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Master's Thesis

SmartStop: An Inclusive Public Transport Pre-Boarding Communication System

Making the "Invisible Passenger" Visible through IoT Integration

A Challenge@PoliTO "Inclusion By Technology" Project

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To me,
myself and I.

Abstract

In urban public transport, passengers with reduced mobility, elderly citizens, and visually impaired individuals face a recurring problem at the boarding stage. Vehicles increasingly have low floors and deployable ramps, but drivers often don't notice these passengers until the vehicle has already stopped, resulting in a rushed boarding or missed buses. In Turin alone, this affects a population that includes over 214,000 citizens above 65 and 43,000 people with disabilities, and a Regional Administrative Court ruling has already found the city negligent on disability mobility rights, a sign that this is a structural failure rather than a series of isolated incidents. This thesis addresses that pre-boarding communication gap with *SmartStop*, an IoT-based bus-stop system. SmartStop gives waiting passengers a direct, real-time channel to approaching drivers. The architecture uses two Raspberry Pi nodes communicating over MQTT on a local network. A touchscreen at the bus stop lets passengers signal what assistance they need; this triggers a bilingual audio and visual alert on a dashboard inside the vehicle. The design itself grew out of field interviews with elderly commuters, parents with strollers, and other end users, whose input shaped details such as the short door-closing window and the difficulty of using a touchscreen while holding a mobility aid. A working prototype was built and tested in the lab, reaching Technology Readiness Level 3–4. Cost and scalability analysis shows the system can be deployed city-wide on a low-cost structure compatible with national inclusion funding, including Italy's PNRR, alongside the "Single Fund for Disability Inclusion" and the "Fund for Non-Self-Sufficiency". A SWOT analysis further situates SmartStop against existing digital wayfinding tools and commercial smart-shelter platforms, none of which offer a comparable zero-registration, driver-facing alert. The thesis builds on the Challenge@PoliTo "Inclusion By Technology" initiative, turning the group's technical and business work into a formal academic framework. It sets out a roadmap for end-user validation and operator integration, with field-testing planned alongside transit operators such as Gruppo Torinese Trasporti (GTT), and outlines a longer-term path toward cloud-based, GTFS-Realtime integration and expansion to trams and other transport modes.

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1 Introduction

1.1 Background and Problem Definition

In today's public transport system in Turin, people with reduced mobility, elderly citizens, wheelchair users, and visually impaired passengers frequently face a systemic barrier: the inability to reliably communicate their boarding needs to bus drivers before the vehicle arrives. In Turin alone, demographic data indicates a pressing need, with over 214,000 citizens over the age of 65 and 43,000 individuals living with disabilities [1, 2]. Vulnerable users often wait behind crowds or need extra time to position themselves, resulting in a condition described as the "invisible passenger".

User personas such as Grazia (an elderly woman with a rollator), Davide (a visually impaired commuter), and Elena (a parent with a stroller) illustrate how this lack of pre-boarding communication leads to missed buses and unsafe, rushed boarding attempts. This issue is not isolated; recent news reports have documented multiple instances of passengers being stranded, bypassed, or trapped at stops [4, 5, 6, 7]. Furthermore, a Regional Administrative Court (TAR) judgment explicitly highlighted Turin's negligence regarding mobility rights for disabled individuals [8], demonstrating that this is a structural failure that erodes trust in public transit.

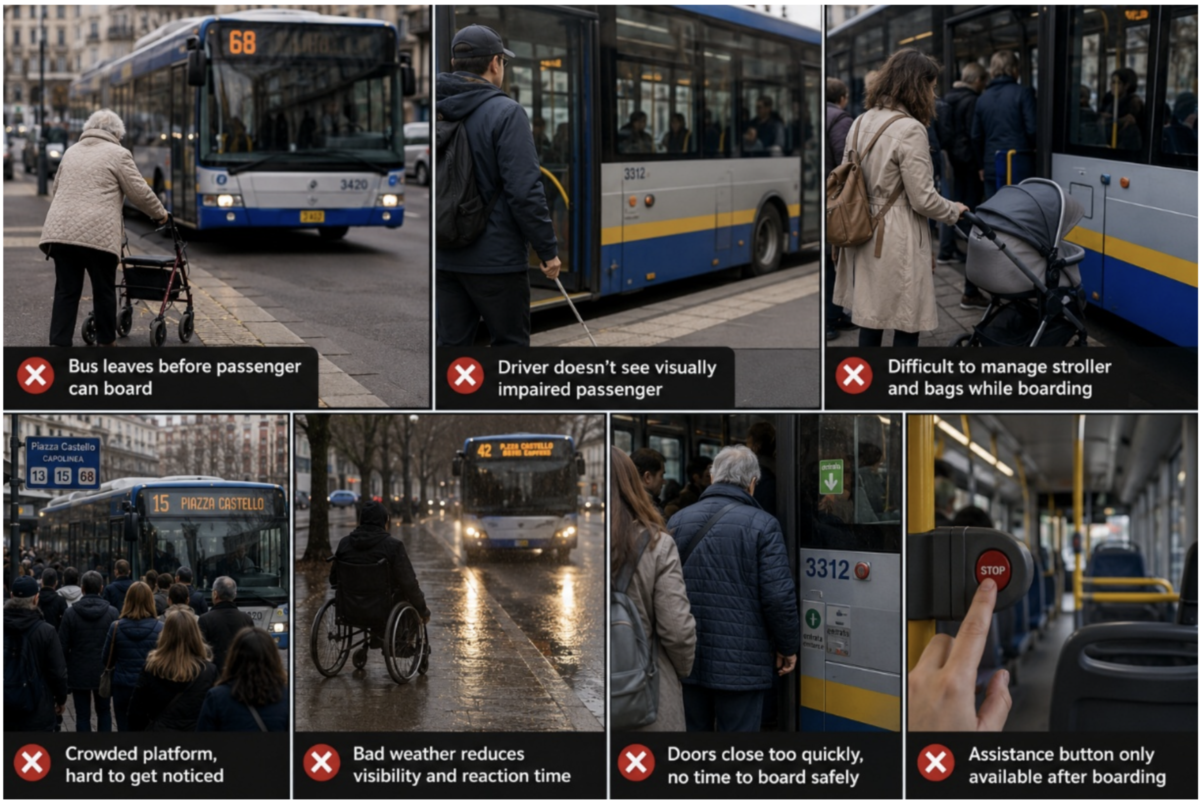

Figure 1.1: Collage showing key accessibility challenges in Turin's bus system, including missed buses, limited driver visibility, crowded boarding, and lack of pre-boarding communication for vulnerable passengers.

