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Beyond hail ‘n’ ride: A demand-centric multi-level framework for bus hailing in intelligent cities

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Abstract

Conventional bus stopping mechanisms, reliant on hailing or fixed stops, often compromise operational efficiency and passenger comfort due to missed stops, unnecessary dwell times, and accessibility challenges. This paper proposes a novel demand-centric multi-level bus stopping framework for real-time passenger requests via onboard interfaces, mobile apps, and IoT-enabled infrastructure to align stops with actual demand. Integrating principles of Demand-Responsive Transport (DRT) and Mobility-as-a-Service (MaaS), the system offers a scalable, passenger-driven solution adaptable to local, rapid, and express bus services across diverse stop types. Structured in three progressive levels: basic (push-button/buzzers), intermediate (web/app-based with Near Field Communication (NFC)), and advanced (Mobility-as-a-Service (MaaS) integrated with Internet of Things (IoT)), the framework balances cost, inclusivity, and technological sophistication. This demand-centric approach is the first of its kind, offering a transformative pathway for smart and equitable public transport within intelligent cities.

1 Introduction

Public bus systems remain a cornerstone of urban and regional mobility, offering an affordable and sustainable alternative to private vehicles. However, conventional bus stopping mechanisms relying on bus hailing, specifically hail ‘n’ ride often undermines operational efficiency and passenger satisfaction. Hailing systems, where passengers signal drivers to stop, increase driver workload and risk missed stops, particularly in low-visibility conditions or busy urban environments. Fixed-stop systems, while predictable, lead to unnecessary stops when no passengers board or alight, contributing 20–30% to total trip time through extended dwell times (Heidarigharehsoo & Saidi, 2023; Kuipers & Palmqvist, 2023).

The rise of Demand-Responsive Transport (DRT) systems offers a promising avenue to address these issues by aligning services with passenger needs. DRT leverages technologies like GPS, mobile apps, and real-time data analytics to enable flexible routing or stopping. However, existing DRT systems often cater to low-demand areas using smaller vehicles, limiting their scalability to high-capacity urban bus networks. This same reason leads to high failures among DRT projects (Currie & Fournier, 2020). Mobility-as-a-Service (MaaS) is an innovative framework that integrates various transport modes into a single, user-centric platform, offering seamless access to public transport, active travel, shared mobility, and other services through digital interfaces. MaaS aims to enhance accessibility, efficiency, and sustainability in urban mobility by prioritizing multimodal transport over private car ownership. The implementation of MaaS offerings is in the early stages around the world. MaaS significantly improves public transport by increasing ridership, promoting sustainability, and integrating diverse mobility options. However, challenges such as digital exclusion, equity, and governance must be addressed to maximize MaaS’s contributions to public transport (Daou & Leurent, 2024; Hensher, 2024; Kriswardhana & Esztergár-Kiss, 2023).

This paper proposes a multi-level request-based bus stopping system, a novel approach where stops are triggered by real-time passenger requests submitted via an onboard interface or a mobile app supported by GPS and cloud-based processing. Unlike traditional hailing, the

system eliminates driver guesswork by providing automated stop notifications, reducing missed stops and unnecessary dwell time. Unlike fixed-stop systems, it ensures stops align with actual demand, saving travel time. By building on dynamic online DRT principles, the system offers a hybrid solution: the flexibility of DRT within the structure of conventional bus routes, making it suitable for both urban and regional contexts.

Therefore, a request-based system aligns with global trends towards a smart and user-centric transit system. However, implementing such a system raises questions about technology adoption, accessibility for less tech savvy and non-smartphone users, implementation and operational cost, necessitating a critical evaluation of its feasibility and design. This conceptual paper aims to introduce and evaluate the demand-centric bus stopping system, drawing on an extensive literature review of DRT, bus efficiency, passenger interaction, and enabling technologies. It seeks to answer: How can a passenger-driven stopping mechanism improve bus operations, and what are the key opportunities and challenges in its implementation? The paper contributes to transport research by proposing a scalable, technology-enabled solution that bridges the gap between traditional buses and fully flexible DRT.

