SMART WHEELCHAIR SAFETY AND ACCESSIBILITY IN PUBLIC TRANSPORT: A DATA-DRIVEN EVALUATION OF DESIGN LIMITATIONS AND REAL-WORLD CHALLENGES

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CANDIDATE DECLARATION

I hereby declare that the dissertation entitled: **“Smart Wheelchair Safety and Accessibility in Public Transport: A Data-Driven Evaluation of Design Limitations and Real-World Challenges,”** submitted in partial fulfillment of MSc in Medical Device Technology & Business, is the result of my work and due acknowledgment is given. I also assure you that I have not plagiarized anyone else’s work.

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ABBREVIATIONS

Abbreviation	Full Form
AI	Artificial Intelligence
ALS	Amyotrophic Lateral Sclerosis
ANOVA	Analysis of Variance
BCI	Brain–Computer Interface
ECG	Electrocardiogram
EEG	Electroencephalogram
EU	European Union
GDPR	General Data Protection Regulation
GPS	Global Positioning System
HMI	Human–Machine Interface
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organization for Standardization
IWA	Irish Wheelchair Association
MI	Motor Imagery
MTA	Metropolitan Transportation Authority
PRM	Persons with Reduced Mobility
RGB-D	Red-Green-Blue plus Depth (imaging)
SPSS	Statistical Package for the Social Sciences

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ABSTRACT

The mobility of people with disabilities is increased and safety is enhanced when modern technology like self-navigation, obstacle avoidance sensors, or automatic brakes is incorporated into smart wheelchairs. Yet, despite such a raw deal, we continue to encounter accessibility problems with the Irish public transport system resulting from a lack of facilities, variable performance, and social attitudes. This mixed-methods study aims to provide evidence, from the identification of persistent environmental and design barriers present on buses, trams, and trains to the development of a broader sensor-audio alert system, and to determine whether this will improve safety for getting on board smart wheelchair technology.

The views of wheelchair users, carers, clinicians, and commuters were gathered through a cross-sectional survey ($n = 56$) that combined open-ended questions with Likert-scale measurements. Quantitative analysis revealed that 50% of respondents were uncertain about boarding without assistance (mean score = 2.41%), and the most frequent obstacles were platform gaps (44.6%), high ramp slopes (60.7%), and railing or door interference (53.6%). Sensor-based systems may increase safety, according to 69.6% of interviewees; they preferred spoken alerts (48.2%), auditory tones (46.4%), and visible signs (60.7%).

The thematic study revealed six recurrent needs: automation and hazard identification, experienced people support, improved stop-ramp alignment, routine maintenance, public awareness, and inclusive design. The suggested prototype, a modular ultrasonic/infrared sensor with configurable visual, audio, and vibration alerts, was well received for its potential to increase confidence and decrease incidents, even though participants emphasised the importance of affordability, dependability in bad weather, and customisable alert settings to avoid false alarms or stigma.

The results show that although smart wheelchairs promote safety, they cannot completely eradicate accessibility inequalities without further advancements in operational procedures, public perceptions, and transportation systems. Policy recommendations, operational instructions for transit providers, and design advice for wheelchair manufacturers are provided in this study to assist the safe, respectful, and inclusive mobility of wheelchair users in Ireland's public transit systems.

1. CHAPTER ONE: INTRODUCTION

1.1. Purpose of the Study

This research examines how smart wheelchairs with sensors, automated brakes, and navigation systems interact with actual transit situations while assessing their safety and use in Irish public transport ((Nguyen *et al.*, 2013; Leblong *et al.*, 2021). The study critically frames technology within its larger social and infrastructural context, guided by universal design principles that promote inclusively designed environments for all users, and the social model of disability, which places disability within environmental barriers rather than individual impairment (Digital Culture Network, 2024). By specifically combining these theoretical frameworks, concentrating on the little-studied Irish transit environment, and adopting a concurrent mixed-methods approach to record both quantitative indicators and qualitative experiences across stakeholder groups, this study is unique. By doing this, it goes beyond merely pointing out issues or outlining advances to examine how infrastructure, policy, and lived experience influence and are influenced by smart wheelchair technologies.

1.2. Context of the Study

Accessible In Ireland, accessible public transit is still only partially available, despite being crucial to wheelchair users' mobility and social inclusion. Many transit vehicles and stations still have issues like limited aisles and doors, steep boarding ramps, and wide platform gaps because they were built before the current accessibility rules (Mwaka *et al.*, 2024). A few Dublin buses, for instance, have aisle widths that are smaller than the 840 mm minimum required for wheelchairs. On older lines, cars can be as far away as 80 mm from train or tram platforms, compared to the EU's 50 mm maximum (IWA, 2020). Beyond the 50 mm platform-gap limit, accessible platform heights, reduced gaps, suitable door dimensions, passenger assistance, and tactile guiding are required in rolling stock and infrastructure under the EU's Persons with Reduced Mobility Technical Specifications for Interoperability (PRM TSI) (Wikipedia contributors, 2025d). Furthermore, by June 2025, all EU member states must have public transport services such as ticketing and check-in machines, digital information systems, and self-service interfaces that meet standardised accessibility requirements under the European Accessibility Act (EAA)(Wikipedia contributors, 2025b).

Wheelchair users are forced to execute unsafe boarding manoeuvres because of these physical restrictions, which raises the possibility of mishaps like chairs tipping over inclined ramps or wheels getting trapped in gaps. Uneven or makeshift ramps in rural regions frequently have gradients higher than the advised 5–6%, which can lead to further instability and even sensor issues for smart wheelchairs (Nichols, 2024; Smith S, 2024).

Despite their sophisticated features, smart wheelchairs still have significant problems in some real-world situations. Although autonomous control algorithms and sensor-based collision avoidance may reduce accidents in controlled trials, public transport environments are dynamic and unpredictable (Leblong *et al.*, 2021). There may not be enough space for movement on crowded trams or buses during rush hour, which raises the possibility of crashes or sensor interference. Infrastructure breakdowns, such as a broken lift or a power outage that necessitates unplanned replacement buses, can also cause boarding systems to become outdated in the middle of a trip (Stjernborg, 2019).

Controlled trials cannot replicate the uncertainties of the real world, which emphasises the need for assistive technology that can withstand quick changes, fluctuating demand patterns, and sporadic infrastructural reliability.

The recent incident on Dublin's Luas tram system in 2024, where a wheelchair with a sensor became stuck in a platform gap, shows that even the most advanced assistive technology cannot fix every infrastructure issue. Many employees of public transport lack disability-awareness training, which makes the situation more complex and leads to uneven assistance during boarding (National Disability Authority, 2020). Accessibility improvements also vary by region; for example, level boarding and low-floor cars have been introduced in urban transport systems, but some rural stops still lack basic facilities like elevated curbs or working lifts. These contextual factors emphasise that understanding accessibility issues fully requires an understanding of both wheelchair technologies and the transit environment (O’Donoghue, 2015; Lecrosnier *et al.*, 2020).

