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Autonomous bus adoption in public transport networks: A systematic literature review on potential and prospects

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Abstract

The recent emergence of automation technology has created a discussion amongst policymakers and researchers in the field of Public Transport (PT), to enhance the overall system efficiency and quality of service for its users through the deployment and integration of Autonomous Buses (ABs) in the network. While the complexity of automation technology has presented challenges in this process, research and development are bridging the gaps towards real-world AB applications. This paper systematically reviews the existing literature in the emerging field of ABs in PT, primarily focusing on the foreseen impacts of deployment and integration. Thus, five impact factors were considered: (a) travel behaviour, (b) financial, (c) safety, (d) environment, and (e) transport network. Based on the findings, this paper advocates the importance of effectively identifying the AB deployment and integration mechanisms depending on the impacting factors to provide the highest quality of service for passengers and to ensure smooth operation of the PT system.

1. Introduction

The integration of ABs in PT systems generates benefits such as improved safety, quality of service for passengers, and cost reductions, thus, improving the overall system efficiency (Poinsignon et al., 2022). Improved labour productivity, reduced subsidies and flexible modes benefit passengers provide the transit agencies and transport industry with more effective operations (Abe, 2019). According to the International Association of Public Transport (UITP), AB operations in the PT network help to meet sustainable and public policy goals, through reduced emissions and improved travel comfort (Transport, 2017). ABs could be implemented in the PT network working either as Driverless Shuttles (DSs) or as feeders to a transit network/traditional line-based service. The literature on AV-related studies in PT systems uses a variety of terms and definitions, which can be classified into three: transit, vehicle, and service classification (Table 1).

Table 1: Terms and definitions in AV-PT systems

Term	Definition
Transit Classification	
Fixed-Route Transit (FRT)	"Operates on a defined route according to a defined schedule." (Kittelson & Associates, 2013)
Demand-Response Transit (DRT)	"Has a flexible route, schedule, or both." (Kittelson & Associates, 2013) Interchangeability: mobility-on-demand (MoD), microtransit
Flex-Route Transit (FlexRT)	"A hybrid of DRT and FRT, emerged as a new service mode of public transit to balance the flexibility of DRT and the cost efficiency of FRT. Operated by a fleet of vehicles adhering to a base route to serve regular passengers at predetermined checkpoints; the flex-route transit is also allowed to deviate from the planned route for curb-to curb requests." (Liu et al., 2021) Interchangeability: Mobility Allowance Shuttle Transit (MAST)

Vehicle Classification	
Autonomous Vehicle (AV)	"A vehicle that can drive without any human intervention by sensing the local environment, detecting objects, classifying them, and identifying navigation paths with information coming from different sensors while obeying transportation rules." (Campbell et al., 2010)
Driverless Shuttle (DS)	"A bus-like form of automated vehicle used for group transit often designed to be used as part of public service." (Smolnicki and Sołtys, 2016)
Shared Autonomous Vehicle (SAV)	"Combines elements of conventional carsharing and taxi services with AVs to provide inexpensive mobility-on-demand services and could play a vital role in sustainable transportation systems, by providing conventional last-mile solutions, which could facilitate multimodality." (Krueger et al., 2016)
Autonomous Modular Vehicle (AMV)	Consists of modular units that can combine and split as required, with each unit or combination of units capable of operating independently. (Khan et al., 2023) Interchangeability: Autonomous Modular Buses (AMBs)
Semi-Autonomous Bus (SAB)	"Represent a transition (or intermediate) state between conventional buses and fully autonomous buses. More precisely, the level of automation for conventional buses is 0 (no automation) and for fully autonomous buses is 5, the semi-autonomous buses belong to level 4 (high automation)." (Zhang et al., 2019)
Service Classification	
Autonomous Mobility on Demand (AMoD)	"A service similar to MoD or taxi, with the difference that vehicle operations are driverless." (Basu et al., 2018) Interchangeability: Autonomous Demand Responsive Transit (ADRT)
Point-to-Point (P2P)	"Any service in a vehicle with 12 seats or less (including the driver) that can take customers on the route they choose, at the time that suits them, for a fare. This includes taxis, chauffeurs, tourist services and ride-sourcing (rideshare)." (Department for Infrastructure and Transport, 2022)
First Mile Last Mile (FMLM)	First Mile - "A traveller requests a vehicle that can transport him/her from the origin to the station, where he/she can transfer to a PT mode." Last Mile - "A traveller requests a vehicle that can transport him/her from the station to the destination." (Stevens et al., 2022) Interchangeability: Door-to-Door (D2D)
Automated Transit on Demand (AToD)	"A taxi-bus hybrid, as it is station-based, has a headway or predefined departure times, and allows connection from any station to any other station without making detours. At the same time, the passengers who have the same origin and destination stations at a particular time can share their ride." (Räth et al., 2023)
Paratransit	"On-demand shared-ride public transportation specifically for people with disabilities that complements fixed-route transit service provided by the transit agency operating in an area." (Miah et al., 2020)
Dynamic Autonomous Road Transit (DART)	"A new PT solution seeks to bridge the existing capacity gap between the existing Mass Rapid Transit (MRT) and Bus systems featuring fully autonomous vehicle modules integrated within a hi-tech, sustainable and efficient system design." (Rau et al., 2019)
Shared Autonomous Vehicle-Bus Rapid Transit (SAV-BRT)	"An integrated system that takes advantage of the flexibility of SAVs and the mass transport capability of BRT." (Maruyama and Seo, 2023)
Automated Last-Mile Transport (ALMT)	"Consists of a fleet of small, fully automated, electric vehicles to improve the last mile performance of a trip." (Scheltes and de Almeida Correia, 2017)
Modular Adaptive and Autonomous Transit System (MAATS)	"Operated exclusively with AMBs that is designed to provide door-to-door service on a large scale with a unique transfer operation, termed as in-motion transfer, to transfer passengers between coupled modular buses in motion." (Wu et al., 2021)