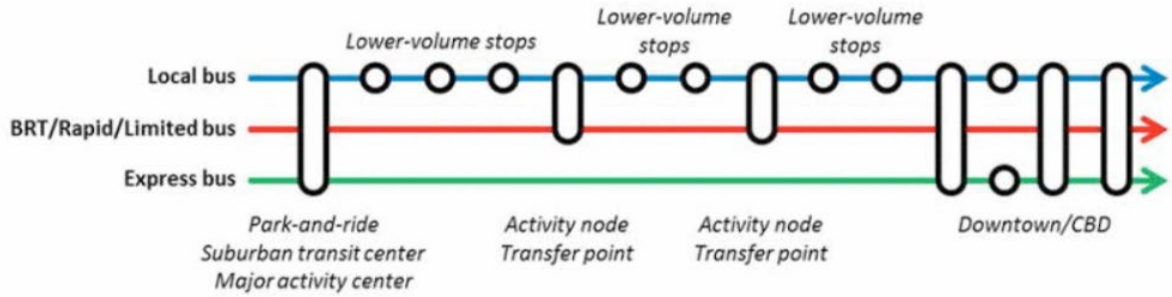
2 Literature Review

This section explores bus stopping patterns of Fixed Route Transit (FRT), providing a detailed foundation for understanding their operational principles and service impacts. It further evaluates the conventional bus hailing system, especially at lower-volume stops in local bus routes, critically analysing their effects on passenger comfort, accessibility, and safety. The latter delves into existing DRT systems and their advanced system architectures, offering innovative strategies for integrating DRT's flexibility into fixed operations to enhance service quality for passengers at low-demand stops.

2.1 FRT and bus stopping patterns

As defined in the *Transit Capacity and Quality of Service Manual* (TCQSM), FRT has three main bus service types: local bus, BRT/rapid/limited bus, and express bus. These bus services are served at major nodes (including park-and-ride, suburban transit center, major activity center, activity node, transfer point and downtown/CBD) and lower-volume stops. The bus stop patterns govern how buses interact with designated stops along fixed routes, balancing operational efficiency, passenger accessibility, and service reliability (Kittelson & Associates, 2013). While there are different bus stopping patterns, request stops are particularly significant in low-volume areas due to their ability to enhance efficiency by minimizing unnecessary stops. As presented in Figure 1, low-volume stops are mainly on local bus routes, which can also be known as flag-stops or request stops.

Figure 1: Main types of stopping patterns (Kittelson & Associates, 2013)



Request stops allow buses to bypass designated stops unless explicitly signalled by a passenger, either through a roadside action (raising a hand to hail the bus) or an onboard mechanism (pressing a stop request button). This pattern is prevalent in low-demand suburban or rural routes where passenger activity is sporadic. By stopping only when requested, buses reduce dwell times and improve travel speeds, enhancing operational

efficiency. The success of request stops hinges on clear communication between passengers and drivers. For instance, roadside hailing requires passengers to be visible and proactive, while onboard systems necessitate functional buttons or pull cords and driver awareness. In most systems, visual or auditory cues (including a lit “Stop Requested” sign or a buzzer) reinforce the alighting request, minimizing errors. Request stops are particularly effective in areas with low ridership, as they prevent buses from stopping at empty locations, conserving time and fuel.

While request stops reduce unnecessary stops, thereby decreasing dwell times and improving route speed, they present unique challenges across multiple perspectives. For requesting passengers, challenges include the need for clear signalling and fear of missing out. Bus drivers face difficulties in safely detecting and responding to requests, particularly in poor visibility or high-traffic conditions, which can increase workload and stress. Safety concerns arise from passengers signalling near roadways, buses stopping abruptly, or conflicts with other traffic, necessitating careful stop design and clear communication protocols.

2.2 Conventional bus hailing

Hail ‘n’ ride, a hallmark of request stops, or flag stops in fixed-route transit systems, requires passengers to actively signal bus drivers to stop at designated locations, typically by raising a hand or moving toward the curb. This process imposes considerable cognitive and physical demands on passengers, leading to stress and exhaustion. Research highlights that passengers must maintain constant vigilance to spot approaching buses, particularly in systems without real-time transit information (Yendra et al., 2024). This perpetual scanning of the roadway, often in unpredictable schedules, induces fear of missing the bus. The TCQSM notes that request stops exacerbate this issue in low-frequency routes, where missing a bus could result in long wait times, amplifying stress. For passengers, the need to remain alert and oriented toward the roadway detracts from comfort, as it precludes relaxation or engagement in other activities while waiting.

Once a bus is sighted, passengers must physically move to the curb line and signal the driver, a process that introduces both inconvenience and safety risks. This requirement to stand and approach the roadway is particularly burdensome in adverse conditions, such as extreme heat, cold, or rain, reducing passenger comfort and increasing fatigue. Moreover, positioning oneself near the curb line to hail the bus poses a safety hazard, as passengers are exposed to moving traffic. The Federal Highway Administration (FHWA) emphasizes that pedestrians near roadways face heightened risks, particularly at poorly lit or unmarked stops (Zegeer et al., 2005). In low-visibility scenarios such as darkness, fog, or heavy rain the challenge intensifies, as passengers may struggle to see the bus, and drivers may fail to detect hailing passengers. Low-visibility conditions significantly increase pedestrian-vehicle collision risks at bus stops, further compromising safety (Yendra et al., 2024).

The challenges of conventional bus hailing are disproportionately severe for disabled and mobility-impaired passengers. Individuals with visual, physical, or cognitive impairments face extreme difficulty in spotting buses, moving to the curb, and signalling drivers effectively. Research by the National Cooperative Highway Research Program (NCHRP) highlights that request stops often lack accessibility features, such as tactile paving or clear signage, exacerbating barriers for these groups (Campbell et al., 2012). The need to quickly respond to an approaching bus induces significant tension and anxiety, as mobility-impaired passengers may fear being unable to signal in time or safely reach the stop (Marilyn & Alan, 2007). This discomfort is compounded in low-visibility or adverse weather conditions, where the physical and cognitive demands of hailing become nearly insurmountable, leading to reduced transit use among these populations (Kashfi et al., 2013; Mwaka et al., 2023).