1.3. Significance and Justification of the Study

At the nexus of public infrastructure and assistive technology, this research offers two contributions. Practically speaking, it offers evidence-based suggestions for enhancing Irish public transport policy and design, emphasising the successful integration of smart wheelchair technologies with staff training, infrastructure upgrades, and legal frameworks. It addresses a significant research gap in academic knowledge by providing a mixed-methods, theory-informed (based on universal design and the social model of disability) assessment of smart wheelchair use in actual transit contexts, an area that has received little empirical research up to this point (Leaman and La, 2017; Gebresselassie, 2023)

Examining the reasons why technology alone hasn't eliminated accessibility obstacles is essential from both an academic and practical standpoint. The Irish Accessibility Act of 2019 and EU directives for inclusive transport are just two examples of the accessibility rules and guidelines that are not always followed on the ground. By the end of 2023, only roughly one-third of Ireland's suburban rail platforms had achieved the 50 mm limit gap, and most buses did not follow the advised ramp slopes. However, there hasn't been much research done on the specific effects of these infrastructural defects on smart wheelchair users (Frost *et al.*, 2015; Almoshaogeh *et al.*, 2025). Accordingly, few studies have routinely monitored the frequency of boarding failures under actual transit settings (Nguyen *et al.*, 2013; Ramaraj *et al.*, 2024). Similarly, there is no information on user characteristics like fear and confidence in similar circumstances (Poli and Malagas, 2024).

This research will fill these knowledge gaps and give information to guide policy and design changes. To address these issues and enhance users' safety in the real world, wheelchair manufacturers and transit authorities can work together with the help of these studies.

1.4. Research Aim, Questions, and Objectives

Aim of this research

The purpose of this study is to determine whether smart wheelchair technology effectively improves accessibility and safety in Irish public transport and whether it is enough to remove current obstacles on its own. It is hypothesised that without parallel organisational and infrastructure changes, smart wheelchair technology will not be able to adequately address accessibility and safety concerns.

To investigate this hypothesis, the research pursues the following objectives:

1) **Critically examine the key design and safety limitations** of smart wheelchair technology in the context of Ireland's buses, trams, and trains.
2) **Evaluate how infrastructural features** such as vehicle layouts, ramp gradients, Platform gap standards under PRM TSI, and ISO testing requirements (e.g., ISO 7176 series for stability and braking), interact with smart wheelchair performance and contribute to boarding failures.
3) **Assess the real-world efficacy of assistive features** like proximity sensors, automatic wheel-locks, and autonomous navigation systems when challenged by infrastructural and operational constraints.
4) **Investigate the perspectives** of wheelchair users, caregivers, transport staff, and accessibility professionals to understand how stakeholder experiences and feedback reveal alignment—or mismatch—with existing accessibility norms and system design (including PRM TSI, EU directives, ISO standards).
5) **Integrate quantitative data on boarding outcomes and incident frequency with qualitative stakeholder experiences** to propose holistic policy and design improvements that consider both technological innovation and environmental accessibility standards.

Primary Research Question:

To what extent do smart wheelchair technologies effectively enhance safety and accessibility in Irish public transportation, and what design or infrastructural factors influence their real-world performance?

Sub-Questions:

1. What are the key safety and usability challenges faced by smart wheelchair users when navigating buses, trams, and trains in Ireland?

2. How effective are current assistive technologies (e.g., sensors, wheel-locking systems, and autonomous navigation) in addressing real-world transport conditions such as ramps, platform gaps, and vehicle layouts?
3. How do users, transport staff, caregivers, and clinicians perceive the performance, reliability, and limitations of smart wheelchair systems during public transport boarding?
4. What practical design modifications or infrastructural improvements could be proposed to improve smart wheelchair integration and accessibility in Irish transit environments?

1.5. Overview of Dissertation Structure

This dissertation is organized into six chapters as follows:

- **Chapter 1: Introduction** – Introduces the research topic, outlines the study's purpose, context, significance, hypothesis, and objectives.
- **Chapter 2: Literature Review** – Examines scholarly and industry literature on wheelchair accessibility in public transport and smart wheelchair technologies. It highlights known barriers, technological capabilities and limitations, user experiences, and regulatory frameworks, thereby identifying gaps that the current study will address.
- **Chapter 3: Research Methodology** – Describes the research design and methods. This includes the mixed-methods approach adopted (combining quantitative and qualitative techniques), details of the survey instrument and data collection procedures, the participant sampling strategy, and ethical considerations (consent processes, anonymity, and compliance with relevant guidelines). It also outlines the analytic techniques used for interpreting both statistical data and qualitative responses.
- **Chapter 4: Results and Discussion** – Presents the findings of the study. Quantitative results (such as statistics on boarding outcomes and safety perceptions) are reported alongside qualitative insights (themes from open-ended responses). Together, these results illustrate the real-world performance of smart wheelchairs in Irish public transit and the nature of challenges encountered. This chapter also interprets and discusses the significance of the results in light of the research objectives and the literature from Chapter 2. It evaluates whether the findings support the initial hypothesis, explores implications for design and policy, and addresses any limitations of the study.

- **Chapter 5: Conclusion** – Summarizes the key findings and contributions of the research. It reiterates how the study’s objectives were met and provides recommendations for stakeholders (such as improvements in wheelchair design, transit infrastructure, and staff training). The conclusion reflects on the broader impacts of the research and suggests directions for future work toward safer, more accessible transportation. Chapters 2 through 6 maintain a clear **golden thread**—a consistent and logical progression from literature review through methods, results, discussion, and conclusion, that ties back directly to the study’s aims and research questions, ensuring coherence and purpose throughout

1.6. Conclusion

In conclusion, the groundwork for this inquiry has been laid out in Chapter One. It described the study's goal and the practical setting that renders this inquiry both relevant and essential. Given the identified research gaps, especially surrounding smart wheelchair access in real-world transit, a critical review of existing scholarship is required to anchor the investigation. Chapter Two, therefore, offers a systematic literature analysis, identifying key theories, methodologies, and deficiencies that justify and guide the empirical study that follows.

2. CHAPTER TWO: LITERATURE REVIEW

2.1. Empirical Studies

2..1.1. Public Transportation Accessibility Challenges for Wheelchair Users

People with disabilities still encounter obstacles when utilising public transportation, even in spite of legal requirements for accessible transit (Almoshaogeh *et al.*, 2025). A systematic review found that barriers can be classified into five main categories: inaccessible infrastructure (such as high gaps or narrow aisles), information and communication (such as poor signage or announcements), attitudinal (such as unfavourable attitudes of employees or passengers), economic (such as financial limitations), and safety/security issues (World Health Organization and World Bank, 2011). For example, many buses still have aisle widths of less than 840 mm (often 800 mm), making it difficult for wheelchair users to turn and align with ramps.

Due to their 80 mm gaps, older train platforms constitute a tipping hazard since they surpass the 50 mm restriction set by EN 14752:2020+A1 (Rail vehicle entrance systems) and PRM TSI (Commission Regulation (EU) No 1300/2014 Annex). When boarding, steep ramp slopes of more than 6% may result in instability or a sensor-triggered brake. These obstacles result in lengthier commutes, missed activities, and dangerous situations, which emphasise the need for assistive technologies that can make up for deficiencies in the infrastructure.

There is insufficient evidence to support the claim that sensor technologies, such as LiDAR and RGB-D camera systems, in smart wheelchairs can identify impediments and make up for design flaws. One promising method under controlled settings is automated inclination identification using point-cloud analysis (Nejati and Argall, 2016). Nevertheless, several field tests show that when surface deterioration, congested boarding zones, or irregular ramp designs add uncertainty, navigation errors continue (Johnson *et al.*, 2023). Recent empirical evidence unique to Ireland highlights that passengers continue to perceive accessibility as being poor: a study of 462 respondents revealed that wheelchair users gave Ireland's accessibility a much worse rating than the general public (mean score 7.83 out of 10, where 10 is the worst) (Pearlman, n.d.).