The growing interest in full autonomy in bus transit has led to a proliferation of studies on the subject in recent years, with a wide range of scopes. However, review studies on this topic are still limited as presented in Table 2. Although there is ongoing discussion regarding the potential benefits of ABs, it is also important to acknowledge the existing limitations. Technical and systematic challenges continue to impede the successful integration of ABs into the PT networks. Moreover, there is a crucial need to accurately assess the impact of AB adoption on PT networks to ensure seamless implementation.

Table 2: Previous review studies on AV-PT systems

Review Study	Focus Areas
(Azad et al., 2019)	Impacts of ABs: technology deployment, user acceptance, safety, social and economic aspects, and regulations, policies, and legal issues
(Hasan et al., 2019)	Benefits of AVs in the PT system: travel time, traffic congestion, cost, environmental factors along with barriers based on technology, regulatory, awareness and safety concerns
(Iclodean et al., 2020)	AV implementation implications with respect to shuttle buses in PT: powertrain (driveline, high-voltage battery, steering, braking, charging system), sensor system (LIDAR, radar, camera, GPS/GNSS, inertial measurement unit), autonomous driving systems (algorithms), safety and cybersecurity, route specification, legal framework, social implications
(Narayanan et al., 2020)	SAV service impacts: traffic & safety, travel behaviour, economy, transport supply, land-use, environment, and governance
(Golbabaei et al., 2020)	Service attributes and impacts of SAVs: urban mobility, infrastructure and land-use, travel behaviour, environment
(Golbabaei; et al., 2020)	Predictors of AV public acceptance and intention to use: demographic (gender, age, education, employment, household income and structure), psychological (perceived usefulness, ease of use, benefits, risks, awareness, personal innovativeness, environmental concerns), mobility behaviour characteristics (vehicle ownership, driving license, exposure to in-vehicle tech, in-vehicle time, commute mode choice, driving frequency, crash history, trip purpose, daily travel times, mobility impairment)
(Othman, 2021)	Predictors of public acceptance and perception of AVs: safety, ethics, liability, regulations, recent COVID-19 pandemic

While there have been previous literature reviews on the impacts of AV integration on PT networks, a further updated review would be beneficial. This would allow us to summarize and present the findings from recent studies and compare them with the findings of previous studies. Thus, ‘autonomous buses’, ‘automated public transportation’, ‘self-driving shuttle buses’, ‘driverless buses’, ‘semi-autonomous buses’, ‘modular vehicles’, and ‘RoboTaxi’ were chosen to be the main keywords. An online search was conducted using a university online library search engine, enabling access to different databases such as Scopus, Science Direct, Web of Science, Wiley Online Library, TRID, ASCE, and Open Access Journals. The present study is based on a descriptive analysis of literature rather than a statistical one. Therefore, the articles were “eye-balled for consistency and accuracy of the keyword search” (Yin, 1994). However, research papers including public perception, acceptance or satisfaction were excluded to ensure that the literature search aligned with the aim. This paper aims to systematically review the potential impacts of adopting ABs to the PT network, including travel behaviour, financial, safety, environmental, and transport network aspects, as well as the methodological approaches used to identify these impacts. This paper is structured as follows: research design (section 2), public transport and first mile last mile connectivity (section 3), potential deployment of ABs in the PT network (section 4), and conclusions (section 5).

