and IRL [137] maturity levels.

Level	TRL	IRL
1	Basic principles observed and reported.	An *Interface* between technologies has been identified with sufficient detail to allow characterisation of the relationship.
2	Technology concept and/or application formulated.	There is some level of specificity to characterise the *Interaction* (i.e. the ability to influence) between technologies through their interface.
3	Analytical and experimental critical function and/or characteristic proof of concept.	There is *Compatibility* (i.e. common language) between technologies to orderly and efficiently integrate and interact.
4	Component and/or breadboard validation in laboratory environment.	There is sufficient detail in the *Quality* and *Assurance* of the integration between technologies.
5	Component and/or breadboard validation in relevant environment.	There is sufficient *Control* between technologies necessary to establish, manage, and terminate the integration.
6	System/subsystem model or prototype demonstration in a relevant environment.	The integrating technologies can *Accept, Translate, and Structure Information* for its intended application.
7	System prototype demonstration in an operational environment.	The integration of technologies has been *Verified and Validated* and an acquisition/ insertion decision can be made.
8	Actual system completed and qualified through test and demonstration.	Actual integration completed and *Mission Qualified* through test and demonstration, in the system environment.
9	Actual system proven through successful mission operations.	Integration is mission-proven through successful mission operations.

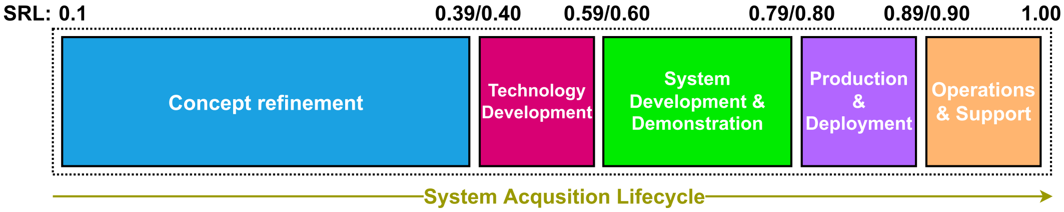


FIGURE 5. SRL number mapping to system acquisition lifecycle.

can be calculated as the average of the SRLs for all individual systems:

$$SRL = \frac{\left(\frac{SRL_1}{n}\right) + \left(\frac{SRL_2}{n}\right) + \cdots + \left(\frac{SRL_n}{n}\right)}{n}. \qquad (5)$$

The final SRL number will indicate the overall system's readiness level. The algorithm for calculating SRL is explained in Algorithm 1. Meanwhile, individual elements and statistical analyses, such as standard deviation comparisons, can be used to analyse the constituent systems [136]. The resultant SRL in 5 provides a value between 0 and 1, with a number closer to 1 indicating a higher readiness level within the system. There have been efforts to relate the SRL number to the system lifecycle process. An appealing recommendation is proposed in [135] and [140], which maps various SRL numbers to different stages of the system's lifecycle. It aligns the SRL number with the various maturity stages of a system acquisition lifecycle, including: 1) concept refinement, 2) technology development, 3) system development and demonstration, 4) production and deployment, and 5) operations and support. This mapping is shown in Figure 5 and forms the basis for our analysis in this paper. The next section conducts an SRL analysis for the DRT with the automated bus SoS system.

Algorithm 1 calculates the SRL using 1D and 2D arrays of TRL and IRL, respectively. Steps 1-5 of the algorithm initialise three empty arrays and one variable: arrays for normalised TRL (*normTRL*), normalised IRL (*normIRL*), intermediate SRL calculations (*interSRL*), and variable *numberOfTechs* is the number of technologies (numberOfTechs), which is determined by the length of the TRL array. In lines 6-8, the algorithm normalises each TRL value by dividing it by the maximum TRL value, and the result is inserted into *normTRL*. Since the IRL is a 2D array, lines 9-15 normalise the IRL values by dividing each row by the maximum TRL value. The resulting normalised values are stored in the *normIRL* array. lines 16-23 calculate intermediate SRL values by iterating through each normalised IRL row. It multiplies the corresponding TRL and IRL values, accumulates the result in a variable *res*, and inserts this result into the *interSRL*. Finally, lines 25-29 compute the total SRL by taking the average of *interSRL* values.

B. SRL FOR AUTOMATED BUS DRL SERVICE

Four constituent systems are considered for the automated bus DRT as explained below:

- **A. Automated Bus System (TRL 7)**: The system, with Level 4 automation, is under development with proven functionality in controlled environments but requires further real-world testing and refinement before full deployment, which is aimed to achieve Level 5 in the coming years. The system typically operates on known routes, resulting in a more manageable autonomy problem due to its limited operational domain. It is a technical system, focusing on vehicle autonomy and control. This technology can be categorised as TRL 7 since it is currently being tested in similar environments.