The effectiveness of bus hailing relies heavily on drivers’ ability to perceive and respond to passenger signals. Conversely, when drivers do identify passengers, the timing of perception is critical. Studies on driver reaction times indicate that delayed recognition of hailing passengers due to high perception-reaction times in complex traffic environments can prompt

abrupt braking. This sudden deceleration poses significant safety risks to onboard passengers, who may be unseated or injured, and to other road users, as abrupt stops can trigger rear-end collisions or traffic disruptions (Beck, 2015; Feng et al., 2024). When drivers can identify hailing passengers early, the boarding process becomes seamless, enhancing comfort and safety. Advance detection allows for smoother deceleration and stopping, reducing the risk of abrupt braking and improving the onboard experience. Emerging technologies, such as real-time passenger detection systems or mobile app-based hailing, have been proposed to mitigate the challenges of conventional hailing. For instance, studies on DRT systems proves that app-based stop requests can eliminate the need for roadside signalling, improving comfort and accessibility, particularly for disabled passengers. However, such solutions are not yet widely implemented in conventional fixed-route systems, leaving the challenges of hailing largely unaddressed.

2.3 DRT systems and their architecture on FRT

DRT systems are characterized by their adaptability to passenger needs, operating without fixed routes or schedules in their purest form. Passengers request rides via phone, mobile apps, or online platforms, and vehicles dynamically adjust routes to serve these requests within a defined area of service. The TCQSM classifies DRT as a flexible transit mode, often used in suburban, rural, or paratransit contexts where demand is sparse or variable (Kittelson & Associates, 2013). Key features include door-to-door or curb-to-curb service, real-time scheduling, and smaller vehicles (e.g., vans or minibuses). Studies by Mageean and Nelson (2003) highlight DRT's ability to reduce passenger wait times and improve accessibility in low-density areas, where fixed-route services are cost-inefficient due to low ridership.

Incorporating DRT principles into FRT, such as app-based request stops, allows passengers at lower-volume stops to signal buses in real-time, similar to conventional hailing but with technological enhancements. Research suggests that mobile app-based hailing reduces the physical and cognitive burden of traditional hailing, improving comfort and accessibility, especially for disabled passengers (Cochran & Chatman, 2021). This approach maintains FRT's structure while adding DRT's responsiveness. There are other models such as time-based hybrid operations where FRT operates during peak hours with fixed stops, while DRT takes over during off-peak periods or in low-demand areas. Research suggests that this approach optimizes vehicle utilization and reduces operating costs, providing consistent service to low-volume stops during off-peak times when FRT is less viable (Alonso-González et al., 2018; Gorev et al., 2020; Quadrifoglio & Li, 2009).

These hybrid models enhance QoS by addressing the limitations of standalone FRT and DRT. For lower-volume stops, passengers benefit from reduced wait times, improved accessibility, and tailored service, as DRT components ensure stops are served only when needed, while FRT provides reliable connectivity to major destinations. Hybrid systems increase ridership in underserved areas as passengers perceive higher service quality and convenience.

Integrating DRT architecture into FRT systems requires strategic adaptations to enhance QoS for lower-volume stops. Key incorporation strategies include unified booking platforms, hybrid routing algorithms, interoperable fleet management, and real-time passenger information (Buics et al., 2024).

1. Unified Booking Platforms: A shared app or platform can allow passengers to request DRT-style stops within an FRT network. For example, passengers at lower-volume stops could use an app to signal a bus, reducing the need for conventional hailing. Such systems improve passenger comfort by eliminating roadside signalling, particularly in adverse weather.
2. Hybrid Routing Algorithms: FRT systems can adopt DRT's dynamic routing algorithms for flex zones or feeder services. Hybrid algorithms, combining fixed-route optimization with DARP, enable buses to deviate for demand-responsive stops without significant

schedule disruptions. This approach ensures efficient service to low-volume stops while maintaining FRT reliability.

3. Interoperable Fleet Management: Integrating DRT and FRT fleets under a unified management system allows seamless coordination. For instance, DRT vehicles can serve as feeders during off-peak hours, while FRT buses handle peak demand.
4. Real-Time Passenger Information: Incorporating DRT's real-time data capabilities into FRT enhances QoS by providing passengers with accurate bus arrival times and request confirmations. Real-time information reduces passenger anxiety and improves satisfaction, particularly at low-volume stops with infrequent services.