2. Public transport and FMLM connectivity

Public transport systems can generally be classified into two service modes: Fixed-Route Transit (FRT) and Demand Response Transit (DRT) (Kittelson & Associates, 2013). FRT operations are conducted in densely populated areas with predefined routes. However, DRT operations cater to individual travel requirements for Door-to-Door (D2D) services in suburban or rural areas. Hence, DRT operations are more costly for transit agencies than FRT operations. The combination of FRT and DRT is considered as Flexible-Route Transit (FlexRT), which has emerged to balance the flexibility of DRT and the cost efficiency of FRT. Generally, FlexRT systems are operated in base routes to service passengers at predetermined checkpoints. Additionally, they are allowed to deviate from the planned routes to service the customers depending on the demand in low-density areas (Quadrifoglio, 2008). PT systems such as flexible bus systems, Personal Rapid Transit (PRT), customized buses, ABs, and Autonomous Modular Buses (AMBs) are novel technologies developed with cutting-edge technology to improve the level of service in PT (Zheng and Peeta, 2015).

The definition of last mile is the distance between public transport and the end destination, whilst the first mile can be defined as the distance between the residence and the public transport (Kåresdotter et al., 2022). The main FMLM problem that persists with public transport is referred to as the dysconnectivity between public transport and an individual's origin or destination (Tight et al., 2016). The FMLM problem lies when the destination or bus stop is outside the distance an individual is typically willing to walk. The Willingness to Walk (W2W) to PT varies by city, country and even mode of transport. The W2W to access a frequent bus service, in Sydney, Melbourne, Brisbane, Adelaide, Perth and Canberra are 234m, 327m, 206m, 260m, 289m, and 251m respectively (Rose et al., 2013).

One in six people has a disability with accessibility concerns, having difficulty in using some or all forms of PT, causing a low W2W of 61m (Hughes, 2023). Thus, the FMLM connectivity problem should be addressed appropriately to improve the overall quality of service for all users. FMLM connectivity in public transportation has been researched for several decades, which dates back to the 1970s when concepts such as PRT, ride-hailing, bike-sharing systems and electric scooters have been employed (Zheng and Peeta, 2015). However, certain limitations such as limited coverage, high cost, safety concerns, lack of integration, accessibility and reliability remain steadfast with the existing options (Kåresdotter et al., 2022). On-demand transport feeders implemented to the PT network, which has a maximum capacity of 8 passengers, negates not only the FMLM connectivity problem but also enhances the overall system performance.

3. Potential deployment of ABs in the PT network

The deployment scenarios of ABs were evaluated by Zubin et al., (2021), to identify the applicability of DSs as a FMLM connection in PT networks. According to Hagenzieker et al., (2021) and iMOVE, (2023), there are over 150 smart mobility projects and trials across the world at the time of writing. To mention a few, a DS pilot program was launched in the rural community of Nishikata, Japan to provide mobility services for its elderly residents. The shuttle was scheduled to travel between a service area and a healthcare facility at a speed of 10km/h (Tajitsu, 2017). Another on-demand transit service was deployed in Shenzhen, China using buses that are capable of carrying up to 19 passengers and reach a maximum speed of 40 km/h (SPACE, 2017). If ride-sharing automated taxis are merged with on-demand transit travel, it is simply transformed into a flexible DS (also known as minibuses), which could occupy 5 - 10 passengers (Ainsalu et al., 2018), and automated shuttle buses occupying a maximum of 60 passengers as a transit on schedule service (Hatzenbühler et al., 2020). The framework developed by Mahmoodi Nesheli et al., (2021), explains the potential application of AVs in the PT network. The framework includes four applicability streams: transit, airport, business, and entertainment. In the transit stream, ABs could be used as FMLM, demand responsive, on-schedule and point-to-point options. The applicability scenarios of ABs to a transit system within a PT network are further presented in Table 3, with respect to who, what, when and where they can be used along with the opportunities and challenges presented with the applicability.

Table 3: Applicability scenarios of ABs to a transit system within a PT network (Mahmoodi Nesheli et al., 2021)

Scenario	Who	What	When	Where	Opportunity	Challenge
FMLM	Commuter, non-commuter	Minibus, shuttle bus	Peak-time, off-peak	Suburb, rural, CBD	Fill the transport gap, reduce parking requirements	Limited vehicle capacity
Demand responsive	Low demand, paratransit	Minibus, shuttle bus	Flexible	Rural, urban	Transport for all, shared mobility	Complex routing
On-schedule	Commuter, non-commuter	Minibus	Peak-time, off-peak	Fixed route	Reducing pollution, reducing cost, high frequency	Low speed, limited vehicle capacity, limited distance travel
Point-to-point	On-demand	Minibus	Flexible	Rural, urban	Transport for all, door-to-door	Vehicle waypoints, complex routing

The most common vehicle types used as ABs when integrated into the PT network were fully autonomous vehicles/buses (Tian et al., 2022), Semi-Autonomous Buses (SABs) (Zhang et al., 2022), and Modular Autonomous Vehicles (MAVs) (Liu et al., 2021). Due to the variations in the type of vehicle, the integration type of service to the PT network can be found either as direct integration to the PT network with dedicated lanes/connected with transit systems (Wang et al., 2021) or integration as SAVs or mobility-on-demand AV services with independent operations in the road network to promote FMLM connectivity (Hyland and Mahmassani, 2020). The existing literature explains that the adoption of AVs in PT has been mainly a demand-responsive supplement to the current system. In relation to automation levels in PT, drivers can be removed in SABs when it joins a platoon, as they can act as a platoon follower. However, in fully ABs, the drivers can be fully removed. Therefore, a platoon can be considered as a string of vehicles that drives with short inter-vehicle distances, with a driver in the leading vehicle and without any drivers in the following vehicles (Zhang et al., 2022).