1.2 Limitations of Current Interventions

Currently, the challenge of accessible boarding is primarily addressed through vehicle hardware, such as low-floor designs, manual ramps, and priority spaces. However, these physical measures are only effective if the passenger has already reached the bus doors during the brief window they remain open, rendering the hardware useless if the driver is unaware of the passenger's presence.

Furthermore, bus stop infrastructure is largely limited to static or visual information, lacking audio guidance for the visually impaired and tactile confirmation for those who cannot rely on sight. Consequently, passengers are forced to depend on fragile, informal social negotiations, such as waving arms or shouting, which frequently fail in crowded, noisy, or poorly lit conditions. As a result, the current system systematically disadvantages the exact users who most need reliable support.

1.3 The SmartStop Concept

To address this critical gap, this thesis presents *SmartStop*, a smart, inclusive bus-stop system developed to create a direct, real-time communication channel between passengers with reduced mobility and bus drivers. The solution relies on a two-node IoT architecture: a touchscreen kiosk at the bus stop allows passengers to easily signal their intention to board, which then triggers a visual and bilingual audio alert on a dedicated display inside the approaching bus. By providing a guaranteed pre-boarding request mechanism, *SmartStop* aims to eliminate the anxiety of the "invisible passenger" and make inclusive mobility a realistic operational standard.

1.4 The Use of Co-Design in Assistive Technology

A central pillar in the development of inclusive infrastructure is the shift from designing for vulnerable user segments to designing with them. This paradigm, widely known as co-design or participatory design, posits that the end-users of a product, service, or system should actively participate in the development process as expert partners of their own experiences. As defined by Sanders and Stappers (2008), co-design fundamentally alters the traditional researcher-designer relationship by bringing the citizens who will ultimately use the technology directly into the creative and technical ideation phases [9]. In urban mobility and assistive systems, top-down engineering approaches frequently suffer from cognitive biases where developers project functional capabilities onto users, ignoring subtle physical, sensory, or psychological barriers.

The necessity of this approach is amplified when addressing users facing situational or permanent mobility limitations. By conducting iterative field research, structured interviews, and direct observations, the development lifecycle shifts from speculative design to evidence-based architecture. For *SmartStop*, this methodology was analyzed during the primary research phase in Turin, where direct engagement with elderly citizens using mobility aids and parents navigating with strollers exposed critical edge cases, such as crowding dynamics and short door-closing windows, that a purely laboratory, bound design would fail to anticipate (see Figure 1.2). Ultimately, co-design ensures that efficiency does not overcome dignity, yielding street infrastructure that is inherently intuitive, trusted, and operationally viable.

Figure 1.2: Field interviews and user research conducted in Turin, gathering direct operational feedback from elderly commuters with rollators, parents with strollers, and citizens with reduced mobility.

1.5 Scope of the Thesis

This thesis builds upon the *SmartStop* project, which was collaboratively developed by the Yellow Team during the Challenge@PoliTo "Inclusion By Technology" initiative. While the core problem definition, state-of-the-art review, and overarching system architecture were developed as a group, this manuscript focuses specifically on my individual contributions to the project's validation and academic consolidation.

To ground this work within the broader engineering framework developed by the team, the members of the *Yellow Team* and their respective focus areas are outlined below, with a specific emphasis on my leadership and synthesis role:

- **Luca Audero (Personal Contribution):** Acted as the overall Team Leader, managing interdisciplinary coordination and project timelines. My core contribution centers on the academic synthesis, engineering logic framing, end-user validation strategy, and operator integration roadmap necessary to transition the laboratory prototype into a real-world deployable mobility service (continues in Section 1.6).

- **Abhishek Kumar:** Focused on management engineering, technical prototyping, cloud-managed enterprise IoT architecture design, and business modeling.

- **Arianna Bartocci:** Contributed from a physics engineering background, focusing on data verification and evaluating the baseline technical principles of the system.

- **Giovanni Susca:** Handled energy engineering analysis, business modeling, startup strategy formulation, and scaling frameworks.

- **Bahareh Najmi:** Provided architectural and spatial design expertise, focusing on user behavior tracking and physical prototype integration testing.
- **Mohammed Hafeez Shaik Dawood:** Contributed from an architectural perspective, developing the user-functionality narrative and evaluating human interaction with public transport spaces.
- **Shang Ying:** Focused on spatial architecture, on-site field observation workflows, user behavior mapping, and shelter integration design.

1.6 Personal Contribution to the Project

While the *SmartStop* system itself was the product of a collective, interdisciplinary effort by the seven members of the Yellow Team, my own role within the project was primarily one of coordination, communication, narrative construction, and field validation rather than hardware or software engineering. This chapter documents that contribution in detail.

1.6.1 Team Coordination and Communication

Over the four months of the Challenge, the team held mandatory weekly online meetings, alternating between Google Meet and Microsoft Teams depending on availability and the presence of external contacts. As team leader, I was responsible for organizing these sessions, setting the agenda, and following up on action items between meetings. Over the course of the project I sent more than 80 emails, coordinating internal task assignments, syncing with the two academic supervisors, and managing outreach to external stakeholders. This volume of communication reflects a role that was largely invisible in the final technical deliverable, but that was necessary to keep a seven-person, interdisciplinary team aligned on scope, deadlines, and deliverables throughout a project with no fixed daily structure.

In addition to the weekly online meetings, the team held three in-person checkpoints to present progress to the supervisors and discuss the direction of the project. For more than half of these sessions I was personally responsible for designing the presentation materials and for presenting them, drawing on prior experience with public speaking and presentation design to ensure the team's work was communicated clearly and persuasively to an academic audience unfamiliar with the day-to-day technical details.