- **B. Communication and Connectivity Systems (TRL 7)**: It encompasses communication and connectivity systems, including V2X (Vehicle-to-Everything) technologies such as V2D (Vehicle-to-Device) for booking systems, V2N (Vehicle-to-Network), and V2I (Vehicle-to-Infrastructure). It should be noted that these technologies (in this study) are intended solely to enable the DRT service, rather than for AV navigation and safety features, which the latter could be assigned a lower TRL. Hence, these technologies are well-developed, with successful trials in various everyday applications like updating train schedules, mobile apps, online maps, and passenger information systems. This is also primarily a technical system, despite its minor user interactions, as it focuses mainly on communication technologies. Nevertheless, broader integration in the intended areas requires further validation, as well as enhancements such as smart bus stations with service request hubs (which are not considered here). Given the current use of core communication systems in the UK transportation network, we assess it at TRL 7.
- **C. Fleet and Traffic Management Systems (TRL 8)**: These systems are mature, benefiting from existing urban applications, with successful adaptation to manage vehicle operations and traffic in rural settings. It is a socio-technical system, combining technical management and human decision-making. Considering our assumptions for the integration to an existing transportation system, the system TRL can be assigned as TRL8.
- **D. User Interface and Booking Systems (TRL 7)**: The booking and payment platforms are widely used and well-established, but require customisation and testing for specific DRT services. Hence, it is considered at TRL 7. This system is socio-technical, as it directly involves user interactions with technology.

The next step in determining the SRL is to define the integration readiness among the various constituent systems of the SoS. Table 5 summarises the IRL matrix for the SoS, accompanied by a few explanations:

Based on Table 5, the IRLs for the fleet and traffic management systems show the lowest integration level, which is expected given the novelty of the system. The user interface exhibits the highest IRL, as it is already used in current systems and will require integration and verification with existing systems (see Table 4). Figure 6 depicts the interaction diagram for the constituent systems, along with their corresponding TRLs and IRLs.

Taking into account the aforementioned details, the TRL vector and IRL matrix for SoS are as follows:

$$[TRL] = \begin{bmatrix} 7 \\ 7 \\ 8 \\ 7 \end{bmatrix}, \quad [IRL] = \begin{bmatrix} 9 & 6 & 5 & 6 \\ 6 & 9 & 5 & 7 \\ 5 & 5 & 9 & 6 \\ 6 & 7 & 6 & 9 \end{bmatrix}. \tag{6}$$

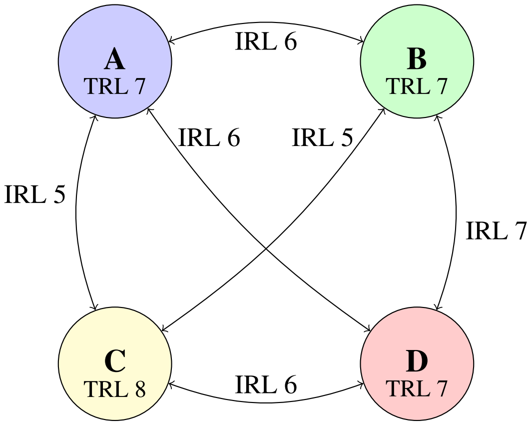


FIGURE 6. SoS interaction diagram indicating the TRLs and IRLs for the constituent systems.

By performing the necessary calculations, the SRL vector and overall system SRL can be obtained as:

$$SRL = \begin{bmatrix} 0.730 \\ 0.758 \\ 0.719 \\ 0.789 \end{bmatrix}, \quad SRL = 0.749 \tag{7}$$

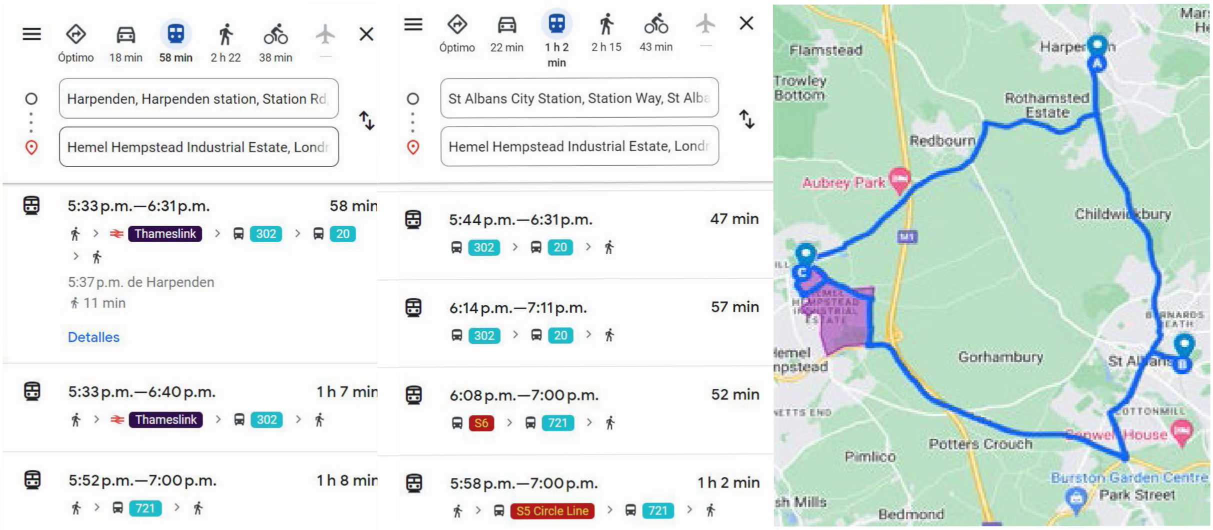
The first outcome of this analysis is an overall SRL number of 0.749 for the DRT system, indicating a maturity level at the upper stages of the "System Development and Demonstration" phase based on Figure 5. This value suggests that the DRT system is relatively advanced in its development and integration stages, but there is still room for improvement. Considering the current status of constituent systems, such as the automated bus, which is under testing in similar areas, we estimate that the system will progress to the "Deployment" stage once testing begins in the intended environments. The SRL level for the constituent system C (fleet management) is the lowest, reflecting the challenges associated with integrating this subsystem, despite its higher TRL. This is due to the subsystem's lower IRLs, highlighting the complexities in its integration with other components of the DRT system. The promising result is a generally consistent readiness across all technologies involved, which could facilitate smoother system acquisition and implementation. However, additional actions and validations will be necessary to fully integrate and deploy the DRT system, particularly in projects like HertsLynx CAM on demand.