The introduction of an AB can be beneficial as a FMLM service compared to the conventional system, yet less feasible in a large scale due to the increased cost and decreased service efficiency (Chen and Wang, 2018). Therefore, the implementation of a flexible transit system should be limited to small areas with low demand (Nourbakhsh and Ouyang, 2012). As a result, system inefficiencies, such as bus bunching, can arise in the operations of the PT network. To address the problem of reduced service efficiency, numerous researchers have explored various sustainable approaches that not only enhance system efficiency but are also more cost and time effective. A transit network redesign can assist in utilizing additional ABs to serve passengers on the road network (Tian et al., 2022). Furthermore, fleet optimization (Poinsignon et al., 2022) and timetable synchronization (Wang et al., 2022) in real-time based on varying passenger demands during peak and off-peak times can further streamline operations. To assert this, the innovative AMB transit system proposed by (Wu et al., 2021), which adapts to dynamic demands on a large scale with competitive efficiency presents the practicality of the concept. The idea of an AMB transit system is that modular vehicles can be flexibly coupled and decoupled as desired. In this manner, the capacity utilization rate can be increased while reducing the overall energy consumption to provide D2D services (Wu et al., 2021). The exceptional study by Wu et al., (2021) reflected on the benefits such as providing in-motion-transfer operation for passengers between coupled modules, and the ability for the transit system to operate with no virtual transfer stops without any fixed routes or predetermined timetables. Therefore, the AMB transit system is a novel approach to overcome the limitations of the existing conventional AMB-like flexible transit systems.

4. Potential deployment of ABs in the PT network

According to Golbabaei et al., (2020), the service attributes and impacts of Shared Autonomous Vehicles (SAVs) in the context of smart urban mobility can be assessed based on four categories: urban mobility, urban infrastructure & land use, social & travel behaviour, and environment. Urban mobility can be determined by fleet size, traffic volume and congestion, travel cost and fares. Urban infrastructure and land impacts rely on household location, parking spaces, pick-up/drop-off and charging stations. Social and travel behaviour impacts were evaluated through trip and mode choice, and vehicle ownership (Golbabaei et al., 2020). Thus, the incorporation of ABs into PT networks has significant implications for passengers, transit agencies, and the whole road network. To evaluate this impact, in this study the literature was classified into five impact factors: travel behaviour aspects, financial aspects, safety aspects, environmental aspects and transport network aspects.

4.1. Travel behaviour aspects

Travel behaviour in a transport network is referred to as how individuals make decisions about their travel with respect to the route, time, and distance of travel (Joewono et al., 2008). Thus, various travel parameters such as quality of service (QoS), service frequency, travel time, in-vehicle time, passenger waiting time, access and egress time, Vehicle Kilometres Travelled (VKT) are impacted by the integration of ABs to the PT network (Hasan et al., 2022). The variations of travel behaviour parameters as a result of integration of ABs to the PT network as reported in the literature are shown in Table 4.

Table 4: Variations of travel behaviour parameters as a result of integration of ABs to PT network

Parameter	Author	Variation
QoS	(Zhang et al., 2022)	(+)
	(Wu et al., 2021)	(+)
	(Hatzenbühler et al., 2020)	(+)
	(Zhang et al., 2020)	(+)
	(Leich and Bischoff, 2019)	(+ *with larger SAV fleets / partnering with PT lines)
	(Zhang et al., 2019)	(+)
	(Winter et al., 2018)	(+)
Service frequency	(Hatzenbühler et al., 2021)	Insignificant
	(Zhang et al., 2019)	(-)
	(Rau et al., 2019)	(-)
Travel time	(Hasan et al., 2022)	- 48%
	(Wu et al., 2021)	-16.6%
	(Hatzenbühler et al., 2020)	(-)
	(Leich and Bischoff, 2019)	-3%
	(Jäger et al., 2018)	+17%
	(Mendes et al., 2017)	-36%
	(Moorthy et al., 2017)	Insignificant
In-vehicle time	(Thorhauge et al., 2022)	(-)
	(Hatzenbühler et al., 2021)	(+ *for smaller networks) / (- *for complex PT networks)
	(Huang et al., 2020)	(- *with low train headways)
Waiting time	(Thorhauge et al., 2022)	(-)
	(Hatzenbühler et al., 2021)	(-)
	(Ji et al., 2021)	-12.62%
	(Wang et al., 2021)	(-)
	(Huang et al., 2020)	(- *with low train headways)