1.6.2 Steering the Concept: From Smart Traffic Lights to SmartStop

The project did not begin as *SmartStop*. The team's original proposal centered on intelligent traffic lights capable of detecting pedestrians with reduced mobility and extending the crossing window accordingly. As discussions progressed, it became clear that this idea, while conceptually appealing, would require integration with the city's existing traffic management infrastructure, a complex, tightly regulated system largely outside the team's technical and institutional reach within the timeframe of the Challenge. Recognizing this constraint early was a turning point in the project: together with the team, I helped steer the concept away from traffic-light integration and toward the bus stop-to-vehicle communication problem that ultimately became *SmartStop*, a solution with a comparable social impact but a far more tractable technical scope for a student team operating without formal access to municipal infrastructure.

1.6.3 Managing a Mid-Project Team Change

The most intense friction points occurred in the first weeks of the project, when the team had generated many candidate ideas but struggled to converge on a concrete, buildable concept. This period required active mediation to move the group from open-ended brainstorming toward a committed direction. A second, unplanned challenge arose two to three weeks into the project, when the supervisors added a new member to the team. This member was initially passive and disconnected from the group's existing workflow, and integrating the new member constructively required deliberate effort on my part, checking in individually, assigning a concrete entry point into the project, and ensuring they were not sidelined by a team that had already begun to establish its own working rhythm. This member went on to become the person responsible for building the core software and hardware of the *SmartStop* prototype, an outcome that, in retrospect, validated the effort spent on that early integration.

1.6.4 Stakeholder Outreach

As part of the effort to move *SmartStop* beyond a purely academic exercise, I attempted to establish contact with Gruppo Torinese Trasporti (GTT) and other relevant public transport bodies, with the aim of gathering operational feedback and assessing the feasibility of a future pilot. Despite multiple attempts, these outreach efforts did not receive a response within the timeframe of the project. This outcome is itself documented in this thesis, in Section 4.3 and Section 5.2, as it directly informs the operator-integration roadmap and underscores a realistic constraint on near-term deployment: institutional engagement with a public operator takes longer than a single academic semester allows.

1.6.5 Field Research and User Interviews

I personally conducted the field interviews that underpin the user personas and edge cases discussed throughout this thesis, approaching elderly citizens using rollators, parents with strollers, and other individuals with reduced mobility at bus stops across Turin (see Figure 1.2). These interviews were not a formality: they surfaced concrete operational constraints, such as the short window during which bus doors remain open and the physical difficulty of interacting with a touchscreen while managing a mobility aid, that directly shaped the human-machine interface requirements described in Chapter 3 and the future development priorities described in Chapter 5.

1.6.6 Narrative Design of the Final Presentation

For the final presentation of the Challenge, I took ownership of structuring the material as a coherent narrative rather than a sequence of disconnected technical slides, a choice partly suggested by the supervisors during the in-person checkpoints. I defined the order in which the problem, the field research, the system architecture, and the feasibility analysis were presented, with the explicit goal of leading the audience from the lived experience of the "invisible passenger" toward the technical and economic case for *SmartStop*. This narrative structure is reflected in the organization of this thesis itself, which follows the same problem-to-solution progression established for the final Challenge presentation.

Throughout the following chapters, the pronoun "we" is used to describe the general conceptualization and architecture developed by the team, while "I" highlights the specific synthesis, validation strategies, and academic framing that represent my direct contribution.

2 State of the Art

2.1 The Accessibility Gap in Public Transport

Despite significant structural improvements in modern urban transit, such as low-floor buses and deployable ramps, passengers with reduced mobility (PRM) still encounter profound barriers. Recent data highlights the urgency of this issue: in Turin alone, there are over 214,000 citizens over the age of 65 and 43,000 individuals living with disabilities [1, 2]. Furthermore, two out of five individuals over the age of 75 live alone, increasing their reliance on accessible public transit for independence [3].

However, physical infrastructure is only effective if passengers can successfully interact with the vehicle. The lack of a reliable pre-boarding communication channel frequently leaves vulnerable users stranded. This systemic failure has been widely documented in local news: incidents range from wheelchair users stranded at stops because ramps were not deployed [4], to visually impaired commuters being repeatedly bypassed [5], and disabled passengers being trapped by double-parked cars or rushed boarding procedures [6, 7]. The Regional Administrative Court (TAR) recently condemned the city as "negligent on disability mobility rights," underscoring that the "invisible passenger" condition is a structural flaw rather than an isolated anomaly [8].

As part of the primary user research phase, on-site interviews were conducted across key transit nodes in Turin to map these daily friction points. User personas derived from this fieldwork, such as Grazia (an elderly woman using a rollator) and Elena (a parent managing a stroller), highlight how crowding, low visibility, and tight door-closing windows systematically compromise user safety and dignity (see Figure 1.2).

2.2 Academic Literature on IoT and Accessible Mobility

To address these gaps, recent academic literature has increasingly focused on the intersection of the Internet of Things (IoT) and inclusive urban design.

The physical and psychological barriers of public transport have been extensively mapped. Kourouthanassis et al. highlight the potential of "Smart Bus Stops" to act as interconnected public spaces, though many current iterations prioritize general passenger information over targeted accessibility interventions [10].

From a technical perspective, the deployment of IoT in transit infrastructure offers viable solutions for real-time passenger-to-driver communication. To ensure true universal access, researchers advocate for multimodal interfaces that combine physical, tactile, and digital inputs at the bus stop, ensuring that elderly and digitally excluded passengers can trigger driver alerts without relying on personal devices [11].

2.3 Market Solutions and Their Limitations

Several commercial products and digital platforms attempt to address transit accessibility, though most fall short of solving the pre-boarding communication gap:

- **Digital Wayfinding and Apps:** Platforms like *Moovit*, *NaviLens*, and *Wayfindr* provide excellent real-time arrival data and audio-based spatial navigation for visually impaired users. However, they are entirely passenger-facing and smartphone-dependent, failing to alert the driver that a passenger requires extra boarding time.

- **Smart Infrastructure:** Solutions like London's "Countdown" screens, Singapore's PIDS, and Barcelona's *BusPas* smart shelters provide highly advanced passenger flow analytics and visual arrival data. Yet, they lack a dedicated, tactile assistance-request button linked directly to the approaching vehicle's dashboard.