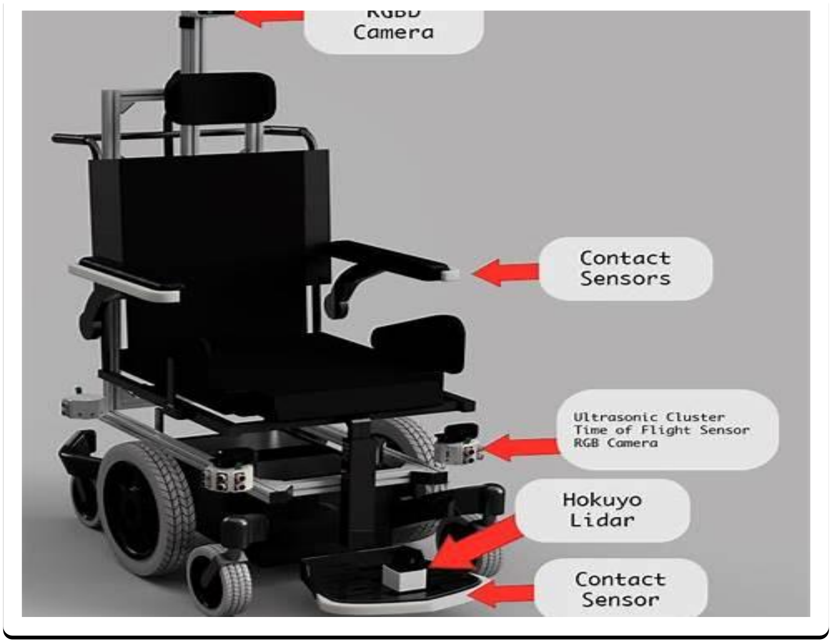


***Figure 1**: Smart wheelchair prototype with sensors (from Bingqing Zhang et al.)*

2.1.2. Boarding and Securement Innovations in Transit

Independent boarding and securement on buses and trains are among the most crucial areas of focus. Wheelchair attachment with conventional boarding frequently necessitates driver assistance and manual ramp deployment, which causes dependence and delays. One noteworthy innovation is the Quantum Self-Securement Station, an automated wheelchair restraint system that was piloted by the New York City Transportation Authority (MTA) in 2023. Without the assistance of a driver, a wheelchair user can use this device to back into a station and press a button to mechanically secure their chair in place (Metropolitan Transportation Authority, 2023).

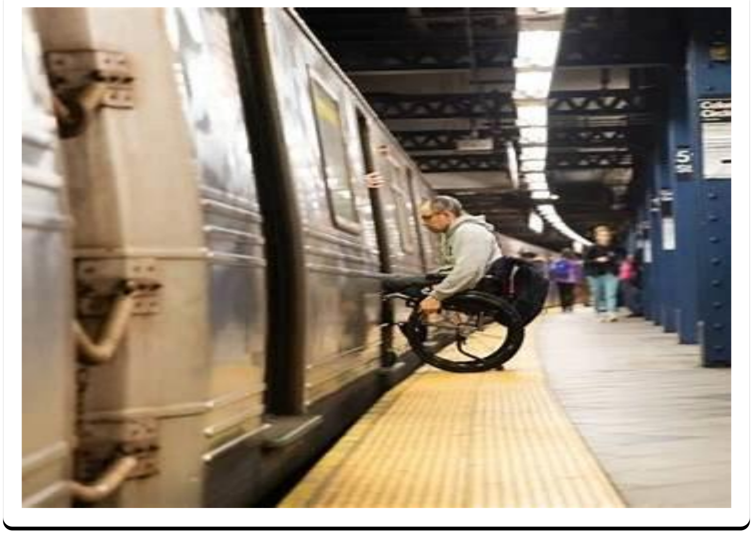


*Figure 2: Real-world example of platform-train gap (**By Jose Martinez, THE CITY**, October 26, 2022)*

On 10 buses, the MTA tested Quantum and found that it "allows customers to board and secure themselves more quickly and effortlessly, while requiring minimal to no assistance from the bus operator," promoting self-reliance among passengers. The disabled community is particularly concerned about autonomy, which is fostered by this technology in addition to expediting the boarding process, which benefits all passengers by guaranteeing punctuality (Martinez, 2022; Metropolitan Transportation Authority, 2023). Robotic ramp sensors and automated lift controls are being investigated by researchers as potential retrofits for non-bus vehicles. To detect blockages in curb ramps or vehicle entry and swiftly alert authorities and transit users, for instance, a networked ramp sensor system would be recommended (Polenakis *et al.*, 2024)

Through real-time feedback on limited boarding sites, these cyber-physical solutions address the prevalent problem of wheelchair users being unable to find a usable ramp that is blocked by parked automobiles or other impediments. Wheelchair users can now request help or reroute dynamically thanks to this (Polenakis *et al.*, 2024). Overall, studies show that the safety and dignity of wheelchair users as they board can be significantly improved by integrating sensors and automation into transit systems.

2.1.3. IoT-Enabled Wheelchairs and Remote Monitoring

Smart wheelchairs with Internet of Things (IoT) capabilities are evolving from stand-alone mobility aids to networked systems that can monitor a user's health, safety, and mobility. For real-time monitoring, remote control, and data analysis, IoT features fundamentally enable wheelchairs to send sensor data to cloud platforms, such as web dashboards or mobile applications (Cui *et al.*, 2022). This increased connectedness is particularly important for vulnerable groups, including the elderly or people with complicated medical conditions, when environmental awareness and health supervision are equally important.

The utilisation of these technologies is demonstrated by recent advancements. Using a Wi-Fi microcontroller, the IoT-enabled wheelchair system outlined by Cui *et al.* connects to cloud-based systems. Temperature, obstacle proximity using LiDAR, GPS-based tracking, and other multimodal environmental and positional data are collected by the system, enabling users and carers to remotely assess conditions. This is similar to a prototype reported by Hou *et al.* that uses onboard sensors to monitor and communicate vital health signs to doctors, such as oxygen saturation and heart rate. This prototype also incorporates AI-assisted navigation to improve autonomous mobility, including path planning and obstacle recognition (Hou *et al.*, 2024).

Although the applications' capability appears promising, a critical analysis exposes some limits and contextual dependencies. High data needs, privacy issues, and possible system failures raise questions about dependability in practical situations, particularly in public infrastructure that might not provide seamless connectivity. Strong ethical frameworks for consent, security, and access are also necessary because of the constant streaming of user data. Hou et al. (2024) admit that telemonitoring and AI together do boost independence, but they also need the socio-technical ecosystem, which consists of transportation networks, policy regulation, and carers, to be able to support these technologies.

To sum up, IoT integration has a lot of promise to improve the operation of smart wheelchairs. However, in addition to technical viability, these systems' use, accessibility, and reliability in the public transportation and hospital environments in which they are implemented are also critical to their efficacy.

2.1.4. Advanced Wheelchair Control Interfaces (BCI, Voice, and Multimodal)

Multimodal control interfaces, which combine techniques such as EEG-based brain–computer interfaces (BCI), eye blink, gesture, head motion, and voice input, are being investigated more and more in smart wheelchair research for users who are unable to operate a conventional joystick (Cui *et al.*, 2025). Using eye blinks and mental commands through a consumer headset, Sarkar *et al.*, 2025 showed a low-cost EEG-based BCI that is enhanced with ultrasonic collision sensors and a smoke detector for added safety. Four input options voice, head-tilt via IMU, eye-blink via infrared, and manual joystick—are included in another prototype by Thakur *et al.*, 2018, enabling users to switch between control techniques according to context or ability. Another modality is provided by gesture recognition systems that make use of sensors such as PAJ7620. According to research, combining several inputs such as EEG, head posture, and joystick fallback improves dependability and meets a range of user requirements (Cui *et al.*, 2025).