By combining DRT and FRT, hybrid systems address the specific needs of passengers at lower-volume stops, who often face long wait times, limited accessibility, and poor service reliability. DRT's flexibility ensures that stops are served only when needed, reducing wasted trips and improving cost-efficiency. FRT's structured routes provide connectivity to major destinations, ensuring that passengers from low-volume stops can access urban centers or transit hubs. Hybrid systems improve QoS metrics, including waiting time, accessibility (increased coverage for rural stops), and passenger satisfaction (higher due to tailored service). For disabled or mobility-impaired passengers, app-based DRT components eliminate physical barriers associated with hailing, enhancing inclusivity. Moreover, hybrid systems reduce environmental impacts by optimizing vehicle use, aligning with sustainable transport goals (Shaheen & Chan, 2016). Despite their potential, hybrid DRT-FRT systems face challenges, including high implementation costs, technological barriers in rural areas, and the need for robust demand prediction models. Integrating DRT's dynamic scheduling with FRT's fixed operations requires sophisticated coordination to avoid service disruptions. Emerging technologies, such as autonomous vehicles and AI-driven routing, hold promise for further enhancing hybrid transit efficiency (Shen et al., 2018).

2.4 Tech-driven public transit for intelligent cities

The evolution of transit systems has been profoundly influenced by technological advancements, transitioning from traditional infrastructure-based models to sophisticated, data-driven frameworks. Technology-driven transit systems, particularly Intelligent Transport Systems (ITS), the Internet of Things (IoT), Artificial Intelligence (AI), and Machine Learning have emerged over the years. IoT represents the next frontier in transit system evolution, enabling interconnected networks of devices to collect, process, and share real-time data. IoT applications in transit include smart traffic sensors, connected vehicles, and real-time fleet management systems. These systems enhance operational efficiency by providing transit authorities with actionable insights into traffic patterns, vehicle performance, and passenger demand.

Effective interaction is crucial for the success of request-based transit systems. Melis and Sörensen (2022) introduced the real-time on-demand bus routing problem, highlighting the increased cognitive demands placed on drivers when handling dynamic passenger requests without intuitive dashboards. There is a high adoption rate among younger users, who prefer app-based systems for their convenience. However, this reliance on smartphone technology can exclude non-smartphone users, necessitating the development of alternative onboard interfaces to ensure inclusivity. The Kutsuplus project in Helsinki aimed to reduce travel times through an on-demand microtransit system. Despite its innovative approach, the project was ultimately discontinued due to high operational costs (Haglund et al., 2019). In contrast, Kraków's Tele-Bus service successfully integrates app and phone-based request options, effectively serving peri-urban areas and demonstrating the viability of combining multiple communication channels (Interreg Europe, 2018).

Smart ticketing systems in public transport have evolved considerably from magnetic stripe cards to more sophisticated solutions, transforming fare collection and passenger access. These systems typically feature core components including fare media, validation equipment,

back-office systems, and communication infrastructure, with implementations categorized as card-centric, server-centric, or hybrid models (Bagchi & White, 2005). The increase of smartphones has driven growth in mobile ticketing applications through concepts such as Be-in/Be-out (Narzt et al., 2015). These services offer advantages including reduced implementation costs and integration with journey planning tools. Simultaneously, smart ticketing has become increasingly integrated with MaaS platforms, with Sochor et al. (2018) proposing a four-level MaaS integration taxonomy where level 3 specifically addresses integrated pricing across multiple transport modes. Despite technological advancements, implementation challenges persist, including institutional barriers to integrated ticketing and technical challenges such as system interoperability and data security. Emerging technologies are shaping the future of smart ticketing, including biometric authentication, blockchain-based architectures, Bluetooth-based solutions and sensor-based technologies (Abhishek Nair et al., 2019; Campos Ferreira et al., 2020; Yigitcanlar et al., 2024)