- **Integrated Assistance Platforms:** Services like *INIT GmbH's ASSISTIVEtravel* allow registered users to pre-book assistance via an app. While powerful, this requires advance planning and digital literacy, excluding spontaneous travel and unregistered users.

2.4 Review of Relevant Patents

The intellectual property landscape reveals several attempts to bridge the passenger-driver communication gap. Patent [12] describes a general passenger notification system for approaching vehicles. Later innovations, such as [13] and [15], introduce intelligent digital request modules at the bus stop. The *SmartStop* architecture differentiates itself from this prior art by strictly combining low-cost open-source hardware, real-time bilingual audio-visual feedback, and a physical, zero-registration interface designed for immediate operational impact.

3 The SmartStop Concept and System Design

3.1 Redesigning the User Journey

The fundamental premise of the *SmartStop* solution is to transform the public transport boarding experience from a passive, anxiety-inducing event into an active, predictable, and two-way communication process. In the current operational baseline, the previously presented vulnerable passengers, such as Grazia (an elderly passenger using a rollator), Davide (a visually impaired commuter), and Elena (a parent managing a stroller), experience a condition of invisibility. Their user journey is characterised by uncertainty at the stop, an inability to communicate their presence to the approaching vehicle, and a rushed, unsafe boarding process.

SmartStop directly intercepts this communication gap by introducing a dedicated assistance-request mechanism before the bus arrives. When a passenger taps the physical interface at the kiosk, a clear intent is broadcast to the system. The passenger receives immediate reassurance via visual and audio feedback, placing them in a secure "two-way confirmation state". Consequently, when the bus arrives, the driver is already aware of the passenger's presence, eliminating the need for rushed boarding and restoring dignity and safety to the transport experience.

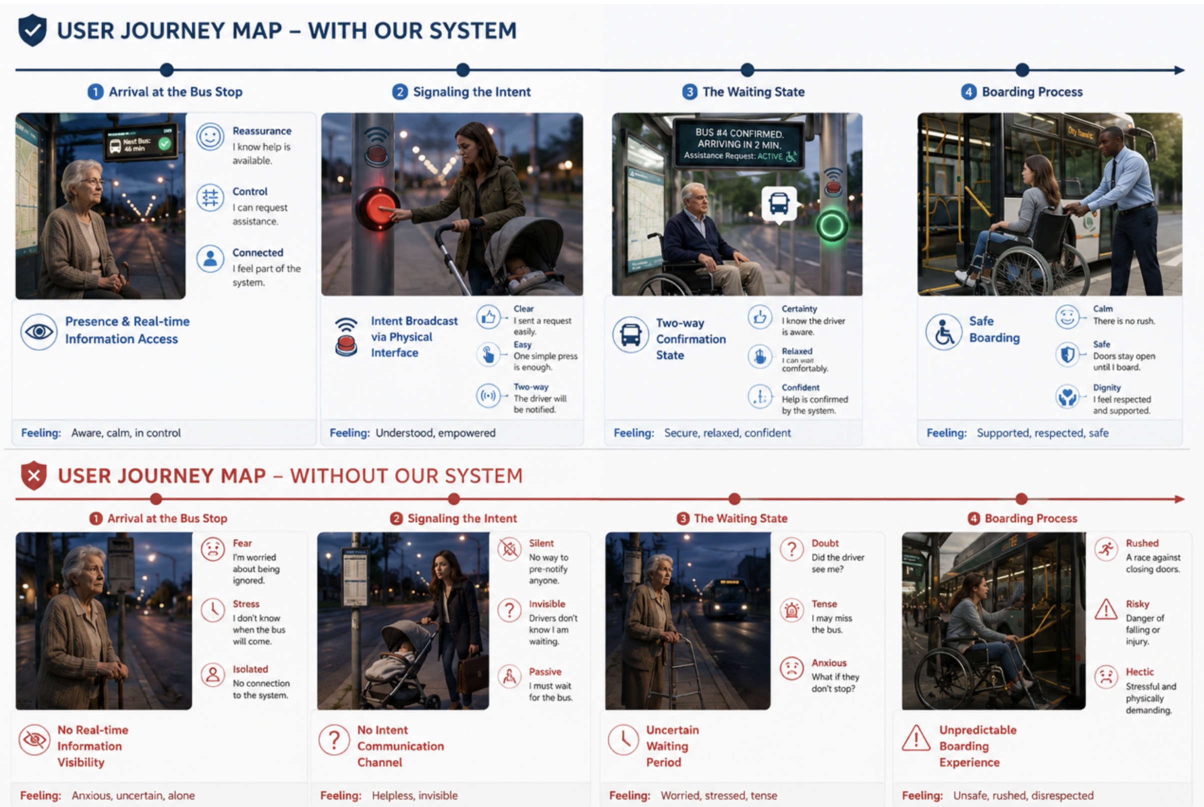

Figure 3.1: User journey map comparing the passenger experience with and without the SmartStop system.

3.1.1 Universal Design and the Two-Page Interface

To ensure the *SmartStop* kiosk provides value to the broader public and not solely to passengers with reduced mobility, the graphical user interface (GUI) was developed using a Universal Design approach. As shown in Figure 3.2, the default home screen functions as a general-purpose digital transit board. It prominently displays the approaching bus lines, the stop name, and the real-time expected arrivals, ensuring that all commuters, including students, tourists, and daily travelers, can benefit from the infrastructure.

To prevent accidental triggers and ensure a deliberate request process, the interface operates on a two-page logic. On the first page (that is visualized in Figure 3.2), the bus line and arrival time panels are purely informational and non-clickable. The only interactive element on this home screen is a large, highly visible "Tap here if you need assistance" button located at the bottom.