However, these systems also bring with them new difficulties. Furthermore, the tendency of BCIs to produce false positives, especially accidental blink detection, may compromise safety. For example, people with cognitive disabilities may not be able to use MI-based BCIs due to their 13–30% false positive rates and the requirement for extensive calibration and user training (Padfield *et al.*, 2022; Song *et al.*, 2022). Device fatigue and signal variability are additional difficulties. Prolonged mental tiredness impairs performance, and physiological changes (such as stress or sleepiness) drastically affect accuracy (Ozdenizci *et al.*, 2019).

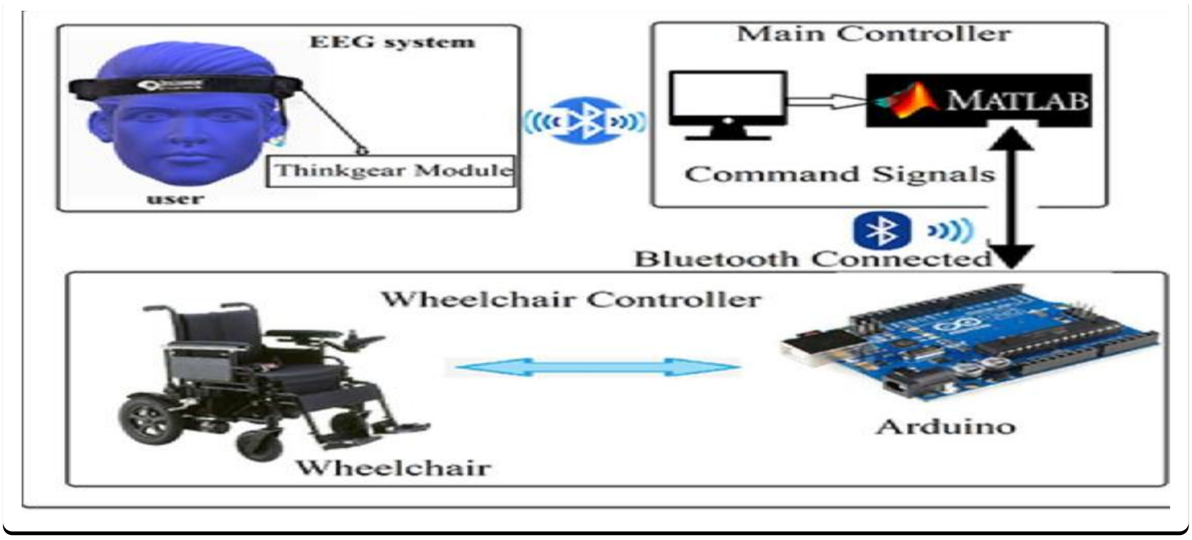


*Figure 3: Complete architecture of the system (?**EEG Based Smart Wheelchair For Disabled Persons Using Non-Invasive BCI**; Rao et al., 2022)*

For shared-control systems to effectively balance automated safety interventions with user intent, sophisticated sensor fusion algorithms are needed. However, this intricacy makes testing and dependability validation in natural environments more difficult (Menon, n.d.).

Figure 4: An intelligent wheelchair based on a BCI and an autonomous navigation system (Pan and Li, 2018)

Furthermore, the practical constraints are still little understood. Initial training may become inefficient and necessitate periodic recalibration in individuals with progressive illnesses (such as ALS) who suffer from long-term cognitive or motor impairment. When devices track brain signals or take control of human conduct, ethical questions about privacy, permission, and autonomy also arise.

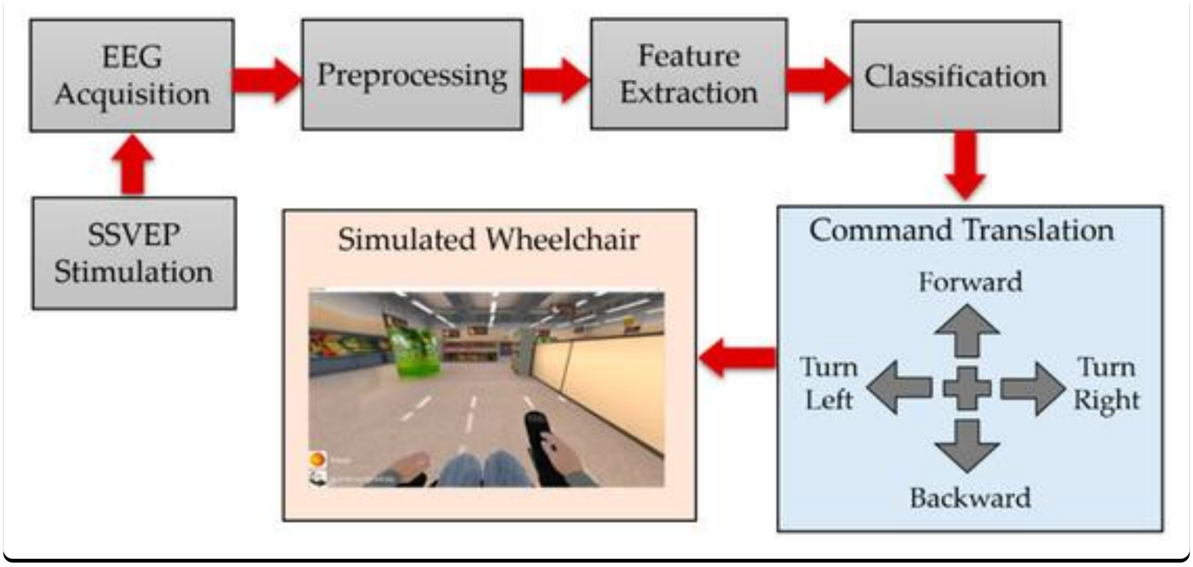


Figure 5: Proposed SSVEP-based BCI system using QR code visual stimulus pattern for simulated wheelchair control (Siribunyaphat and Punsawad, 2023)

Early models show that BCI-enhanced wheelchairs can empower people with severe physical disabilities, but until long-term usability, error recovery, and adaptability to changing capacities are addressed, these technologies will not be practical in real public transportation environments.

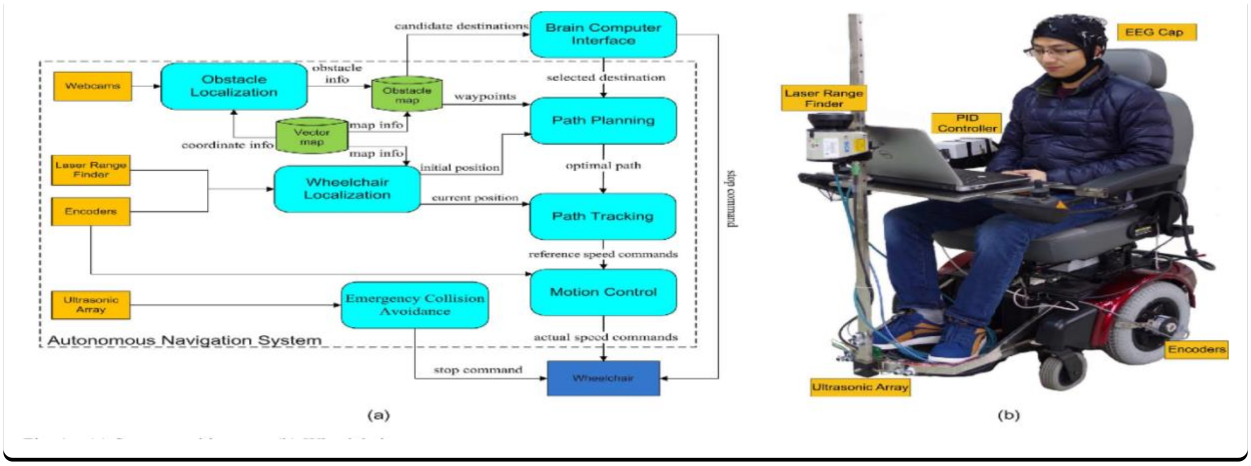


Figure 6: Brain-computer collaborative control intelligent wheelchair system (iFLYTEK, 2017)

2.1.5. Sensor Integration for Obstacle Detection and Avoidance

From basic ultrasonic arrays to sophisticated camera systems with SLAM capabilities, all smart wheelchairs employ a range of sensors to identify obstructions and avoid collisions. Ultrasonic sensors are frequently used as the first line of protection because they are dependable and reasonably priced at close range. For instance, to reduce the number of accidents in controlled experiments, Pokyse *et al.*, 2024 fitted a front-mounted ultrasonic module that turns off the motors and sounds a warning buzzer when impediments are within 20 cm.