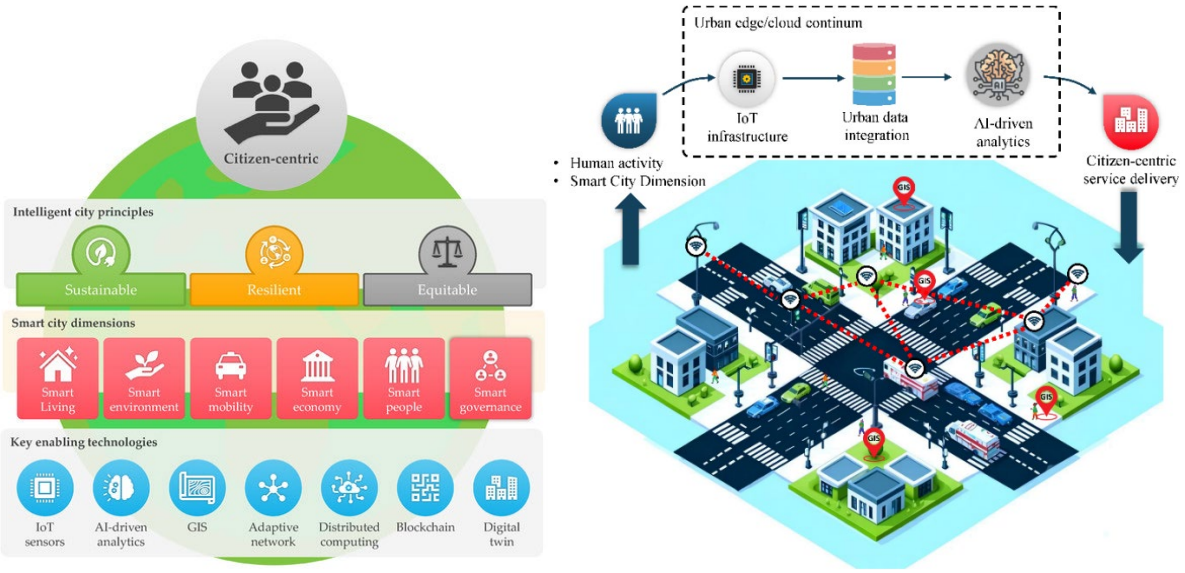
Near Field Communication (NFC) technology has been extensively used in various Australian states, including Brisbane. It had demonstrated to offer superior protection against potential cybersecurity threats, and its low implementation cost and the capability to deliver digital services that are resistant to vandalism are significant factors driving its widespread adoption. Currently, NFC technology has been deployed at 15,500 urban bus stops across Queensland, providing stop-specific information such as timetables, real-time updates, service notifications, and general stop information. NFC technology also offers substantial benefits for individuals with visual impairments, while non-native English speakers can translate the webpage into their preferred language. Additionally, customers have the option to scan a QR code, conveniently located on printed timetables at bus stops (Translink, 2025). However, scanning public QR codes introduces a higher level of cybersecurity risk, as malicious actors can potentially overlay harmful websites on the QR codes (Krombholz et al., 2014).

The concept of smart cities has evolved significantly, driven by technological advancements and a focus on efficiency. Recent studies suggests that, transportations is one of the key smart city application domains (Gracias et al., 2023). Out of which, the main focus has been on promoting innovation, accessibility and sustainability through smart transport (Chen & Silva, 2021). According to Bittencourt et al. (2025), smart cities are built on six core dimensions: smart living, smart environment, smart mobility, smart economy, smart people, and smart governance. In contrast, intelligent cities represent a shift from traditional, technology-centric urban planning long dominant in city design toward a holistic, citizen-centered approach. The primary distinction between smart cities and intelligent cities lies in their scope. Smart cities prioritize the technological domain, leveraging digital infrastructure to collect and analyse data, anticipate trends, and automate processes in a predictive, adaptive manner. Key enabling technologies include IoT sensors, AI-driven analytics, Geographic Information Systems (GIS), adaptive networks, distributed computing, blockchain, and digital twins. Figure 2(a) highlights that, intelligent cities go further by integrating the social domain, emphasizing accessibility, inclusivity, and community engagement to foster a connected and equitable urban environment. Figure 2(b) presents that combining key enabling technologies of smart cities, while promoting intelligent city principles help create sustainable, resilient and equitable cities (Bittencourt et al., 2025).

Social domain focuses on integrating social factors into urban development to improve accessibility, promote inclusivity, and encourage community engagement. Intelligent cities are developed on three foundational principles: sustainability, resilience, and equity (Bittencourt et al., 2025). Sustainable technologies focus on reducing environmental harm, improving resource efficiency, and supporting circular economies (O'Dwyer et al., 2019). Resilient technologies, on the other hand, are built to withstand and bounce back from disruptions like natural disasters, cyberattacks, or infrastructure failures (Jesus et al., 2024). Lastly, equitable technologies aim to provide all residents with equal access to urban services, regardless of socioeconomic background, age, gender, or ability. They promote inclusivity and accessibility,

preventing the deepening of inequalities, such as through AI platforms that deliver tailored public services to meet diverse needs (Buttazzoni et al., 2020).

Figure 2: Citizen-centric intelligent cities. (a) integration principles (b) technology integration (Bittencourt et al., 2025)



(a) (b)

Several researchers have explored the opportunity of IoT based smart city bus stops, using sensors to relay requests, but noted high infrastructure costs (Jeyakkannan et al., 2021; Kamal et al., 2019). The study of Elijah et al. (2023) provides evidence for a public bus fleet tracking system using proximity-based Bluetooth beacons. This is an IoT-enabled Bluetooth low energy system which is an alternative approach to fleet tracking. The results proved a 5–10-minute travel time reduction on public holidays compared to a normal day. However, this is a supply-centric approach, proving space for a IoT-based demand-centric approach. Equity remains a critical challenge in MaaS and on-demand systems. Digital exclusion affects non-smartphone users, particularly low-income and elderly populations who rely on public transport. While MaaS platforms empower tech-savvy users, the lack of alternative access channels risks marginalizing vulnerable groups (Delaere et al., 2024; Durand et al., 2023; Jayatilleke et al., 2025; Yigitcanlar et al., 2024).