	(Pinto et al., 2020) (Zhang et al., 2019) (Scheltes and de Almeida Correia, 2017)	(-) (-) (-30% *for morning peak /-10% *for evening peak)
Access and egress time	(Thorhauge et al., 2022) (Gurumurthy et al., 2020)	(-) (-)
VKT	(Huang et al., 2020) (Zhang et al., 2020) (Fagnant et al., 2019) (Javanshour et al., 2018) (Liu et al., 2018)	+4% (- *with low number of service passengers) +8% +19% +77% (+)

Note: (+) indicates increase and (-) indicates decrease; (%) indicates variation with respect to the base-case/existing scenario of each study.

SAB platooning, AV integrated transit systems, and integration of SAVs with road networks can all improve public transport. However, there are limitations to their benefits, such as bunching problems with high-frequency buses and longer passenger boarding times with ABs integrated directly to the PT network (Zhang et al., 2022). ABs can be utilized for FMLM services and can improve system reliability and decrease transit demand (Huang et al., 2020). Additionally, automation of buses can lead to reduced crew costs and improved level of service, but maintaining minimum speeds is crucial to ensure competitive service (Zhang et al., 2019). Long-range, fast-charging SAEVs and DART platoons can also improve service quality, with a low response time of 5.12 min/trip (Loeb et al., 2018). The slow operational speeds of AVs have been a critical concern in most of the AV trials, as it creates longer queue lengths leading to heavy congestion. In the case of the AV trial on Karragarra Island, South East Queensland, the maximum shuttle speed was 20 km/h, even though the speed limit in the area was 50 km/h (Redland City Council, 2021).

The direct deployment of ABs to the existing PT network also tends to increase travel time, causing delays to the passengers and increasing VKT due to detours away from fixed lines to service passengers (Jäger et al., 2018). However, VKT can be reduced with a low number of service passengers (Zhang et al., 2020). In contrast, studies have also shown that AV shuttle operations in settings such as universities improves the overall experience of users with the reduced in-vehicle time, wait time and egress time, when compared with existing FMLM travel options in the PT network (Thorhauge et al., 2022). Therefore, AV shuttles were considered to be more suitable as demand responsive feeder systems. Moreover, the introduction of ABs to the conventional bus lines slightly increased the passenger load by 5% due to the higher service frequency, transport supply and reduced travel times (Hatzenbühler et al., 2020). On the other hand, AMBs in particular provide better service on long trips due to their abilities of coupling and decoupling from other modules. Thus, the transfer time of passengers is reduced, subsequently, reducing the overall travel time (Wu et al., 2021).

4.2. Financial aspects

The financial costs related to the implementation of ABs to the PT network are mainly related to the Demand-side (passenger) and the Supply-side (transit agency) (Hatzenbühler et al., 2020). The cost components related to transit agencies in PT networks are capital, operating, and end-of-life costs. The capital cost variables are bill of materials, vehicle body and chassis components, powertrain, autonomous driving technology, HMI system, assembly labor, energy costs, taxes and fees, excise duty, goods and services tax, registration fee, additional registration fee, certificate of entitlement, and carbon emissions-based vehicle scheme. The operating cost comprises of road tax, energy cost, maintenance cost, insurance cost, cleaning cost, and personnel cost (Ongel et al., 2019). The variations of financial parameters of demand side and supply side as a result of integration of ABs to the PT network as reported in the literature are shown in Table 5.

Table 5: Variations of financial parameters as a result of integration of ABs to PT network

Parameter	Author	Variation
Demand-side cost	(Leich and Bischoff, 2019) (Ongel et al., 2019) (Liu et al., 2018) (Moorthy et al., 2017)	(- *with ABs on conventional lines) / (+ *with lower waiting time prioritization) - More than 50% - 38% - 10%
Supply-side total cost	(Loeb and Kockelman, 2019) (Shen et al., 2018) (Winter et al., 2018)	(- *long-term) (- one third) (-)
Supply-side capital cost	(Hatzenbühler et al., 2021) (Hatzenbühler et al., 2020)	(+ *infrastructure cost) (+)
Supply-side operation cost	(Hatzenbühler et al., 2021) (Liu et al., 2021) (Hatzenbühler et al., 2020) (Ongel et al., 2019)	(-) - 15 to 23% (-) - more than 50% *reduction of operator cost

Note: (+) indicates increase and (-) indicates decrease; (%) indicates variation with respect to the base-case/existing scenario of each study.