Beyond this foundation, vision-based systems enable self-navigating in challenging environments by combining cameras with simultaneous localisation and mapping, or SLAM. Without requiring significant hardware changes like wheel encoders, Ramaraj et al. created a modular stereo-camera system in 2024 that mounts to common power wheelchairs and allows for real-time visual mapping and corridor navigation.

Sensor fusion technologies, which combine several sensory modalities, further improve safety. Grigioni *et al.*, 2024 utilised depth cameras from various angles to construct a combined aerial-ground obstacle recognition system that used a wheelchair and an aerial drone. This greatly increased the accuracy of risk detection at road crossings.

Additionally, negative impediments (such as stairs or curbs) are addressed via specialised sensor development (Favey *et al.*, 2021). A laser-based downward sensor uses optical triangulation to detect drops; it is fast enough to warn before a fall occurs and robust even in the presence of rain or sunlight. Although sensor integration has several safety advantages, there are still a number of real-world limitations.

In real-world scenarios, performance can deteriorate; for example, fog, rain, or intense sunshine might affect camera/laser precision (Ušinskis *et al.*, 2025). Because SLAM systems require a lot of processing power and battery life, they may limit the range of wheelchairs. Ultrasonic sensors may also produce false positives from reflective surfaces. Users could become frustrated by many false alarms, and complicated multi-sensor systems could be expensive or challenging for regular users to maintain.

All things considered, smart wheelchair sensing has surely advanced from low-cost, straightforward systems that instantly avoid crashes to complex sensor-fusion frameworks and negative-obstacle detectors. However, through user-centred evaluation and real-world application, research should also concentrate on environmental resilience, sensor reliability, energy efficiency, and user acceptance to translate these capabilities into dependable public transit environments.

Sensor Type	**Approximate Cost**	**Benefits**	**Limitations**	**Real-world Applicability (incl. Ireland)**
Ultrasonic	Low—budget-friendly	Reliable at close range, unaffected by lighting conditions	Limited range; prone to reflections, causing false positives	Works well indoors; outdoor use may generate alarms from rain or curved surfaces common at crowded Irish boarding points.
Infrared	Low to moderate	Effective in low-light or foggy conditions	Short range, less accurate; dust or fog can impair detection.	It may help during minimal visibility (e.g. Dublin’s rainy conditions), but the limited coverage area remains a concern.
LiDAR / Depth Cameras	Moderate to high	High precision, wide field-of-view, effective mapping.	Expensive; performance degrades in rain, fog, and glare.	Useful in well-weathered environments; struggles in Ireland's variable rain and fog—needs fusion support for reliability.
SLAM Vision Systems	High—hardware + processing	Dense mapping and corridor navigation (e.g., stereo-	Power- and compute-intensive; sensitive to weather-induced visual noise.	Offers autonomy indoors or dry stations; outdoors, performance may suffer on Dublin’s foggy mornings.

		camera SLAM)		
Sensor Fusion (e.g., depth + drone)	High—complex setup	Layered obstacle detection improves recognition accuracy	Cost, complexity, and maintenance limit feasibility	Potential in controlled environments; impractical for public transit field deployment in Ireland.
Radar SLAM	Moderate to high	Reliable SLAM in poor weather, robust tracking	More experimental in wheelchair applications; integration complexity remains	Promising for adverse weather typical in Ireland—a potential solution for fog and rain resilience.

Table 1: Comparison of Obstacle-Detecting Sensors in Smart Wheelchair Systems

2.1.6. Shared Control and Semi-Autonomous Navigation

While completely autonomous wheelchairs are still mostly restricted to controlled laboratory settings, shared control offers a quicker and more useful solution that lets users maintain their agency while receiving intelligent support. This paradigm strikes a compromise between automatic safety actions and human intention rather than completely giving up control. The CoNav Chair, a shared-control wheelchair powered by ROS that was tested indoors and showed better navigational efficiency than manual or completely autonomous modes, was introduced by Xu *et al.*, 2025. While the system managed low-level path planning and obstacle avoidance, users could set high-level goals, improving performance without compromising trust.

Similarly, in difficult circumstances, users can switch between manual control and system support with a modular retrofit kit created by Ramaraj *et al.*, 2024 that adds assisted and autonomous modes to standard powered chairs. These systems always have override capabilities, which allow users to stop autonomy by manually steering or by using voice commands. Crucially, shared control systems have been shown to reduce anxiety and build confidence among users—especially during training or in challenging environments. One study described shared control as increasing both safety and user comfort in structured training contexts (Smith *et al.*, 2019)**.**

Technically, shared control usually depends on command blending and sensor fusion, which mix obstacle-avoidance vectors and user input statistically. By using eye contact or patterns on the joystick, some controllers may even deduce intention and selectively interfere when a collision is about to occur. These benefits do have some real-world drawbacks, though: the required onboard computing may result in reaction latency, necessitate more expensive hardware, and use more power, which shortens battery life. Furthermore, it is not easy to tune the system for reliability; too harsh interventions can damage trust, while too lax ones are unable to stop problems.

Research demonstrates that while shared control increases safety without significantly affecting user pleasure, its effectiveness depends on low-latency performance, strong fail-safe behaviour, and the careful balancing act between autonomy and control. Although Xu et al.'s finding that "integrated designs promoting trust and autonomy are crucial for acceptance" is accurate, industrialising these systems would necessitate resolving these experiential and technical issues before they can be successfully implemented in dynamic public transportation situations.

2.1.7. Integrated Health and Safety Monitoring Systems

In order to transform from mobility aids to mobile health platforms, wheelchair systems are progressively incorporating biometric and environmental monitoring. These devices frequently take vital signs like heart rate, blood pressure, temperature, and oxygen saturation in order to provide remote monitoring and safety responses (Cui *et al.*, 2022; Hou *et al.*, 2024). A wheelchair prototype, for example, continuously uploads biometric data to the cloud (Hou et al., 2024). Then, when critical signs vary from permissible bounds, real-time analytics can set off alarms to be delivered to users or doctors. Users with significant levels of reliance or chronic conditions should pay special attention to this feature.

These systems are frequently topped with additional safety sensors. A BCI-controlled wheelchair was improved by Sarkar et al. (2025) with fall-detection algorithms activated by pressure or inertial sensors and smoke/gas alarms that can instantaneously alert carers to danger. A system that can detect arrhythmias using ECG, oxygen monitoring, and GPS-based emergency warnings was further developed by Alam and Mohanty (2023), indicating a move towards integrated clinical control during transportation (Alam and Mohanty, 2023; Meligy *et al.*, 2024).