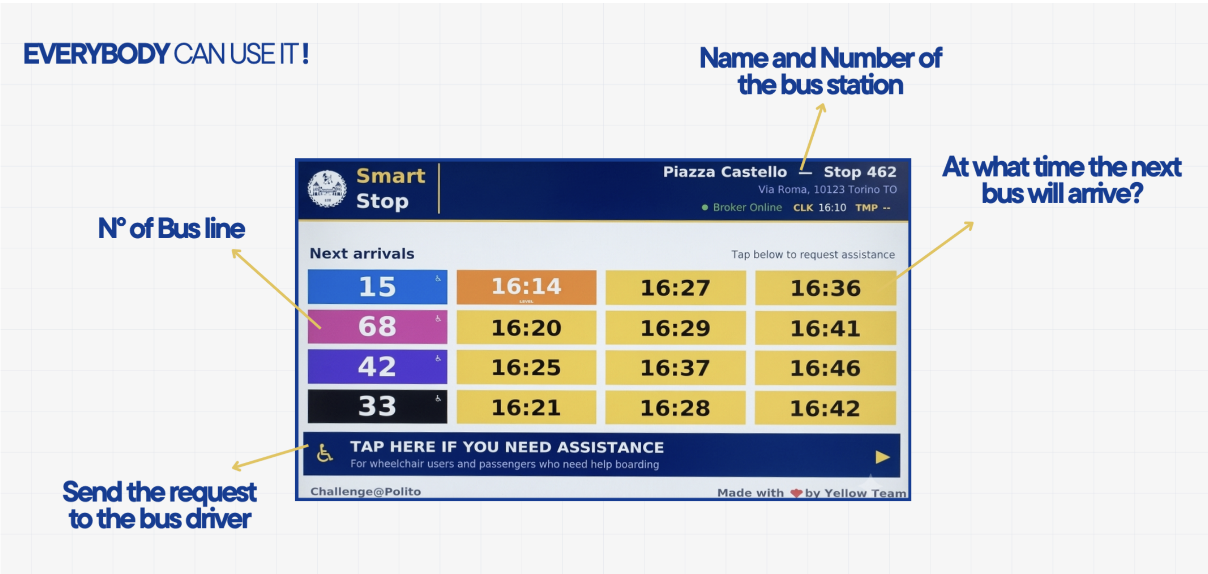

Figure 3.2: The default SmartStop home screen, displaying real-time bus arrivals for general public use, with the dedicated assistance request button located at the bottom.

Pressing this button transitions the user to the second page (that is visualized in Figure 3.3), which serves as the core assistive interface of the *SmartStop* system. It is only on this second page that passengers select their specific bus line to broadcast the actual assistance request to the approaching driver.

This two-tier workflow achieves two critical goals:

1. It drastically reduces the risk of "accidental tapping" by rushed commuters interacting with the arrival times on the main screen.
2. It effectively "sells the product" to municipalities as a universal smart-city amenity that serves the entire population, rather than a niche medical device, while fiercely preserving its dedicated core function for vulnerable passengers.

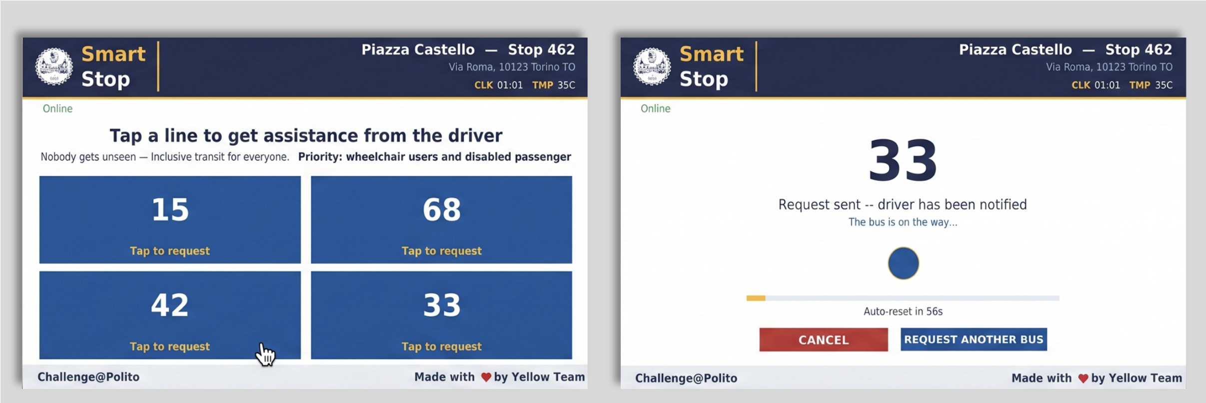

Figure 3.3: SmartStop touchscreen interface flow. Passengers can easily trigger an assistance request by selecting their approaching bus line (left), receiving immediate, clear confirmation that the vehicle's driver has been alerted (right).

3.2 System Architecture Overview

To achieve this real-time communication, *SmartStop* functions as an integrated Internet of Things (IoT) system operating on a local network architecture. The system is intentionally designed to be network-agnostic and relies on standard open-source components, ensuring scalability without vendor lock-in.

The architecture is built upon a two-node configuration:

- **The Stop Node (Stop Pi):** Installed at the bus stop infrastructure, acting as the passenger-facing interface and the message publisher.
- **The Vehicle Node (Bus Pi):** Installed on the dashboard of the approaching bus, acting as the driver-facing alert system and the message subscriber.

These two nodes communicate over a local network using the lightweight MQTT (Message Queuing Telemetry Transport) protocol, a standard widely adopted for low-bandwidth, high-latency IoT messaging [16]. To eliminate the need for hard-coded IP addresses, which are impractical in dynamic transit environments, both units utilise Avahi to implement mDNS (Multicast DNS) discovery [17]. This allows the nodes to locate each other automatically via hostnames (`smartstop-pi.local` and `smartbus-pi.local`).

3.3 Hardware and Software Components

The prototype developed to validate this architecture reached Technology Readiness Level (TRL) 3–4, successfully demonstrating end-to-end communication in a laboratory environment. The hardware was selected to balance cost-effectiveness with functional reliability.

3.3.1 The Stop Node Configuration

The bus stop kiosk is powered by a Raspberry Pi 4 Model B controller [19]. It features an official 7-inch Touchscreen Display with an 800x480 resolution [20], which runs a full-screen Tkinter software interface. This digital display presents live arrival times for configured routes (e.g., lines 15, 33, 42, 68) alongside a highly visible "Tap here if you need assistance" interactive area.

To ensure the interface remains accessible to users with visual impairments, the hardware configuration supports a Haptic Vibration Motor (connected via an optional HAPTIC PIN 12) to provide tactile confirmation when a request is successfully registered.