2.5 Research gap

The literature has explored various avenues, revealing a significant gap in research within bus hailing systems. Although some isolated studies have explored real-world applications, particularly DRT services in public transport, there is a notable lack of specific research on bus hailing. Additionally, the complexities and high capital costs associated with existing tech-driven solutions highlight the limited attention from transit agencies. As cities evolve into smart, intelligent hubs, adopting a technology-driven alternative to hail ‘n’ ride presents a promising and innovative solution to adaptive public transit within intelligent cities.

3 Multi-level framework

This study proposes a conceptual multi-level framework for a demand-centric bus stopping system, designed to replace conventional hailing in fixed-route bus services with a passenger-driven, technology-enabled approach (Figure 3). The methodology adopts a multi-level design process, integrating DRT principles to enable real-time stop requests while addressing technology, costs, inclusivity, and operational scalability. The framework was developed through a systematic synthesis of literature, analysis of DRT case studies, and consideration

of stakeholder needs (passengers, drivers, transit operators). It accounts for diverse bus service types, including local, BRT/rapid/limited, and express, and bus stop types, including park-and-ride, suburban transit centers, major activity centers, activity nodes, transfer points, and downtown/ CBD stops. The methodology is structured around three progressive levels: basic, intermediate, and advanced each tailored to balance technological sophistication, cost, and inclusivity.

3.1 Framework development process

The framework was developed through a three-step process:

1. **Literature Synthesis**: A comprehensive review of DRT systems, bus operation efficiency, passenger-driver interaction, and enabling technologies (Section 2) informed the framework's conceptual foundation. This synthesis identified gaps in scalable, real-time, passenger-driven stop mechanisms.
2. **Case Study Analysis**: Real-world DRT projects were analysed to extract lessons on technology adoption, inclusivity, and cost management (Currie & Fournier, 2020; Currie & Wong, 2020). These informed design choices, such as inclusive interfaces and cost-effective technologies.
3. **Stakeholder-Informed Design**: The framework was shaped by considering passenger needs (accessibility, convenience), driver needs (reduced workload, clear notifications), and operator needs (cost-efficiency, scalability). Design principles emphasized equity, aligning with studies on inclusive transit for elderly and non-tech-savvy users.

3.2 Multi-level framework design

The request-centric system is structured in three levels, each building on DRT principles to shift from supply-driven (timetabled stops) to demand-driven (passenger-requested stops) operations. Each level was designed to accommodate local, BRT/rapid/limited, and express bus services, with adaptations for bus stop infrastructure types based on passenger volume, location, and connectivity.

Level 1: Basic Request System

The basic level prioritizes low cost and universal inclusivity, ensuring equitable access for all passengers, including those without smartphones or technological proficiency. For boarding, a simple push-button or buzzer system is installed at bus stops, activating a "stop requested" light visible to drivers. Isolated, low-volume stops use durable, vandalism-resistant buttons to minimize maintenance costs, requiring minimal integration with existing infrastructure for reliability in diverse environmental conditions. For alighting, passengers request stops onboard via stop request buttons or buzzers, triggering visual or auditory cues ("Stop Requested" sign) to alert drivers. This button-based system requires no digital literacy, ensuring access for elderly, less tech-savvy, or non-smartphone users, aligning with the demographic profile of low-demand areas where smartphone penetration is lower (60% among seniors vs. 90% in urban Australia) (Jayatilleke et al., 2025). Implementation costs involve installing buttons at stops and onboard, leveraging existing infrastructure to minimize upgrades. Level 1 incorporates smart ticketing functionality limited to onboard transaction processing, establishing foundational digital payment infrastructure. The absence of real-time integration with dynamic routing limits its applicability in complex urban networks, but its inclusivity makes it ideal for low-volume stops, supporting social inclusion in rural or suburban areas.

Level 2: Intermediate Digital Request System

The intermediate level enhances technological integration while maintaining moderate costs, targeting urban and suburban stops with higher passenger volumes. For boarding, NFC tags enable passengers to request stops via smartphones, with an optional mobile application

verifying proximity (~20 meters) using GPS and relaying requests to drivers via an onboard dashboard. A pop-up or vibration notification alerts passengers when the bus approaches, aiding disabled individuals in preparing to board. For alighting, passengers use the mobile app to request stops, with requests displayed on the driver's dashboard, ensuring clear communication and reducing missed stops. This system is implemented across all bus stop types, with touchscreen kiosks at major transit nodes to support boarding requests for non-smartphone users, enhancing inclusivity. Due to cost and safety considerations, kiosks are limited to major nodes. Implementation costs include NFC tags, app development, and kiosk infrastructure, with ongoing maintenance and cybersecurity expenses. Level 2 expands smart ticketing through multiple channels: passengers can procure fare media via the app, web interface, or kiosks, with onboard ticketing as a complementary option. While less inclusive for non-smartphone users at low-volume stops, the system reduces dwell times by confirming requests for both boarding and alighting, enhancing efficiency at high-demand stops during off-peak periods (Cochran & Chatman, 2021).