But before these health-conscious technologies can be applied in practical situations, a number of issues must be resolved. Wireless data transmission and continuous sensing require a significant amount of battery power, even though ACE compression can significantly limit operational range; sensor connectivity may be responsible for up to 80% of energy usage (Hou et al., 2024). Additionally, false alarms—like incorrect fall detections or unexpected vital spikes—occur frequently in remote patient monitoring systems, which can cause alert fatigue for emergency services or carers (Arora *et al.*, 2023). ISO 14971 treats false alarms as potential safety hazards that must be included in risk analysis. Manufacturers must assess their severity and probability, implement effective risk controls, and evaluate residual risk to ensure safety thresholds are not exceeded (Medical Device HQ, 2024). Wheelchairs that are made available to the general public pose special privacy and security risks since unencrypted or improperly regulated private health data, such as GPS position or ECG readings, might be misused (Hireche *et al.*, 2022; Sun *et al.*, 2024).

Edge computing enables critical wheelchair safety functions such as obstacle detection and emergency braking—to run locally, ensuring reliability even on buses with flaky internet. This strategy mitigates latency and bandwidth issues and aligns with accepted IoT design for real-time, safety-critical applications (Wikipedia contributors, 2025a)

Systems that require regular firmware upgrades, recalibration, or clinical supervision may be burdensome for users and carers, which would decrease their practical usefulness from a usability perspective. Additionally, there may be problems with user acceptance and healthcare compliance, particularly if technologies are seen as unreliable or obtrusive.

In summary, although smart-wheelchair health monitoring has a lot of potential to increase independence and safety, especially for vulnerable groups, successful adoption necessitates striking a balance between technological innovation and power management, data accuracy, privacy protections, and user-friendly interfaces. To make sure that health-conscious wheelchair systems are useful, reliable, and sustainable outside of lab settings, future research should thoroughly assess these limitations, ideally through field testing in transit settings.

2.1.8. Future Directions and Emerging Trends

Implementing edge-only retrofit modules, which provide emergency braking, regulated alarms, and obstacle recognition, is now the most feasible investment. These localised devices provide quick, dependable performance even in crowded urban transportation environments or in rural locations with spotty internet connectivity because they don't rely on the cloud. The ideas of edge computing show how processing data near its source significantly lowers latency, improves responsiveness, and protects privacy. These modules can improve safety without the need for expensive vehicle changes or network upgrades, and they are compliant with Ireland's present regulatory framework, which includes the PRM TSI and the European Accessibility Act (Wikipedia contributors, 2025d; Wikipedia contributors, 2025b)**.**

In addition to chair-side improvements, Ireland can use data-driven insights to test vote-based infrastructure improvements. Platforms at important tram or train stops, where boarding issues are most common, could be given priority for platform-train interface improvements, such as gap reduction and ramp realignment. In addition to human assistance, this makes a significant contribution to accessibility enhancements. Implementing on-vehicle edge gateways provides further benefits by managing telemetry during interrupted service and buffering notifications (such as "wheelchair waiting"). This hybrid approach is consistent with edge orchestration approaches and reflects successful patterns in intelligent transport systems (Hamdan *et al.*, 2020).

While promising, future ideas like V2X communication, in which wheelchairs may communicate with adapted ramps or smart crossings, remain experimental in Irish situations (Hossan *et al.*, 2025). Widespread standards and urban planning are needed to create infrastructure that can react to assistive devices, which is currently not feasible. Similarly, adding full autonomy or AI-heavy processing to the chair (such as NVIDIA Jetson-level embedded AI) could enhance detection and braking capabilities, but the high-power requirements, expense, and verification load make it unlikely to be implemented in public transportation environments anytime soon (Yee, 2023; Grigioni *et al.*, 2024).

It's crucial to distinguish between innovation that is viable and hype. Even while innovative concepts like drone-assisted navigation or driverless wheelchair taxis draw interest, they need pilot testbeds, continuous funding, privacy frameworks, and standard harmonisation before they can be scaled. Achievable measures that increase user safety and confidence include focusing on functioning retrofit safety modules, upgrading certain PTIs, and coordinating edge gateways (Bennett and Vijaygopal, 2024; Yousfi *et al.*, 2025). Additionally, these actions gradually prepare the ecology for increasingly sophisticated technologies.

Rather than waiting for theoretical breakthroughs, Ireland can expedite inclusion by concentrating on short-term, tested improvements that increase boarding dependability and user dignity right away. A laddered strategy strikes a balance between ambition and pragmatism, beginning with edge add-ons and progressing through intelligent infrastructure pilot projects and connected-city integration. By ensuring that wheelchair technology developments stay rooted in the reality of public transportation surroundings and user trust, this gradual evolution provides both immediate benefit and strategic development.

Technology / Trend	**Hype Claims**	**Feasibility in Ireland**	**Key Constraints**
Edge-only safety modules	Instantly safe, low-cost innovation.	**High** – Proven latency reduction and reliability; easily retrofit onto existing wheelchairs.	Requires standard user testing, battery capacity checks, and user training to avoid over-alerting or power drain.
On-bus edge gateways / alerts	Smart, connected vehicles everywhere.	**Medium-high** – Tech exists (MQTT, MEC patterns); aligns with local infrastructure improvement.	Needs investment in transit IT infrastructure, driver training, and data governance to prevent misuse.
Platform-Train Interface upgrades	Effortless universal boarding.	**High–PRM** TSI already mandates improvements; scope for targeted implementation.	Requires capital investment, accessibility audits, and coordinating agencies for rollout and evaluation.
V2X / Infrastructure communication	Fully automated boarding via	**Low-medium** – Conceptually compelling; pilotable in hubs	Requires urban-wide infrastructure upgrades, standards alignment, and

	smart surroundings.	(e.g., Dublin Docklands).	funding beyond transit budgets.
Autonomous, AI-heavy chair systems	Total independence in all conditions.	**Low** – Promising in research (edge AI), but high energy, cost, and complexity. Not viable for current fleet scale.	High cost, intensive testing/validation, battery and heat constraints, and regulatory hurdles hinder practical deployment.
Drone-assisted navigation, swarm RT	Utterly safe, futuristic mobility.	**Very low** – Experimental and far from infrastructure reality in Ireland.	Regulatory, airspace, privacy, coverage, and cost barriers remain substantial.

Table 2: Critical Comparison of Smart Wheelchair Technologies—Hype vs. Feasibility in the Irish Context

2.2. Theories and models

This section outlines theoretical frameworks that guide smart wheelchair design and evaluation: the social model of disability, the capability approach, inclusive design, HMI/shared control, and medical-device risk standards.

Social Model of Disability & Capability Approach

The social model emphasises design and governmental responsibility by presenting disability as the result of social and environmental constraints rather than personal impairment (Oliver, n.d.). The capacity approach highlights genuine freedoms, such as autonomous travel, as essential to wellbeing and is based on Sen and Nussbaum's research (Mitra, 2006; Layton *et al.*, 2022). In theory, these paradigms drive policies and goals, but in reality, smart wheelchair designs tend to prioritise sensor improvements (such as IoT obstacle detection) above infrastructure redesign or choice-enabling. In Chapter 2.1, for example, the talks of IoT-based health and obstacle monitoring systems demonstrate innovation, but they fall short of improving actual capabilities or removing structural hurdles to accessibility.

Inclusive Design and Universal Access

Considering the entire range of human diversity, inclusive design theories promote products that are usable by a variety of people from the start (Inclusive Design Research Centre) (Wikipedia contributors, 2025c). Despite the many attempts to incorporate multi-modal feedback or retrofit modules for wide applicability in smart wheelchair development, there is still a dearth of true user co-design. Consequently, even while inclusive design goals seem good in theory, they are rarely implemented well (Mwaka *et al.*, 2024). New designs hardly ever incorporate user variety beyond physical disabilities.