V. MAYLANDS USE CASE, UK

This section evaluates the potential of deploying a fleet of CAM vehicles using a hybrid DRT model to bridge the public transport gap between Maylands Business Park and nearby train stations. It highlights the significance of deploying CAM in Maylands Business Park, discusses Padam's simulator workflow and results, and presents Return on Investment (ROI) calculations to compare and analyse the

TABLE 5. Integration readiness levels for the constituent systems of automated bus DRT service.

	Automated Bus System	Communication & Connectivity	Fleet & Traffic Management	User Interface & Booking
Automated Bus System	N/A	**IRL 6**: Currently being deployed, needs verification in new autonomous application	**IRL 5**: A conventional fleet exists, controllable, but needs further investigation to integrate automated bus	**IRL 6**: Communication is deployed in existing systems, can accept automated vehicle
Communication & Connectivity	**IRL 6**	N/A	**IRL 5**: Currently exists, there is control to add a new system	**IRL 7**: Feasible integration to the current system, it will need verification
Fleet & Traffic Management	**IRL 5**	**IRL 5**	N/A	**IRL 6**: There is sufficient Control between technologies to establish the integration
User Interface & Booking	**IRL 6**	**IRL 7**	**IRL 6**	N/A


Harpenden, Harpenden station, Station Rd
Hemel Hempstead Industrial Estate, Londr

5:33 p.m.—6:31 p.m. 58 min
Thameslink › 302 › 20 ›
5:37 p.m. de Harpenden
11 min
Detalles

5:33 p.m.—6:40 p.m. 1 h 7 min
Thameslink › 302 ›

5:52 p.m.—7:00 p.m. 1 h 8 min
› 721 ›

St Albans City Station, Station Way, St Alba
Hemel Hempstead Industrial Estate, Londr

5:44 p.m.—6:31 p.m. 47 min
302 › 20 ›

6:14 p.m.—7:11 p.m. 57 min
302 › 20 ›

6:08 p.m.—7:00 p.m. 52 min
S6 › 721 ›

5:58 p.m.—7:00 p.m. 1 h 2 min
› S5 Circle Line › 721 ›

FIGURE 7. Mayland use case public and private travel journey time.

operational costs and potential savings between automated and human-driven Bus services.

Maylands Business Park is an important commercial hub, home to more than 650 businesses from logistics, distribution, manufacturing, and professional services, and it employs over 20,000 people. It plays a key role in supporting both regional and national economic activities. The Maylands Business Park is at least 6 miles from the nearest train stations—6 miles from St Albans and 7 miles from Harpenden—with no direct public transport links. The only available transportation options are private cars, while the traditional bus service takes three times longer than cars. Figure 7 shows the routes from Harpenden and St Albans Station to the Hemel Hempstead Industrial Estate and details the different transportation options and travel times for each. The left side of Fig. 7 displays two route planners, the right side displays a Google Maps image with the two routes highlighted in blue and the Maylands Business Park area is within a red-highlighted region on the left side of the Google Maps. The best options for the two routes are the journey from Harpenden to Hemel Hempstead, which takes around 58 minutes using a combination of Thameslink trains and buses, and the journey from St Albans City to Hemel Hempstead, which takes around 47 minutes using a combination of buses. In both cases, the travel time using public transport is approximately three times longer than using private cars. The reasons for this include low frequency of service, lack of synchronisation between connections (e.g., almost 20 minutes of waiting time), and a large number of stops (e.g., bus line 302 with 23 stops, resulting in 31 minutes on board before reaching the destination). After analysing the flow of passengers travelling by car, we identified the following spatial distribution at three key times of the day: morning peak hour, inter-peak period, and evening peak hour. We simulated these distributions using Padam's mobility simulator[1] under different scenarios to model the performance of the CAM system.

---

[1] https://www.padam-mobility.com/

Algorithm 1 Algorithm for Calculating SRL From TRL and IRL

```
Input :
        $TRL$: 1D array of $TRL$ values;
        $IRL$: 2D array of $IRL$ values;
Output:
        $SRL$: calculated system readiness level;
begin
    $normTRL \leftarrow []$;
    $normIRL \leftarrow []$;
    $interSRL \leftarrow []$;
    $numberOfTechs \leftarrow length(TRL)$;
    foreach $x \in TRL$ do
        $normTRL$.insert($\frac{x}{\max(TRL)}$);
    end
    foreach $x \in IRL$ do
        $temp \leftarrow []$;
        foreach $y \in x$ do
            $temp$.add($\frac{y}{\max(TRL)}$);
        end
        $normIRL$.add($temp$);
    end
    foreach $x \in normIRL$ do
        $res \leftarrow 0$;
        for $i \leftarrow 1$ to $length(normTRL)$ do
            $irl \leftarrow normIRL[i]$;
            $trl \leftarrow normTRL[i]$;
            $res \leftarrow res + (irl \times trl)$;
        end
        $interSRL$.insert($res$);
    end
    $total \leftarrow 0$;
    foreach $x \in interSRL$ do
        $total \leftarrow total + \frac{x}{numberOfTechs}$;
    end
    $SRL \leftarrow \frac{total}{numberOfTechs}$;
end
```