Level 3: Advanced IoT-based integration

The advanced IoT-based integration merges the request-centric system into a MaaS ecosystem, offering maximum flexibility and automation but incurring high costs. It targets urban networks with smart infrastructure. Passengers use a MaaS app to request stops for fixed-route buses, DRT, private taxis, autonomous shuttles, or other available services. IoT-enabled smart stops (sensors, digital kiosks) at major nodes detect passenger presence and relay requests. Alighting passengers select destinations via the app, enabling dynamic route adjustments where applicable. Cloud-based systems and 5G ensure low-latency notifications to drivers and operators. Smart stops at major nodes while leveraging IoT for real-time coordination. Smart kiosks at major nodes provide touchscreen request options for non-smartphone users, but rural or low-volume stops rely on app-based requests, potentially excluding some users. Level 3 incorporates advanced sensor-based ticketing technology at smart bus stops, eliminating discrete payment transactions. The sensor infrastructure automatically processes ticketing data synchronously with MaaS platforms, calculating fares dynamically based on individual trip parameters or pre-established subscription arrangements. Implementation costs will be high with IoT infrastructure (smart bus stop), MaaS platform development, and ongoing cloud/5G costs, with additional maintenance and cybersecurity requirements. High costs and novel technology require pilot testing to assess user acceptance and operational feasibility.

The advanced level integrates the request-centric system into a MaaS ecosystem, offering maximum flexibility and automation but incurring high costs, targeting urban networks with smart infrastructure. For boarding, passengers use a MaaS app to request stops for fixed-route buses, DRT, private taxis, autonomous shuttles, or other services, with IoT-enabled smart stops (e.g., sensors, digital kiosks) at major nodes detecting passenger presence and relaying requests. For alighting, passengers select destinations via the MaaS app, with additional options like voice-activated requests or integration with wearable devices, enabling dynamic route adjustments where applicable. Cloud-based systems and 5G ensure low-latency notifications to drivers and operators. Smart kiosks at major nodes provide touchscreen request options for non-smartphone users for boarding, but rural or low-volume stops rely on app-based requests, potentially limiting inclusivity. Level 3 incorporates advanced sensor-based ticketing at smart stops, automatically processing fares for both boarding and alighting synchronously with MaaS platforms, calculating fares dynamically based on trip parameters or subscriptions. Implementation costs are high due to IoT infrastructure, MaaS platform development, and cloud/5G requirements, with additional maintenance and cybersecurity costs. At high-demand stops, Level 3 optimizes passenger flow and multimodal connectivity, reducing congestion and dwell times (Bittencourt et al., 2025). Pilot testing is required to assess user acceptance and operational feasibility.

Figure 3: Multi-level framework

	Technology	Service Adaption	Social Inclusion	Cost	Limitations
Basic	Push button/ buzzer	For lower-volume stops on local routes	All demographics	Infrastructure upgrade cost	Lacks real-time integration
Intermediate	NFC-based web application	All bus stop types on local/BRT/limited and express bus routes	May exclude less tech-savvy or non-smartphone users	Equipment, software development and maintenance cost	Less inclusivity for non-smartphone users
	Touchscreen system	Major nodes	May exclude individuals with low digital literacy	Infrastructure upgrade, equipment, software development and maintenance cost	Added infrastructure cost
Advanced	IoT application	Major nodes	May exclude less tech-savvy or non-smartphone users	IoT infrastructure, software development and maintenance cost	High implementation cost
	MaaS integration	All bus stop types on local/BRT/limited and express bus routes	May exclude less tech-savvy or non-smartphone users	MaaS platform development, software development and maintenance cost	Added complexity and technological barriers

3.3 Discussion

The multi-level demand-centric bus stopping framework advances public transport by integrating DRT and MaaS principles, addressing inefficiencies in conventional bus hailing for both boarding and alighting. The framework comprehensively addresses both boarding and alighting, overcoming challenges such as missed stops, safety risks, and accessibility barriers identified in conventional systems (Campbell et al., 2012; Yendra et al., 2024). By enabling real-time passenger requests through push-buttons and onboard buzzers (Level 1), NFC/app-based systems (Level 2), and IoT/MaaS-integrated platforms with advanced alighting options (Level 3), it ensures stops align with actual demand, reducing dwell times (Heidarigharehsoo & Saidi, 2023). This dual focus enhances passenger experience and operational efficiency, particularly for disabled and elderly users, by providing accessible interfaces for both processes, aligning with intelligent cities' emphasis on equity and inclusivity (Bittencourt et al., 2025). The application of demand-centric solutions to high-demand stops, where buses frequently stop, extends beyond routine operations. Real-time request confirmation for boarding and alighting minimizes unnecessary stops during off-peak periods, streamlines passenger flow, and enhances accessibility (Cochran & Chatman, 2021). These features support multimodal connectivity at major nodes, addressing inefficiencies in high-capacity urban networks where traditional DRT systems fall short due to their focus on low-demand areas (Currie & Fournier, 2020). This scalability positions the framework as a hybrid solution, bridging fixed-route reliability with DRT's flexibility across diverse stop types.