3.3.2 The Vehicle Node Configuration

Inside the bus, the driver alert system is powered by a secondary Raspberry Pi 4 (or 3B+). This unit is equipped with a 16x2 Character LCD Display driven by an HD44780 controller chip [21]. The screen communicates with the Pi via a PCF8574 I^2C Backpack Adapter, mapped to the I^2C address `0x3E` [22].

The display's backlight is managed by an integrated PCA9633 I^2C RGB LED Driver (address `0x62`), allowing the screen to dynamically change colours based on alert severity. Additionally, a USB Audio Device (mapped as ALSA card 1, device 0) is connected to an external speaker to provide bilingual (Italian and English) spoken alerts directly to the driver.

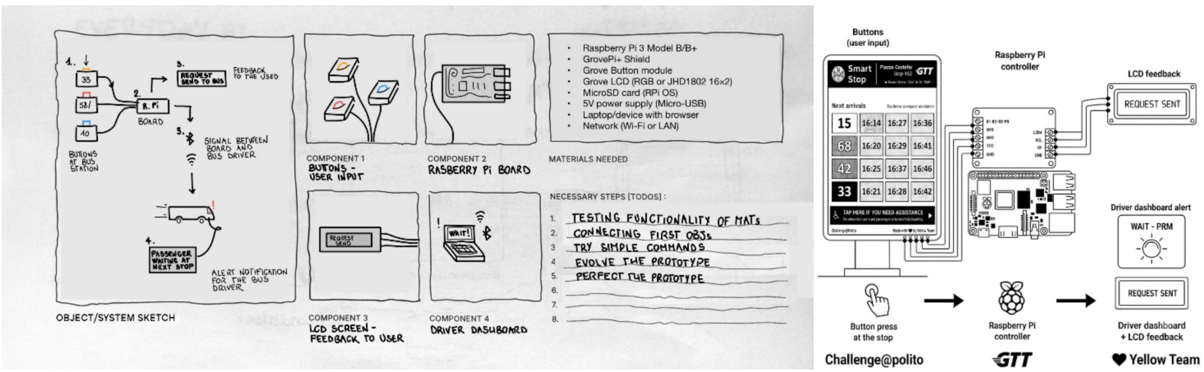

Figure 3.4: System sketch and prototype wiring connecting the stop-side touchscreen to the in-bus LCD driver display.

3.4 Communication Protocol and Logic

The core operational logic of *SmartStop* relies on a seamless publish-subscribe messaging model managed by an onboard Eclipse Mosquitto broker [18].

When an elderly or disabled passenger taps the assistance area for a specific incoming bus line, the Stop Pi publishes an MQTT message to the dedicated topic. The Bus Pi, actively subscribing to this topic, detects the incoming message and triggers a coordinated hardware response:

1. The 16x2 RGB LCD immediately turns red and displays the stop name and requested line.

2. The USB speaker broadcasts a bilingual audio announcement informing the driver that a passenger requires assistance at the approaching stop.

3. A software timer activates, keeping the visual and audio request active for a predefined 30-second window, giving the driver ample time to acknowledge it.

After the timer expires, or the bus services the stop, the in-vehicle display reverts to an idle yellow state ("Smart Stop Ready / Yellow team"), preparing the system for the next passenger request. To ensure maximum reliability, systemd services and watcher scripts are implemented to automatically restart the kiosk or display if network connectivity drops, ensuring continuous plug-and-play operation.

4 Prototyping, Validation, and Feasibility

4.1 Prototype Development and TRL Assessment

To validate the proposed architecture, a fully functional laboratory prototype was developed, bringing the *SmartStop* system to a Technology Readiness Level (TRL) of 3–4. According to the European Commission's Horizon 2020 TRL framework, this level indicates that the critical functions and proof-of-concept have been successfully established and validated in a laboratory environment [23].

The prototype successfully demonstrated end-to-end communication between the bus stop and the vehicle. The stop-side kiosk ran a stable Tkinter user interface on a Raspberry Pi 4, reliably capturing user input via the 7-inch touchscreen. Upon request, the system immediately transmitted MQTT messages to the vehicle-side Raspberry Pi, which correctly triggered the red visual alert on the 16x2 LCD screen and broadcasted the bilingual audio announcement. Furthermore, network-recovery watcher scripts were successfully tested, proving that the system could automatically reboot and reconnect if the local Wi-Fi connection temporarily dropped.

4.2 Cost Structure and Economic Feasibility

A core strength of the *SmartStop* architecture is its reliance on cost-effective, off-the-shelf components, allowing for highly scalable urban deployment. The economic feasibility of the project was analysed across two phases: the laboratory prototype and the production-ready infrastructure.

The hardware cost for the TRL 3–4 prototype totalled approximately €296. This included €185 for the Stop Pi components (Raspberry Pi 4 4GB, 7-inch touchscreen, and basic enclosure) and €111 for the Bus Pi components (Raspberry Pi 4 2GB, I^2C RGB LCD, USB speaker, and enclosure). Software costs were effectively reduced to zero by utilising an open-source stack.

To transition to a street-ready system, the hardware must be upgraded to withstand weather, vandalism, and automotive vibrations. The estimated cost for a production-ready, IP65-rated bus stop unit, featuring a 15-inch industrial touch display, physical braille buttons, a rugged single-board computer (SBC), an LTE modem, and a weatherproof enclosure, is €2,030 per stop. The upgraded in-vehicle unit, featuring a 5-inch rugged LCD and bus-grade speaker, is estimated at €600 per vehicle.

4.2.1 Deployment Scenarios

Based on these unit costs, a scalable deployment model was calculated for the City of Turin:

- **Pilot Phase (10 stops, 40 buses):** €20,300 for stop hardware, €24,000 for bus hardware, and approximately €60,000 for software and integration, totalling €110,000ca.
- **City Centre Scale (30 stops, 120 buses):** €190,000ca.
- **Full Network Rollout (80 stops, 300 buses):** €400,000ca.