The simulator requires two input data to generate results: supply and demand. The supply data includes service schedules, service model (or algorithm) to be implemented, number of vehicles and fleet capacity. The demand data includes information related to the trip (origin, destination, requested arrival/departure time) and the number of people to be transported. Figure 8 presents the simulator components and workflow which are:

1) **The DRT Demand Model** represents passenger demand data collected based on various temporal distributions (e.g., peak hours, inter-peak periods), alongside factors such as car occupancy, population growth, and willingness to use AVs. These factors are considered to accurately model and predict transport demand.
2) **DRT Service** Offers represent available transport services, including vehicle types, number of vehicles, capacity, and routing, as well as vehicle capacities and autonomous capabilities (e.g., SAE Level 3).
3) **Simulator** processes both demand (DRT Demand Model) and supply (DRT Service Offers) to address key questions such as whether certain routes should be prioritised and the feasibility of vehicle allocation for different demand levels.
4) **Simulation Results** produce roadmaps, booking plans, and KPI metrics such as success rates (percentage of requests served), vehicle utilisation, and overall operational efficiency.

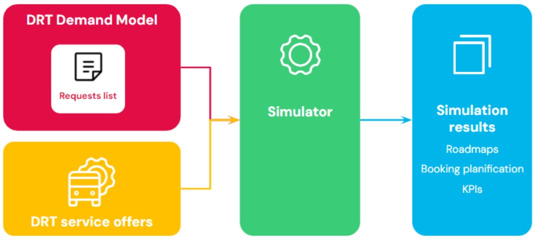
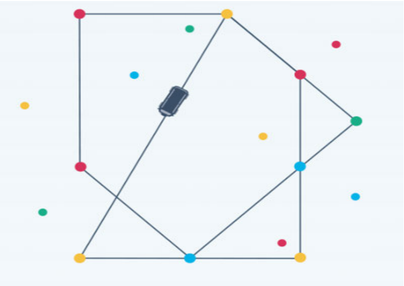
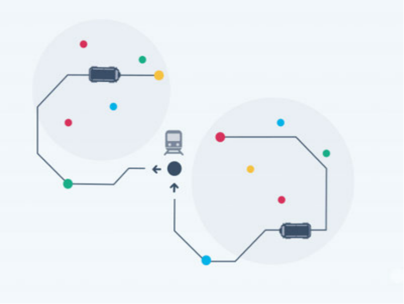


FIGURE 8. Maylands DRT simulation process.



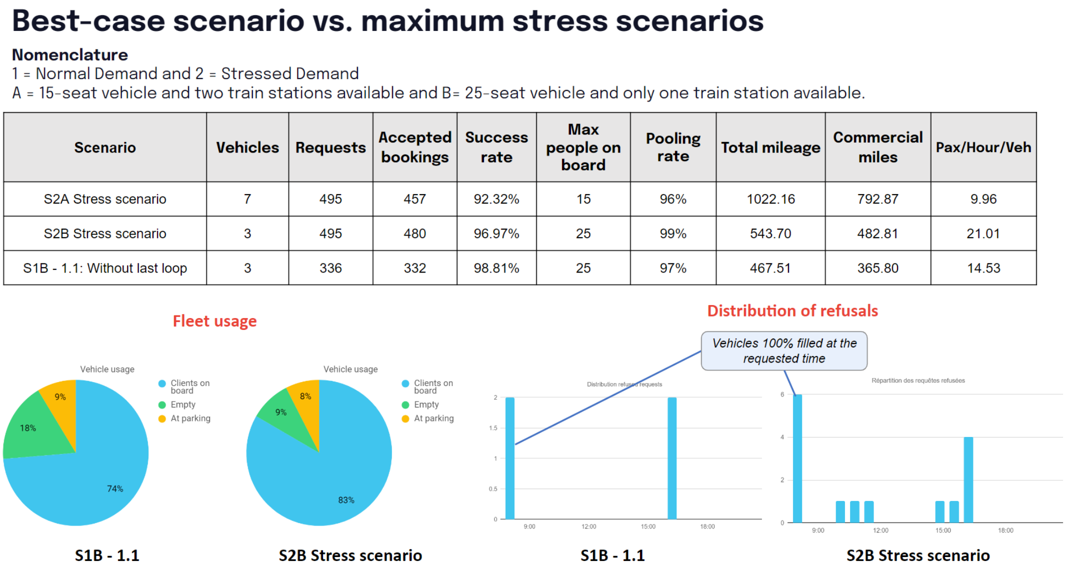
a) Free-floating model: off-peak, flexible routing.



b) Feeder model: peak hours, fixed stops and scheduling.

FIGURE 9. Comparison of free-floating and feeder models for mayland use case.

Two service models were explored in this case study, as seen in Figure 9: the Free-floating model shown in Figure 9.a, and the Feeder model in Figure 9.b. The free-floating model used in the off-peak hours, allows the pick-up and drop-off of the passenger in a specific area without any time constraints, whereas the Feeder model used during the peak hours and passengers pick up and dropped points



Best-case scenario vs. maximum stress scenarios

Nomenclature
1 = Normal Demand and 2 = Stressed Demand
A = 15-seat vehicle and two train stations available and B= 25-seat vehicle and only one train station available.