Human–Machine Interaction & Shared Control

HMI models advocate for interfaces that improve user safety and confidence by supporting shared autonomy and different input modalities. A good example of this is the CoNav Chair, which combines shared-control algorithms to improve navigation efficiency while maintaining user confidence (Xu *et al.*, 2025). Experimental findings clearly align theory with empirical results, with shared-control outperforming manual and fully autonomous modes in terms of minimizing crashes and improving trajectory smoothness.

Medical Device Risk Management

Throughout a device's lifecycle, systematic safety assurance is required by standards such as ISO 14971 (risk management) and IEC 62366 (usability engineering) (Kim *et al.*, 2023; Nichols, 2024). However, such rigorous methodologies are not usually documented by actual smart wheelchair prototypes and research, indicating a lag between theoretical requirements and practical implementation.

2.3. Literature GAP

Research on smart wheelchairs has progressed in controlled settings, but there is still a large lack of field-based, public transportation studies. Usability and boarding obstacles, like short aisles and platform gap problems, have been shown in numerous studies to exist in fixed-route transit systems (Lim and D’Souza, 2021). However, in Ireland's transit context, where ageing railway infrastructure, congested metros, rural buses, and seasonal weather all interact, longitudinal, real-world data on system performance is still lacking.

The inconsistent application of accessibility guidelines is another neglected topic. While safe boarding circumstances (e.g., ≤ 50 mm platform gaps, ≤ 6% ramp slopes) are required by European laws like PRM TSI and EN 14752, audits show inconsistent non-compliance across areas (Lim and D'Souza, 2021; Unsworth *et al.*, 2021). Transit operators lack proof on the effectiveness of smart wheelchair systems in both legally compliant and non-compliant environments due to the lack of systematic monitoring.

The dearth of user-centred studies on acceptance, autonomy, and trust in transportation environments represents another significant gap. Few studies examine how real-world failures, delays, or overrides impact user confidence in buses, trams, or rail stations, despite the potential of lab-based shared-control systems. Adoption may be hampered by the discrepancy between high expectations and irregular on-board realities.

Furthermore, there is no analysis of whether a gadget complies with medical device standards like ISO 14971:2019 + ISO/TR 24971:2020 and IEC 62366-1:2015 + Amd 1:2020 once it has been integrated into an existing wheelchair (International Electrotechnical Commission, 2020). How smart wheelchair systems are maintained, updated, and risk-reassessed after daily use, which is all crucial for ongoing safety and legal compliance, is not well understood.

Lastly, there are still a few findings unique to Ireland. However, user interviews and passenger audits are carried out in nearby locations, such as the UK (Velho, 2019). There isn't a published mixed-methods study that links wheelchair boarding incidents to Irish public services infrastructure compliance. In academic literature, the opinions of important stakeholders, wheelchair users, caretakers and clinicians are rarely heard. Ethnographic fieldwork, user interviews, and system audits that are contextualised within Irish regulatory environments are necessary to close these gaps. Prioritising design enhancements and policy enforcement for truly inclusive transit systems can only be achieved by producing empirical facts.

Objective	Literature Gap Addressed
Objective 1: Design & Safety Limitations	Lack of real-world performance data in Ireland

Objective 2: Incident Frequency & Types	No longitudinal data on boarding incidents in real-world environments
Objective 3: Effectiveness of Assistive Features	Missing comparative data between compliant and non-compliant infrastructure
Objective 4: Infrastructure & Design Recommendations	No infrastructure-specific audits informing improvements
Objective 5: Stakeholder Perspectives	Absence of user trust and confidence data under real-world conditions

Table 3: Mapping to Chapter 1 Objectives

3. CHAPTER THREE: METHODOLOGY & DATA COLLECTION

3.1. Introduction

The approach for assessing the usability of smart wheelchairs on Irish public transport is explained in this chapter, utilising Saunders et al.'s (2019) Research Onion, which organises research from philosophy to methodologies. The discussion now explains each layer, philosophy, approach, strategy, and methods, in the framework of the study's objectives rather than providing a sneak peek. Combining a practical mixed-methods framework, stakeholder-informed sensor-alert design, and ethical considerations fosters both rich narrative insight and statistical rigour. Because of this, methodological decisions are guaranteed to be transparent, consistent, and based on an accepted academic framework.

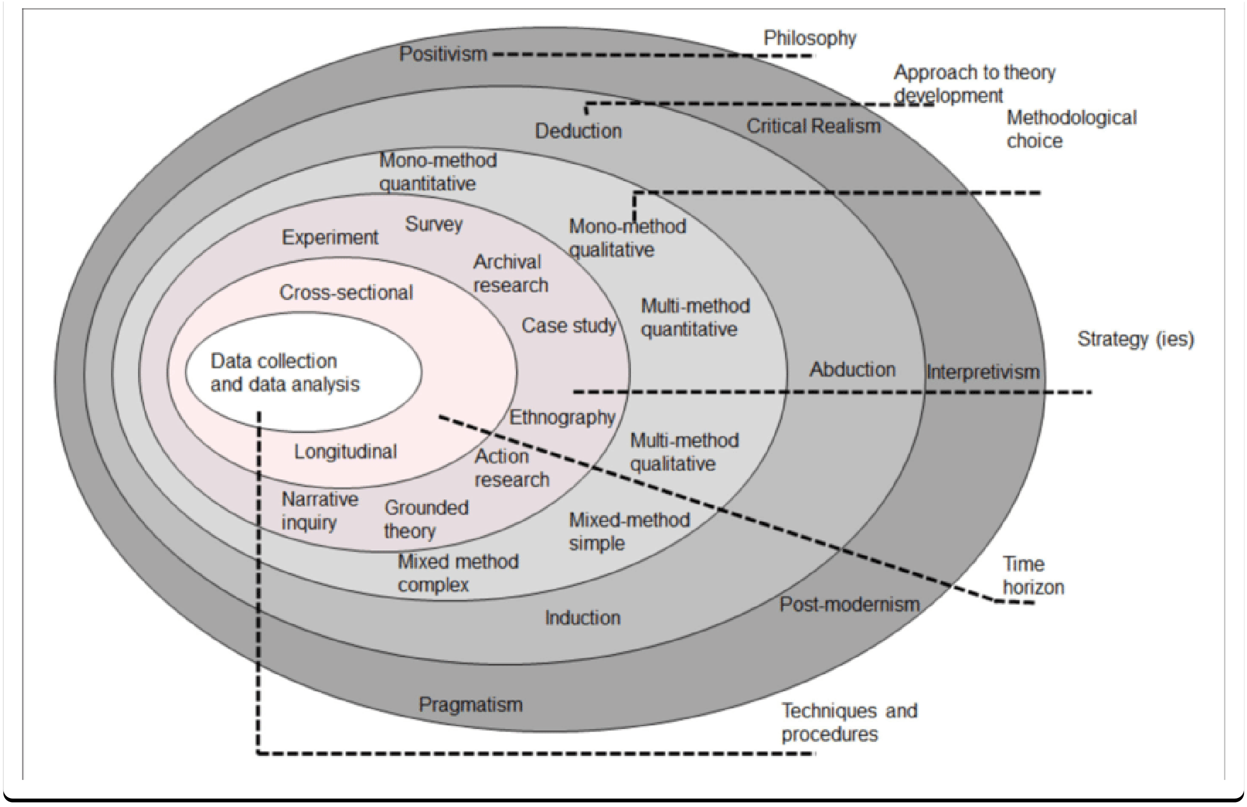


Figure 7: Research onion (Saunders et al., 2019, p. 108)

3.2. Research Philosophy

A pragmatic research philosophy (Gillespie *et al.*, 2024) was chosen for this study because it is adaptable and in line with difficult, real-world problems. In contrast to positivism, which is restricted to objective measurement, or interpretivism, which is exclusively concerned with subjective meaning, pragmatics permits the mix of quantitative and qualitative methods as necessary (Evans *et al.*, 2011). The pragmatic approach promotes suitable mixed-method decisions catered to each research issue by giving precedence to workable solutions over theoretical loyalty. Based on the idea of "what works" for research, this strategy makes sure that technique choice promotes meaningful results rather than strict adherence (Brierley, 2017; Kaushik and Walsh, 2019).