The significant initial capital cost required to purchase ABs and upgrade the infrastructure in the PT network are offset by the considerable reduction in operational expenses due to the elimination of high driver wages, which currently account for approximately 60% of operational costs (Quarles et al., 2020). However, (Iclodean et al., (2020) showed that a human operator is necessary for AB operations in most of the existing pilot studies in any case of emergency, which contributes an additional operator cost. Contrastingly, the cost of automation alone reduces passenger costs significantly by more than 50% (Ongel et al., 2019, Moorthy et al., 2017). However, AV integration requires extensive planning and monitoring, due to the drastic increments in operational cost (Tian et al., 2022).
AVs are more likely to cost more than private HDVs and public transit, but less than human-driven taxis and ride hailing services (Litman, 2023). The costs of SAV operations range between US $0.15 and US $1.0 per vehicle-mile, depending on different estimation methods, parameters considered for fixed and variable costs and other assumptions (Burns et al., 2013, Johnson, 2015, Fagnant and Kockelman, 2016, Stephens et al., 2016, Nunes and Hernandez, 2020). SAEV costs tend to be less than US $0.1 per vehicle-mile due to the low operational cost predictions. However, most of the SAV cost predictions remain to be higher than public transit fares, which range between US $0.2 and US $0.4 per passenger-mile. Poinsignon et al., (2022) revealed that AV operation in parallel with the bus network could increase the operational cost by more than two times when compared with the current bus operation costs. However, the AV deployment in the current system with a 10% additional VKT allowance is viable in providing additional service quality for users while maintaining costs at present levels. While the cost-effectiveness of AVs in the public transport network is a matter of debate, there is optimism that they could be more cost-effective than traditional public transit in the long run.

4.3. Safety aspects

Safety is an imperative concern for passengers, operators, transit agencies, and governments more broadly. The safety concerns of ABs in a PT network can be evaluated based on passenger safety, vehicle safety, road safety, cybersecurity, and emergency preparedness. AV operations are safer compared with human-driven vehicles due to novel technological perspectives such as vehicle-to-vehicle communication and Adaptive Cruise Control (ACC) or Cooperative Adaptive Cruise Control (CACC) (Zhang et al., 2022). Thus, the reduction of conflicts creates a safer environment not only for the passengers but also for other road users (Oikonomou et al., 2020, Rosell and Allen, 2020). To add to this, Chong et al., (2022) revealed that safety features such as obstacle trajectory prediction algorithms incorporated with ABs further enhance safety on roads. These features include obstacle detection, tracking and trajectory prediction. The authors developed the algorithms for a 12m bus, using 2D LIDAR, 3D LIDAR, cameras and radars covering a 360^0 coverage of the environment (Chong et al., 2022). However, concerns arise with the use of 5G technology in AVs, due to the vulnerabilities such as data exposure to third parties as cyber threats (Algarni and Thayananthan, 2022). Furthermore, the absence of on-board supervision raises concerns with the lack of assistance provided to people with disabilities, the resolution of technical issues, prevention of incivilities, and disobedience of regulations (Dong et al., 2017). However, facilitating communication with an emergency contact room can heighten the perceived safety among passengers (Luger-Bazinger et al., 2021).

4.4. Environmental aspects

The environmental benefits of integration of ABs in PT networks are achieved through reduced emissions, energy efficiency, noise reduction, reduced traffic congestion, and improved air quality. The positive impact on the environment is appraised by researchers such as (Hasan et al., 2022, Moorthy et al., 2017). On the contrary, it was alluded by numerous researchers that the addition of ABs increases energy consumption and thus increases Greenhouse Gas (GHG) emissions, due to the additional VKT (Zhang and Guhathakurta, 2018, Lu et al., 2018). Therefore, energy consumption and GHG emissions are heavily dependent on the AV penetration rates (Conlon and Lin, 2019) and the optimum transit system (Rau et al., 2019, Jäger et al., 2018) to ensure sustainable operation. On the contrary, Poinsignon et al., (2022) affirm the reduction of CO_2 emissions through AV integration. In fact, mixed operations of AVs and existing buses reduce CO_2 emissions by 89%.

4.5. Transport network aspects

Transport network improvements are imperative to achieve a better quality of service for passengers and to enhance overall system efficiency. In general, AV integrated on-demand transit systems are Autonomous Modular on Demand (AMoD) systems, which may be interchangeable with Autonomous Demand Responsive Transit (ADRT) (Basu et al., 2018, Golbabaei, 2023). AV integration methods in the literature include optimization of fleet size (Tian et al., 2022, Pinto et al., 2020) or introduction of a novel transit system either connecting to the existing transit system or implementing a new transit system (Rau et al., 2019, Javanshour et al., 2018, Winter et al., 2018, Jäger et al., 2018). Novel transit systems such as SAV-BRT (Maruyama and Seo, 2023), ALMT (Scheltes and de Almeida Correia, 2017), DART (Rau et al., 2019), and MAATS (Wu et al., 2021) are more feasible in terms of the travel behaviour and financial aspects. Figure 1 illustrates the two primary modes of operation for existing AMoD systems: independent and integrated with public transport (PT). All independent AMoD systems can also be integrated with PT networks.