SCENARIO	STOP	BUS	Hardware STATION	Hardware BUS	SOFTWARE	TOTAL 1yr
Pilot	10	40	€ 20.300	€ 24.000	€ 60.000	**~€ 110.000**
City center	30	120	€ 60.900	€ 72.000	€ 60.000	**~€ 190.000**
Full Scale	80	300	€ 162.400	€ 180.000	€ 60.000	**~€ 400.000**

Figure 4.1: Financial scaling projection model for SmartStop deployment across three operational phases (Pilot, City Center, and Full Scale), detailing hardware, software, and total first-year infrastructure costs.

4.3 Business Model and Funding Strategy

The *SmartStop* business model operates on a Business-to-Government (B2G) framework, targeting public transport operators (such as GTT in Turin) and municipal mobility departments.

Because the system specifically addresses the mobility rights of vulnerable citizens, its deployment aligns perfectly with existing public funding streams. The capital expenditures for pilot and city-wide scales can be heavily subsidised, covering up to 95% of project costs, by tapping into Italy's National Recovery and Resilience Plan (PNRR), specifically Mission 5, which focuses on social inclusion and infrastructure accessibility [24]. Additional financial support can be sourced from the national "Single Fund for Disability Inclusion" and the "Fund for Non-Self-Sufficiency".

4.4 SWOT Analysis

To evaluate the strategic viability of the *SmartStop* solution before advancing to field pilots, a comprehensive Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis was conducted [25].

Strengths:

- *Inclusive by Design:* Unlike competing applications (such as Moovit or NaviLens), *SmartStop* provides a physical, shared interface that does not require users to own a smartphone or possess digital literacy.
- *Direct Driver Communication:* It eliminates the reliance on fragile visual signalling from the curb by guaranteeing the driver is alerted before arrival.

- *Scalability:* The low unit cost and network-agnostic architecture allow for modular expansion across transport lines.

Weaknesses:

- *Dual-Node Dependency:* The system requires hardware installations on both the street infrastructure and the vehicle fleet to function.
- *Vandalism Risk:* Outdoor screens and physical buttons are exposed to urban wear and potential damage, requiring robust casing and ongoing maintenance.

Opportunities:

- *Funding Alignment:* High compatibility with PNRR and EU inclusion grants to fund initial deployments.
- *ITS Integration:* The MQTT-based system can be seamlessly integrated into existing Intelligent Transport Systems (ITS) to display live arrival times and vehicle occupancy.

Threats:

- *Vendor Lock-In:* Transit operators may face contractual barriers from existing massive ITS suppliers who resist integrating third-party open-source modules.
- *Driver Compliance:* The real-world impact relies on drivers actively responding to the alerts, requiring adequate training and operational enforcement to prevent the system from being ignored.

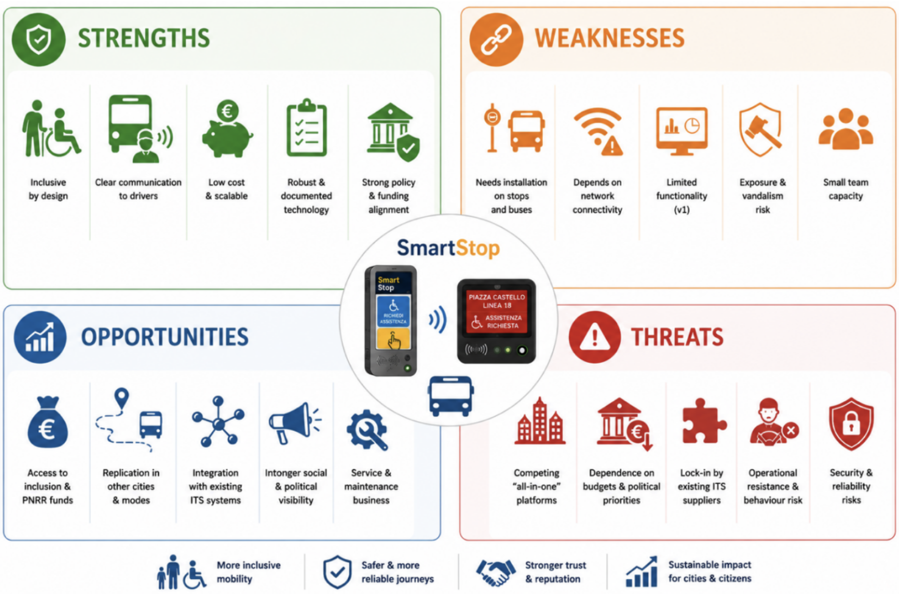

Figure 4.2: Visual SWOT analysis of SmartStop, summarising its key strengths, weaknesses, opportunities, and threats in supporting inclusive public transport.

5 Future Developments

5.1 Evolution of the Human-Machine Interface

While the *SmartStop* laboratory prototype successfully proved the feasibility of a pre-boarding communication channel, transitioning to a fully inclusive public infrastructure requires further evolution of the Human-Machine Interface (HMI). The current iteration utilizes a standard touchscreen kiosk, which must be upgraded for street-level deployment. Future versions will incorporate large, physical tactile buttons with Braille labelling, ensuring high contrast and universal accessibility.

To support visually impaired passengers and non-native speakers, the system must integrate advanced multilingual audio guidance. Additionally, implementing multisensory feedback mechanisms—such as haptic vibration and LED confirmation lights—will provide users with immediate, tangible reassurance that their assistance request has been successfully transmitted to the approaching vehicle.

5.2 Real-Time Integration and Back-Office Architecture

A critical next step is transitioning the system from a localized, standalone assistance tool into a fully integrated node within the city's intelligent transport network. Currently, the prototype operates via a local MQTT broker communicating over a localized network. For a city-scale rollout, the architecture must transition to secure mobile networks (4G/LTE) or connect directly to the operator's existing cloud infrastructure.

This cloud-managed architecture will allow *SmartStop* to pull live General Transit Feed Specification (GTFS-Realtime) data. Consequently, the kiosk could display dynamic information such as live arrival times, vehicle crowding levels, low-floor accessibility status, and real-time wheelchair space availability. Furthermore, a centralized back-office connection will enable transit operators like GTT to log requests, monitor performance statistics, and utilize data dashboards to strategically prioritize future accessibility investments.

5.3 Intermodal Expansion and Scalability

The *SmartStop* concept is highly adaptable and should not be restricted solely to urban bus networks. Future developments will explore expanding the architecture to trams, suburban shuttles, and specialized transport systems within hospital or university campuses. This expansion acknowledges that the pre-boarding communication gap affects a wide spectrum of users, including parents with strollers, travellers with heavy luggage, and individuals with temporary injuries (situational disabilities).