Scenario	Vehicles	Requests	Accepted bookings	Success rate	Max people on board	Pooling rate	Total mileage	Commercial miles	Pax/Hour/Veh
S2A Stress scenario	7	495	457	92.32%	15	96%	1022.16	792.87	9.96
S2B Stress scenario	3	495	480	96.97%	25	99%	543.70	482.81	21.01
S1B - 1.1: Without last loop	3	336	332	98.81%	25	97%	467.51	365.80	14.53

FIGURE 10. Comparison of best-case and maximum stress scenarios.

are at predefined locations, respecting a schedule constraint with some fixed times. For both models, the same route availability limits were applied, since within the service area the authorised roads for AVs were delimited, which caused a loss of performance in route optimisation that needs to be considered, especially in the free-floating case.

Best-case and maximum-stress scenarios were generated for both models. The best-case scenario represents a situation in the model where operational conditions are optimal with low demand and high efficiency, and the maximum-stress scenario represents a situation in the DRT system where the system is pushed to its operational limits via high demand and constrained resources. Figure 10 presents the simulation results, Fleet Usage, Distribution of Refusals, and a nomenclature section explaining the naming system. The simulation results are a summary of the performance metrics for three scenarios (S2A, S2B, S1B-1.1), including vehicles, requests, bookings, success rate, pooling, mileage, and passenger efficiency. The Fleet Usage shows the proportion of time vehicles spent with clients on board, empty, or parked in the S1B - 1.1 and S2B Stress scenarios. The Distribution of Refusals shows when and how often vehicle capacity was exceeded, leading to booking refusals, during different times of the day in the S1B - 1.1 and S2B Stress scenarios. By comparing the best-case scenario S1B-1.1 with its respective stress scenario S2B, we can observe that the current fleet is able to transport 45% more than the normal demand with a degradation of only 2% of its success rate. This means that even when the system is saturated, the supply can satisfactorily transport more than 95% of user requests. When we compare the scenarios with A or B (see nomenclature), we realise that the mutualisation of demand at a single train station plays an important role in the success rate. The combination of this factor and a larger fleet capacity (15 seats vs. 25 seats) shows a better performance, especially at peak hours with the feeder model. The Fleet Usage shows that in both scenarios, the majority of the vehicle usage time was spent with clients on board (74% in S1B and 83% in S2B), with smaller portions spent either empty or parked. Finally, The Distribution of Refusals Bar Charts shows that most booking refusals occurred in the early morning (around 9:00) for both scenarios, which indicates that vehicles were fully occupied and unable to accept additional passengers. The challenges and limitations identified in the study were:

- The restricted use of roads in the area due to the technological constraints of AVs in the current state. This resulted in a low performance with low occupancy and higher mileage than the autonomy level available for the electric fleet, especially for the free-floating case.
- The transportation cost was not considered variable, but this should be considered when implementing the system in real conditions. The outcome of this is to obtain high-performance results from the operator's point of view without taking into account the consequences for the users.
- It's necessary to find a compromise between user satisfaction and operational performance. The best balance found for the system achieved between demand and supply is visible in the times shown in the best case S1B-1.1.

An essential aspect of a feasibility analysis for these types of projects is the ROI assessment. ROI evaluates profitability by measuring the proportion of investment gained over time after accounting for costs [141]. The ROI calculator addresses: *Is using Automated Buses cheaper or more efficient than Human-Driven buses? If so, by how* *much, and in what ways?*. It compares operational costs and potential savings between automated and human-driven buses. The comparison begins by selecting the vehicle's power source (electric or ICE), followed by service provider details like service design (e.g., number of buses, operating days). A percentage result shows automation's ROI; if below 100%, it doesn't cover its lifecycle costs.

Our ROI calculations indicate that services best suited for automation involve multiple vehicles operating on fixed routes or where operational hours misalign with human driver schedules, leading to higher labour costs. Conversely, services with fluctuating demand (for this use case) are less suited due to the risk of over-investment and challenges in recouping initial capital. In the initial investment phase (Years 1-2), significant upfront costs would include bus purchases, infrastructure modifications, and the development of automated systems, alongside software integration and training. By the early return phase (Years 3-5), labour costs would decrease as automation reduces reliance on human drivers, and operational efficiency would improve through optimised routing, resulting in fuel and maintenance savings. During the subsequent phase (Years 6-10), cost savings would increase, driven by higher passenger frequency, satisfaction, and reduced downtime, leading to positive cash flows and potential full cost recovery. Our analysis suggests a break-even point around Year 5, with significant returns accumulating between Years 6 and 10, as automation cuts costs and boosts profitability. However, services with fluctuating demand should be carefully planned to avoid over-investment and delayed returns. In conclusion, adaptable operational strategies, such as varying service models based on demand (e.g., Feeder during peak hours, Free-floating during off-peak), and employing a heterogeneous fleet, are crucial for optimising performance. ROI calculations compare operational costs and savings between automated and human-driven buses, with options to account for electric or internal combustion engine power sources.