The flexibility to adjust scheduling with varying passenger demand attracts transport authorities to adopt emerging on-demand transit services (micro transits) (Shi et al., 2020). Empty VKT can be reduced drastically through the effective identification of the optimum system. Further, the AB Timetable Synchronization Problem (AB-TSP), which covers AB timetabling and passenger assignment should be addressed properly to effectively provide a better service for the passengers (Wang et al., 2022). The substitution of ABs to the PT network requires a systematic way to sequentially replace conventional buses (Tian et al., 2022).

Therefore, ABs should be integrated to traditional transport lines with an appropriate ratio at different stages to achieve higher system efficiency.

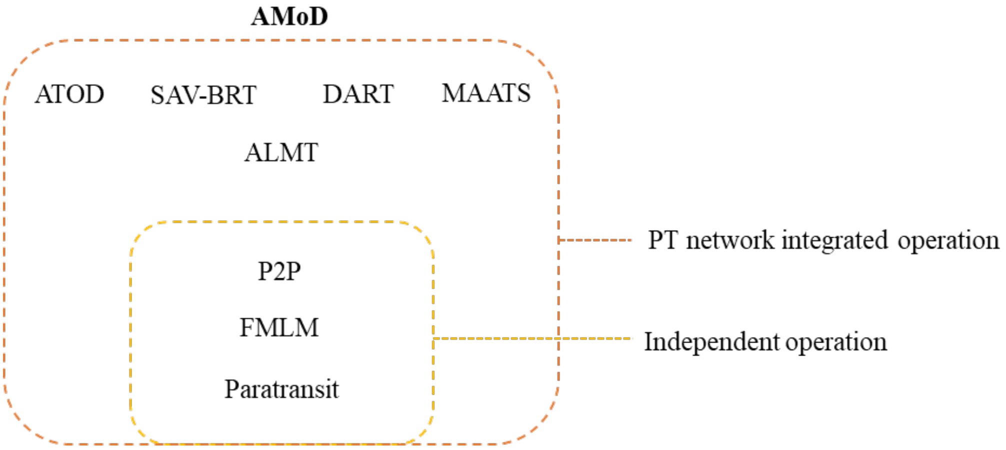

Figure 1: AV-PT service classification

5. Tools and techniques used in modelling and analysing AB deployment in the PT network

The literature on AB integration in the PT network has mainly taken two approaches: simulation models and mathematical programming models. Microscopic simulations using software such as AIMSUN (Oikonomou et al., 2020), VISSIM (Rau et al., 2019), SUMO (Huang et al., 2020), MATLAB (Mendes et al., 2017), MATSim (Gurumurthy et al., 2020), BusMezzo (Hatzenbühler et al., 2020) have focused on agent-based, event-based and discrete event-based agent-based simulations to create realistic forecasts. The simulation study of (Tanveer et al., 2022) considered manual vehicles and AVs under different penetration rates for six vehicle types: manual micro car, manual car, manual bus, automated micro car, autonomous car and AB. Yantao et al., (2021) simulated an overall section of 11,116 sq.mi (28790 km^2), that comprised 1,961 traffic analysis zones with 32,000 road links and 33,000 transit links. Hasan et al., (2022) compared AV-BRT integrated systems with microsimulation models developed through VISSIM using a time-step stochastic modelling approach using the psychophysical Wiedman-74 (merging traffic) and Wiedmann-99 (highway) car-following models. VISSIM's original suite does not allow modelling novel systems such as DART, hence; DART driving behaviours should be utilized with the external function expansion API provided by the original software suite (Rau et al., 2019). A similar approach was taken to model AVs by Vicente, (2022), as a Software Development Kit (SDK) coded in C++ and executed alongside AIMSUN Next. On a different note, Oikonomou et al., (2020) revealed that AIMSUN allows AV modelling with joint consideration of CACC and Gipps's models, in which the vehicle uses acceleration, speed and position of the preceding vehicle. In addition, if no vehicle connectivity is assumed, simulation can be carried out through modified parameters of the car following, lane changing and gap acceptance behavioural models (Tympakianaki et al., 2022). Moreover, simulations are beneficial in line-based AB deployment to the transit network (Hatzenbühler et al., 2020).

The mathematical models are primarily focused on optimal transit network design and operation strategies. A substantial amount of literature is devoted to investigating the optimal design of transit networks. Some studies are designed by proposing a bi-level programming model, to determine factors such as transit route and the bus frequency (Tian et al., 2022). Mixed Integer Non-Linear Programming (MINLP) (Pei et al., 2021, Dai et al., 2020) and Mixed Integer Linear Programming (MILP) (Liu et al., 2021, Shi et al., 2020) models can be utilized for the modular transit network system optimizations and designs. Additionally, the combination of mathematical programming optimizations and simulation solutions further improve transit network operations in relation to AB integration (Hatzenbühler et al., 2020). The modelling frameworks used in the existing studies are summarized in Figure 2. Traffic simulations are used to generate outputs that are used as inputs for mathematical optimizations, and also to conduct sensitivity analysis employing three decision-making variables: demand-side measures, supply-side measures, and economic evaluations. The decision-making variables are used as objective functions in mathematical optimizations, and the outputs from these optimizations are used to conduct case studies using traffic simulations.