To achieve this, the project has outlined a scalable deployment model designed for the City of Turin:

- **Pilot Phase (10 stops):** Focused on priority locations such as hospitals, interchanges, and senior centres, requiring an estimated investment of € 110,000.
- **City Centre Rollout (30 stops):** Expanding to main urban corridors and high-demand areas, scaling the investment to approximately € 190,000.
- **Full Network Deployment (80+ stops):** A comprehensive, city-wide implementation estimated at € 400,000.

To transition from a functional pilot to a certified urban infrastructure product, future iterations will also necessitate industrial-grade, vandal-resistant enclosures, weatherproof screens, and strict cybersecurity compliance.

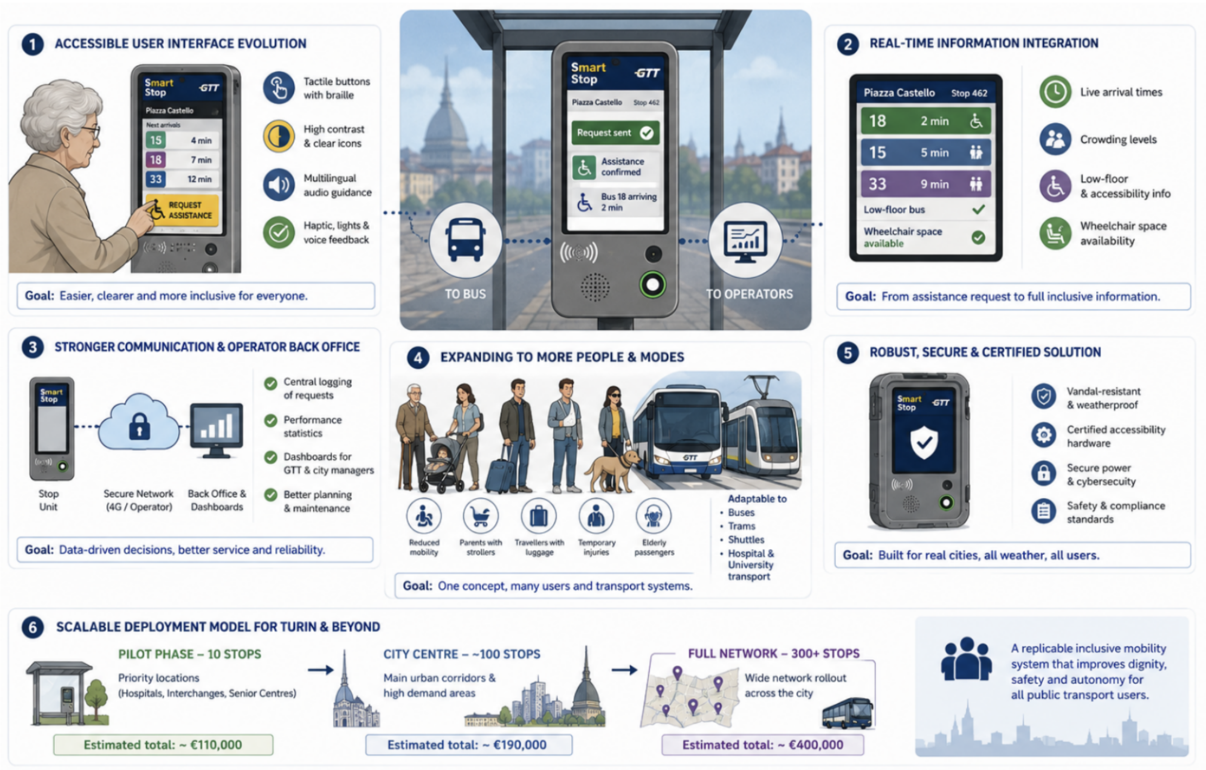

Figure 5.1: Overview of SmartStop's future development roadmap, highlighting improvements in accessibility, real-time integration, scalability, and wider deployment.

6 Conclusion

Modern public transport has improved in many structural ways, yet one gap remains largely unaddressed: there is still no reliable way for a passenger to tell a driver, before the bus arrives, that they need additional time or help to board. This is the condition described throughout this thesis as the "invisible passenger", and it is what *SmartStop* was built to fix. Rather than proposing another abstract concept, this thesis has tried to turn a documented, specific failure in Turin's transit system into something that actually works: a two-node prototype that gives passengers a way to be seen before the doors even open.

A mechanical ramp only helps once a passenger has already reached the bus. *SmartStop* moves the point of intervention earlier, letting a passenger with reduced mobility signal from the platform, with enough lead time for the driver to actually respond. The hardware works with a pair of Raspberry Pi units and open-source software matters as much as the concept itself: no smartphone, no app, no digital literacy required. Most competing solutions on the market quietly assume all of that, which is precisely why they tend to exclude the elderly and digitally under-served users who need them most.

The interviews conducted for this project, with wheelchair users, with parents managing strollers, with visually impaired commuters, did more than validate an existing design. They changed it. Details like the narrow window before bus doors close, or how awkward it is to operate a touchscreen while holding a mobility aid, are not the kind of thing a lab-only process tends to catch. That is the argument for co-design here: not as a checkbox, but as the only way this system ended up fitting the people it is meant to serve.

It is worth being honest about where this project actually stands. The prototype sits at TRL 3–4, which means it has been proven in a controlled setting, not on a real route with real weather, real crowding, and real network drops. The cost figures in Chapter 4 are first-order estimates, not a procurement-ready budget. And nothing in this thesis can answer, on its own, whether drivers will actually respond to the alert once it is in front of them, or whether the hardware will survive a Turin winter, or years of casual vandalism. Those are field questions, not lab questions.

What *SmartStop* is really trying to protect is something that does not show up in a TRL score: the dignity of not having to wave, shout, or hope someone notices you in time. The next step is not another iteration of the prototype, but getting it out of the lab entirely, in front of real users, disability advocacy groups, and an operator like GTT, on a real street. Only that kind of test can tell us whether "nobody left behind" is a slogan or something *SmartStop* can actually deliver.

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