VI. CONCLUSION AND DISCUSSIONS

We conducted a comprehensive study of the state-of-the-art research on demand-responsive mass transit using autonomous bus services. Employing a SoS approach, we identified various components of an autonomous DRT service from multiple perspectives, including optimisation factors, developed algorithms, deployed vehicles, simulation approaches, and devices used to assess the impact of research. The categorised aspects are explored individually, with illustrative comparative tables provided to thoroughly offer insights into the current status and advancements worldwide. We performed an SRL analysis for this SoS, identifying its constituent subsystems and analysing their technology and integration readiness levels. Furthermore, we presented an analysis based on a relevant use case in the Hertfordshire area of the UK, which can be applied to similar scenarios. The research highlights the opportunities and challenges of implementing DRT with autonomous bus services by gathering common best practices. Key findings and future research trends are discussed below.

A. KEY FINDINGS AND LESSONS LEARNED FROM VARIOUS CASE STUDIES

- Whilst academic research in DRT dates back to the 1970s, interest has surged since 2005 and continues to skyrocket in recent years. This progress is thanks to advances in post-4G communication networks, V2X opportunities, and the widespread availability of smartphones and infrastructure-based tools.
- Early intentions were to improve sustainable urban mobility and reduce traffic congestion, while recent research has advanced energy efficiency and significantly reduced greenhouse gas emissions and vehicle miles travelled through various DRT models and frameworks [11], [26], [27], [29], [31], [43], [64], [65], [77], [90], [91].
- Integrating DRT into existing conventional transportation systems results in significant enhancements, including reduced waiting times and total distance travelled [9], [88], improved accessibility [84], increased passenger acceptance rates, and enhanced operational efficiency [4], [85].
- The development and integration of next-generation communication systems, such as 6G networks with DRT, enhance service efficiency in rural areas and scenarios with highly variable demand [95].
- The integration of semi/full AVs and DRT demonstrates significant benefits. For example, the MK Connect project successfully reduced costs from £2.8 million to £1.9 million. Autonomous driving projects in Europe have collectively achieved 36,734 km of driving [93], [94], [95]. However, these initiatives have faced service disruptions and challenges, including higher per-kilometre costs [95], 1,786 instances of parked cars obstructing routes [98], and disruptions caused by construction sites [100].
- Our SoS analysis estimates that the DRT SoS incorporating autonomous bus services in use cases similar to Maylands Business Park use case is at the boundary between system development and deployment, with $SRL \approx 0.75$. This indicates that the system is ready to be integrated into the existing transportation network and can begin its testing phases in real environments once the autonomous buses (already on the roads in testing with safety drivers) are prepared.

B. TRENDS AND FUTURE RESEARCH DIRECTIONS

Based on the discussions presented earlier, the following key trends have been identified for future research:

- Even though automated bus services will offer outstanding flexibility, some uncertainties remain and require further investigation. Key issues include trust, ethics, safety, and effectiveness, along with unique challenges

like accessibility, spoofing threats, and regulatory refinement for CAM DRT services.
- Next-generation DRT services will involve mixed-size vehicles to meet variable demand. Advanced simulations and optimisation algorithms, improved smartphone apps, smart bus stations, and enhanced infrastructure will also be essential.
- Harnessing novel AI algorithms, like Large Language Models (LLMs), in real-time DRT decision-making is a promising trend [89], [142], [143], [144]. For example, [142] introduced LiMeDa, a framework for multi-vehicle dispatching and coordination with civil service vehicles. This aligns with the UK's 2025 self-driving car framework [72]. Future research will focus on LLMs enhancing efficiency in multi-criteria optimisation through advanced language understanding and processing.
- Intelligent transportation systems provide valuable opportunities for applying SoS theory and systems engineering tools. Enhanced probabilistic SRL analysis can reduce subjectivity and improve reliability compared to classical TRL [145], [146]. Systematic V&V procedures [59], advanced simulators, digital twins, and improved effectiveness models [147] can help assess system value and identify areas for improvement in SoS applications..
- The future of DRT depends on cost-effective models, AVs [148], and integration into national transport systems [149], [150]. E-mobility services like MaaS enable seamless multimodal transport [151], but challenges like data sharing require solutions. Blockchain ensures trusted, immutable data, while ontology enables machine-readable contextual information, as proposed for unified rail ticketing [152], [153].
- Similar research streams can be found in other transportation modes, such as maritime transportation. Lessons learned from intelligent ground vehicle systems and projects in maritime environments [154], [155], which have even explored AV applications [156], can mutually contribute to advancing knowledge in this rapidly evolving field, promoting sustainability and unlocking net-zero transport systems.

Overall, integrating CAM and DRT services, along with the associated technological and managerial needs, is one of the leading research fields in ITS, focused on enhancing the efficiency of conventional transportation systems. Employing a system-of-systems perspective, this paper identified the most significant research advances and pinpointed some essential future research needs in this field.