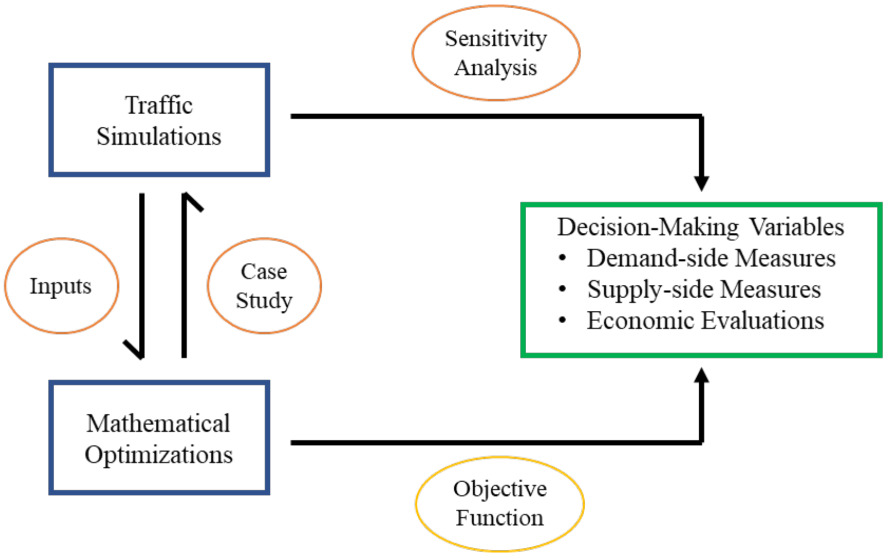

Figure 2: Methodological approaches to modelling techniques

The decision-making variables from simulation and optimization modelling have the potential to play a crucial role as inputs to economic evaluation and performance evaluation as components of a project appraisal approach. However, a complete and rigorous methodology for such an approach in relation to integration of ABs with PT networks has not been found in the literature. The forthcoming stage of this research will fill this knowledge gap.

6. Conclusion

Integration of ABs in the PT network has the potential to revolutionize the way people travel, particularly as FMLM connections, on-demand transit services, and on-schedule point-to-point options. However, in dense areas, AB integration can have negative impacts, including empty VKT and increased travel times (Moreno et al., 2018). Conversely, in low-density areas, AB integration has the potential to enhance the quality of service for users with better FMLM connectivity. While the initial capital cost of AB integration can be high, the reduction in operational costs due to the elimination of driver costs can potentially offset this (Quarles et al., 2020). In this regard, it is recommended that ABs be operated with remote supervision and include an onboard supervisor during the first months of operation as a safety measure (Zubin et al., 2021).

Although it has been suggested to have on-board supervisors for the first few months of operating ABs, the financial impact of this decision is still up for debate as it may not differ much from a conventional bus with driver costs. However, a higher level of financial feasibility can be achieved when ABs are deployed as an optimized transit network, such as AV-BRT, ALMT, FexRT, ADRT, DART, AMoD, or MAATS (Nguyen et al., 2019, Jäger et al., 2018, Shi et al., 2020). Of note, most of the studies have calculated costs based on user travel behaviour and specific cost parameters of transit agencies, yet external factors such as ticket revenue, taxes, and government subsidies have not been given adequate consideration due to lack of realistic operational data availability. The impacts of AB integration and operation in the PT network are heavily dependent on the AB penetration rate (Shen et al., 2018), and the limited assessment of potential impacts on safety aspects is a concern, and further research is necessary. Additionally, certain strategies such as fleet size elasticity and pricing require extensive research to effectively implement ABs in the PT network. The review of the literature indicates a scarcity of simulation studies, with previous research predominantly focused on mathematical optimization for modifying existing transit networks or integrating new transit systems (Tian et al., 2022). In conclusion, further extensive research is needed on AB integration in PT to fill the gap in modelling real-life scenarios and to recommend the optimal applications under various traffic conditions in various elements of transport networks. Especially, defining boundary limitations of AB applications for urban, suburban, and rural traffic conditions, passenger demand and transport supply. The next stages of this research include investigating the potential of ABs to be integrated into the PT network to enhance connectivity and effectiveness, particularly in FMLM applications in suburban settings, and full applications in rural settings. This will be achieved through a modelling approach, followed by a comprehensive project appraisal through performance and economic evaluations to identify the necessary system improvement options.

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