The multi-level request-based bus stopping framework was tailored to six bus stop infrastructure types and three service types to ensure adaptability across diverse transit contexts. Level 1 implementation is practical for lower-volume bus stops, offering high inclusivity. However, it incurs significant costs due to the infrastructure upgrades required for existing stops. Level 1 represents a transitional phase that facilitates the shift from conventional bus hailing to a user-centric model. However, its primary constraint, the absence of real-time integration, significantly limits its applicability within an intelligent city framework. Conversely, Level 2 implementation incorporates a digital interface into the request system, presenting the most cost-effective solution. This approach necessitates minimal infrastructure modifications, though additional expenses may be incurred for its deployment at major nodes with digital screens. Thus, the selection of NFC-based, app-based, or digital screen options critically determines the project's cost profile. A primary limitation of Level 2 is its reduced accessibility for non-smartphone users or individuals less proficient with technology. Level 3 implementation, by contrast, demands substantial capital investment and sophisticated technological advancements, posing significant financial and technical challenges. For service types, local bus operations benefit from all levels, improving dwell times and passenger experience. BRT/rapid/limited services may focus on (Level 2) and (Level 3) technologies at major nodes to maintain speed and operational efficiency. Levels 2 and 3 implementations provide robust support for the advancement of intelligent cities.

In Australia, urban public transport systems, such as Brisbane's Translink, align with Level 2 of the proposed framework for boarding, utilizing NFC tags at 15,500 bus stops to provide timetable information and mobile applications for real-time updates (Translink, 2025). However, these NFC tags currently lack web-based integration for stop requests, limiting their demand-centric functionality. Integrating NFC with a web or app-based platform could fully realize Level 2 for boarding, enabling passengers to request stops in real-time. For alighting, Australian systems operate at Level 1, relying on onboard stop request buttons to signal drivers. Extending the app-based infrastructure with NFC integration could elevate alighting to Level 2, streamlining requests via mobile devices. For lower-volume stops, retaining Level 1's push-button system for boarding ensures equitable access, while digital screen interfaces at major transit nodes enhance inclusivity for non-smartphone users These enhancements leverage Australia's existing technological foundation to advance equitable and efficient transit systems, aligning with intelligent city principles.

3.4 Validation and future evaluation

As a conceptual framework, validation relied on literature and case study insights, ensuring alignment with DRT best practices. Future empirical evaluation is proposed to test the framework.

- **Simulation Modelling**: Use agent-based models to assess dwell time, travel time, and fuel and cost impacts across levels.
- **Pilot Studies**: Implement Level 1 in a mid-sized Australasian city (e.g., Canberra) and Level 2/3 in a smart city (e.g., Sydney), evaluating user acceptance and operational efficiency.
- **User Surveys**: Assess acceptance, inclusivity and satisfaction, particularly for elderly and non-smartphone users.
- **Cost-Benefit Analysis**: Quantify infrastructure and operational costs against time savings and ridership gains.

The system validation should adopt a co-design approach to enhance the performance-based design process. This approach necessitates robust stakeholder engagement throughout the design development phase (Department of Transport and Main Roads, 2020). This validation process should be ultimately aimed at improving accessibility and connectivity of transport networks.

4 Concluding remarks

The proposed multi-level request-based bus stopping framework represents a transformative approach to enhancing fixed-route bus operations by integrating DRT and MaaS principles. Its primary contribution to service adaptation lies in its ability to align stops with real-time passenger demand, reducing dwell times and improving operational efficiency across local, rapid, and express services. The framework's tiered design spanning basic push-button systems, intermediate web/app-based requests, and advanced IoT-based MaaS integration ensures adaptability to diverse stop types and service contexts, from low-volume rural nodes to high-traffic urban centers. The framework prioritizes equitable access by incorporating low-tech solutions like buzzers at Level 1, catering to non-smartphone and less tech-savvy users. Web/app-based with NFC at Level 2, balances low implementation cost with minimal infrastructure upgrades. Level 3's MaaS-enabled solution further enhance accessibility at major nodes, though challenges remain with high implementations costs and technological requirements. This multi-level approach mitigates digital exclusion risks, making the system viable for elderly, disabled, and low-income populations.

The framework balances affordability and sophistication. Strategic deployment, such as limiting advanced features to high-traffic urban stops, optimizes cost-efficiency, with potential for public-private partnerships to offset expenses. The way forward involves rigorous empirical validation through agent-based simulation modeling to quantify efficiency gains, pilot studies in diverse urban settings, and user surveys to assess acceptance and inclusivity. Cost-benefit analyses will be critical to refine scalability and justify investments. By addressing these steps, the framework can bridge the gap between traditional bus systems and flexible DRT, advancing smart, equitable, and sustainable public transport.

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