GLOSSARY

3DVC	3D Video Cameras. 13
ADRT	Autonomous DRT. 16
AET	Average Excess Time. 14
AGDM	Anti-Jamming Defence Mechanisms Algorithms. 13, 18
ALNS	Adaptive Large Neighborhood Search. 13, 16, 17
AV	autonomous vehicle. 2
AVENU	AEutonomous Vehicles to Evolve to a New Urban Experience. 10–12, 18
AVL	Automatic Vehicle Location. 13
AWT	Average Waiting Time. 14
BMCF	Bipartite Minimal-Cost Flow. 8, 16
CAM	Connected Automated Mobility. 5
CBS	Customized Bus Service. 8, 17
CC-DACRh	Pance-Constrained Dial-A-Ride Problem. 17
CNG	Compressed Natural Gas. 14
CNN	Convolutional Neural Networks. 16
DiD	Difference-in-Differences Analysis. 17
DJ	Demand-Jitney. 6, 7, 16
DRT	Demand Responsive Transport. 5–8, 11
DSB	Demand Scheduled Bus. 6, 16
DTPA	Dynamic Transfer Point Allocation. 8, 17
DVC	Driver and Vehicle Costs. 14
EE	Energy Efficiency. 13, 14
EI	Environmental Impact. 13, 14, 16–18
FF	Full Flexible. 6
FM	Fleet Management. 14
FNN	Feedforward Neural Networks. 16
FRPD	Facial Recognition and Passenger Detection Algorithms. 13, 18
FRT	Fixed-Route Transit. 8, 16
GA	Genetic Algorithms. 17
GBDT	Gradient Boosting Decision Trees. 17
GHG	Greenhouse Gas. 14
GIS	Geographic Information Systems. 13
GNSS	Global Navigation Satellite System. 10, 13
GPR	Gaussian Process Regression. 16
GPS	Global Positioning Systems. 16
HMI	Human-Machine Interface. 12, 17
I-DRT	Integrated-Demand Responsive Transport. 9, 14, 17
I-ODBR	InPtegrated On-Demand Bus Routing Problem. 9, 17
ICEVs	Internal Combustion Engine Vehicles. 9
IL	Interface and Logistics. 14
ITM	Initial Trust Model. 16
ITS	Intelligent Transportation Systems. 13
LAN	Local Area Network. 12
LDDA	Linearly Decreasing-Deterministic Annealing Algorithm. 17
MaaS	Mobility as a Service. 4, 7, 12, 17
MDTs	Mobile Data Terminals. 13, 16
MDVRP	Multi-Depot Vehicle Routing Problem. 17
MILP	Mixed Integer Linear Programming. 17
MIP	Mixed Integer Programming. 13, 17
ML	Machine Learning. 13, 17

MLGO	Machine Learning Guided Optimisation. 13, 16
MTVRP	Multi-Trip Vehicle Routing Problem. 13, 17
NITS	Network-Inspired Transportation System. 9, 12
NP	Noise Pollution. 14
OC	Operational Cost. 13, 16–18
OD	Outlier Detection Algorithms. 13, 18
ODT	On-Demand Transit. 7
OP	Operational Planning. 13, 16–18
OS	Odometry Sensors. 13
PDBS	Point Deviation Bus System. 7, 16
PS	Passenger Satisfaction. 13, 16–18
RBFN	Radial Basis Function Networks. 16
RBITS	Rural Bus Integration Transportation Services. 9, 17
RDRS	Rider Demand Responsive System. 8, 16
RO	Route Optimisation. 14
SAMOD	Shared Automated Mobility On-Demand. 7, 17
SAVs	Shared Autonomous Vehicles. 10, 16, 17
SDARP	S-tMocGhaUsStic Dial-A-Ride Problem on a Multigraph with User Satisfaction. 17
SEM	Structural Equation Modeling. 16
SF	Semi Flexible. 6–8
SO	Safety Operators. 14
SRT	Shared Ride Taxi. 7
SUM	Sustainable Urban Mobility. 14
TC	Traffic Congestion. 14, 18
TRT	Total Ride Time. 14
TS	Tabu Search. 13, 17
TWC	Time Window Constraints. 16
ULTIMO	Advancing Sustainable User-centric Long-term Transportation with Intelligent Mobility and Operations. 10, 11, 18
URT	User Ride Time. 13
UTAUT	Unified Theory of Acceptance and Use of Technology. 16
VMT	Vehicle Miles Traveled. 14
VRP	Vehicle Routing Problems. 13

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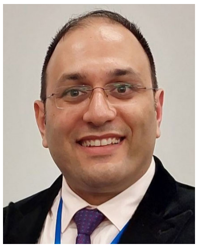
SAJID FADLELSEED received the M.Sc. and Ph.D. degrees in computer science from the University of Hertfordshire. His studies were supported by National University Sudan (NUSU). His current research interests include mixed-criticality scheduling, real-time embedded systems, fault tolerance, NoC architectures, and optimization techniques. He has lectured modules in embedded systems and fault tolerance algorithms. He has conducted research on DRT services and software integrity levels (SIL).



POURIA SARHADI received the B.Eng., M.Sc., and Ph.D. degrees. He was a Research Fellow with Queen's University Belfast, from 2021 to 2022, and the University of Surrey, from 2019 to 2021, and an Adjunct Professor with the Babol Noshirvani University of Technology (BNUT), from 2016 to 2018. He is currently a Senior Lecturer (Associate Professor) with the School of Physics, Engineering and Computer Science, University of Hertfordshire. He has held key roles to play in U.K. Research and Innovation (UKRI) and European Horizon projects and provided consultancy to different industries. In the past 15 years, he has conducted research on a wide range of ground, marine, and aerial AVs which has resulted in more than 50 peer-reviewed journal publications. Furthermore, he is passionate about transforming academic theories into industrial products. His research interests include control theory and applications, adaptive control and machine learning, AVs as well as systems engineering. He is a member of IET (MIET). He is a member of the International Federation of Automatic Control (IFAC) and the Advisory Board of *Machines*. He was also recognized as U.K. "Global Talent" by the UKRI. He is a Chartered Engineer (C.Eng.).

SOODAMANI RAMALINGAM is currently an Associate Professor and a member of the Centre for Networks and Security Research, University of Hertfordshire. She is also the Joint Director of the Smart Mobility Unit, University of Hertfordshire. She has published 40 journal articles and 80 conference publications. Her research interests include artificial intelligence, computer vision and machine learning, and intelligent transportation systems with applications in the areas of biometrics, energy, and decarbonization.

HOCK C. GAN received the Ph.D. degree from the University of Hertfordshire. He is currently a Visiting Lecturer with the School of Engineering and the School of Computer Science, University of Hertfordshire. His research interests include autonomous systems, machine learning, computer vision, blockchains, the IoT security, voice discrimination, brain–computer interfacing, software engineering, and telecommunications.

PANDELIS KOURTESSIS is currently a Professor of communication networks with the University of Hertfordshire, U.K., leading the activities of the Networks Engineering Research Group into communications and information engineering, including next-generation passive optical networks, optical and wireless MAC protocols, 5G RANs, software-defined networks, and network virtualization 5G and satellite networks, and more recently machine learning for next generation networks. His funding ID includes EU COST, FP7, H2020, European Space Agency (ESA), UKRI, and industrially funded projects. He has authored or co-authored more than 80 papers in peer-reviewed journals, peer-reviewed conference proceedings, and international conferences. His research has received coverage in scientific journals, magazines, white papers, and international workshops. He was the general chair, the co-chair, and a technical program committee member, and with the scientific committees and expert groups of IEEE workshops and conferences, such as the European Technology Platforms and the European Networks of Excellence. He has been the Co-Editor of a Springer book and the Chapter Editor of an IET book on softwarization for 5G.

GAV JACKMAN is currently the Managing Director of Sustainicity Ltd., and Leader of the HertsLynx CAM on Demand project funded by CCAV. He has extensive experience in the transport sector, including roles as TRL (The Future of Transport), the Growth Director of City Science, the Managing Director of Aimsun Ltd., and the CTO of Telent Traffic Business. At Aimsun, he directed several successful CCAV/IUK projects, including Flourish and Capri, focused on mass transit pods. He has also led software and network teams in AV studies and served as an Associate of the European Transport Board and Honorary Secretary of the ITS U.K. Local Authority Interest Group.

ATZIRI GUADALUPE SANCHEZ CONTRERAS graduated from the University of Colima, Mexico, specializing in the area of transportation. She received the master's degree from the École Nationale des Ponts et Chaussees, France, following a course in transportation and sustainable development with a specialization in mobility services design. She has been working in the area of mobility for passengers, since 2020, and after her specialization, she joined Padam Mobility Team first as a Transport Consultant and since January 2023, as a Consultant in AVs. She is currently a Mexican Civil Engineer. Her main research interests include passenger transportation, mobility innovation, and mobility service design for urban/peri-urban areas.

JAVIER GUIMERA TENA received the master's degree in transport and sustainable development (TRADD) from the École Nationale des Ponts et Chaussees, Paris, France. After completing his studies at the École Nationale des Ponts et Chaussees, he had his first professional experience in USA. He joined French company Padam Mobility, in 2019, as a Demand-Responsive Transport (DRT) Project Manager and a Consultant. He is currently a Spanish Civil Engineer specializing in innovative and shared mobility. In this regard, he has been involved in more than 25 projects and studies, accumulating more than five years of experience in the field of digitalized and dynamic DRT, being now the Head of Southern Europe. In 2022, he contributed to the creation of a new division dedicated to the global use of this technology with autonomous vehicles, the team that he is now co-leading as its Head of Business Development and Operations, in charge of strategic partnerships, implementations of the solution, live services and EU-funded projects, among others.

JAMES WEST is currently with Siemens Mobility U.K., focusing on business development in England and Wales. Engaging with Operators and Public Authorities, he uses his extensive experience to help them design and fulfill their DDRT ambitions and explore how this can be extended to other services, such as Dial-a-Ride, and for uses such as commuter or airport shuttles. He spent seven years at French Operator RATP Dev, rising from a graduate to leading two flagship U.K. DRT projects before moving to Paris to oversee global DRT developments. He launched U.K.'s first DRT service, Slide Bristol, and then became the General Manager for the DRT Service in partnership with Transport for London, Slide Ealing.

JACK HOLLAND is currently a DRT Operations Specialist at AtkinsRealis, supporting the Royal Commission for Riyadh City (RCRC) in deploying and operating their DRT Program. He has served as a Board of Trustees Member for CoMoUK, representing the DRT sector in U.K. Previously, he was the Head of Northern Europe-Padam Mobility at Siemens, delivering software for DRT, shared autonomous buses/pods, and paratransit services. He has also held other roles in intelligent transportation systems, including an Editorial Board Member at Smart Transport and a Country Manager at Ride On, unlocking micro-mobility solutions like e-bikes, e-scooters, and car-share stations. His research interests include launching and scaling mobility services, with expertise in shared transport and the bus industry.

ALICE MISSLER is currently the Team Leader of Demand Responsive/Community Transport, and has project managed the HertsLynx scheme from concept to curb-side. She was with Hertfordshire County Council for the last five years, leading multiple transport projects for adult care services and the Integrated Passenger Transport Unit. She led the work to secure the £1.4 million funding from the Department for Transport (DfT) Rural Mobility Fund, U.K., and continues to oversee and lead the strategic and operational aspects of the HertsLynx service as it continues to develop within Hertfordshire.

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