3.3. Research Approach

Abductive reasoning is used in this study, which combines inductive theme identification from participant narratives with deductive testing of hypotheses (such as ramp slope or staff support affecting boarding safety). Abduction is particularly effective in mixed-methods research because it allows for iterative movement between theory and data, which makes it easier to generate and verify the best explanations for real-world observations, particularly those that are "surprising" or context-dependent. In complicated, mixed-methods research, abduction is especially useful since it allows for repeated reasoning between theory and data to explain unanticipated discoveries (Mitchell, 2018). Abduction provides dynamic refinement of hypotheses based on both statistical patterns and practical insights, providing richer, actionable understandings than merely inductive or deductive designs alone in accessibility research, since settings and user needs fluctuate greatly (Evans *et al.*, 2011).

3.4. Methodological Choice

This study uses a contemporaneous mixed-methods survey, integrating qualitative (open-ended responses) and quantitative (Likert scales, yes/no items) data into a single instrument. Mixed methods combine both paradigms to strengthen findings through triangulation, enhance interpretation, and reveal hidden intricacies, in contrast to mono-method designs, which restrict depth or breadth, and multi-methods, which combine numerous techniques within a single paradigm. This is especially helpful in accessibility research, as comprehending boarding patterns necessitates both personal context and statistical facts to produce workable, inclusive solutions (Wasti *et al.*, 2022).

3.5. Research Strategy

To gather real-time insights from wheelchair users, commuters, transport workers, and clinicians throughout Ireland, the project uses a cross-sectional, mixed-methods survey that is administered using Google Forms (with various formats available). While methodological triangulation, which combines quantitative patterns with qualitative narratives to validate results across perspectives, strengthens validity, pretesting the instrument, using expert reviews and cognitive interviews to improve question clarity and usability, supports reliability. By establishing replies in authentic circumstances, scenario-based enquiries improve construct validity. Cross-sectional designs provide a rich, representative snapshot of service experiences and prototype usability in the dynamic transportation context, although they restrict causal inference (Mathis and Gowran, 2023).

3.6. Time Horizon

A cross-sectional design offers speed, affordability, and breadth by capturing a picture of stakeholder experiences at a particular point in time. Although longitudinal studies make it possible to draw conclusions about trends and causality, they are less practical for this exploratory study due to their high time, resource, and participant attrition costs.

3.7. Data Collection

3.7.1. Instrument Design

The final survey instrument included 15 questions about demographics, incident experiences, perceived safety across modes of transportation, and wheelchair type. Likert-scale items (1–5 ratings), yes/no questions, and open-ended prompts were all incorporated into the design to gather in-depth descriptions and recommendations.

Example questions included:

- “How safe do you feel boarding buses, trains, and trams in your wheelchair?” (1–5 scale)
- “Have you encountered issues such as ramp misalignment, gaps, or lack of staff assistance?” (Yes/No)
- “Describe a boarding incident and what would have improved the experience.” (Open-ended)

The survey was accessible, using plain language, mobile-friendly formatting, and screen-reader compatibility. For those with limited internet access, responses could be given via phone or in paper form through collaborating organisations.

3.7.2. Participant Sampling and Recruitment

A **Purposive sampling** was used to gather perspectives from four stakeholder groups:

1. **Wheelchair Users** (powered, manual, or smart wheelchairs).
2. **Clinicians** (e.g., occupational therapists, physiotherapists) with experience supporting wheelchair users.
3. **Caregivers** assisting wheelchair users in daily mobility.
4. **General Commuters** with regular public transport use (≥1 trip/week).

This study targeted an **estimated sample size of 80 participants**, guided by usability research benchmarks: quantitative surveys typically benefit from at least 40 respondents for reliable pattern detection, while multi-stakeholder Delphi studies often target 60–80 individuals to ensure result replicability (Memon *et al.*, 2024).

Participants were asked, "How do you feel about adding a sensor to the wheelchair, and what type would you prefer?" as part of the survey to assess the modular sensor-alert prototype, noting both qualitative logic and quantitative preference indicators. Acceptability and user-centred feature preference are measured by this design without being isolated from the larger usability context.

Participants were recruited through multiple channels, including the Irish Wheelchair Association, the Disability Federation of Ireland, and Care Homes (to reach wheelchair users), and professional networks such as LinkedIn (for clinicians).

3.7.3. Data Analysis

NVivo with reflexive thematic analysis and SPSS (patterns, ANOVA, regression) were used in a hybrid quantitative–qualitative analysis. It was decided that inferential statistics on non-probability samples were acceptable as long as the limits were recognised and appropriate model-based techniques were applied to improve validity (Boyd *et al.*, 2023). By using independent coding with memoing to openly regulate researcher influence, reflexive coding, as outlined by Braun & Clarke (2006), was improved (Braun and Clarke, 2006). Through triangulation, richer, more coherent insights were obtained by enriching and validating quantitative patterns against thematic discoveries (Naeem *et al.*, 2023).

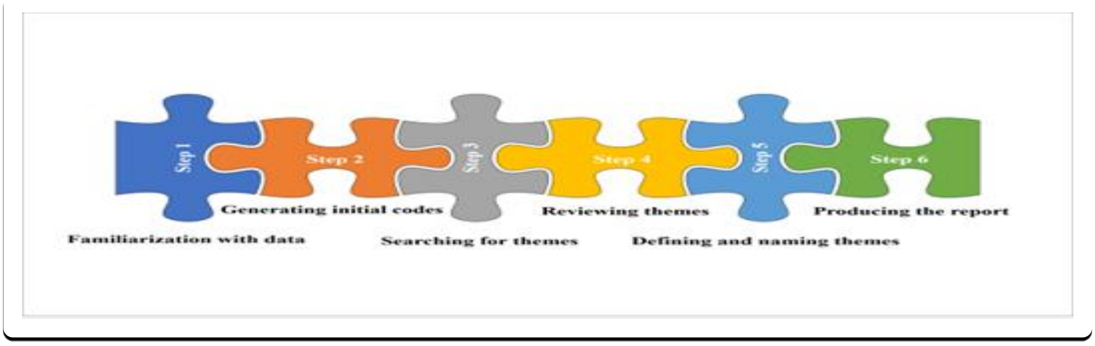


Figure 8: Braun & Clarke thematic analysis

3.7.4. Quantitative Analysis

Various statistical techniques were applied to the survey data using IBM SPSS version 29:

- **Descriptive statistics** were calculated (frequencies, means, and standard deviations) to summarise key variables.
- **One-way ANOVA** was used to compare average safety rating scores across different transport modes.
- **Chi-square tests** explored associations between wheelchairs and reported boarding issues.
- **Binary logistic regression** was applied to estimate the odds of experiencing a boarding incident, with predictors such as wheelchair type, region, ramp conditions, and the presence of staff assistance.

A significance level of $p < 0.05$ was used for all statistical tests. Given the study's non-random sample and cross-sectional design, any significant results were interpreted with caution.

4. CHAPTER FOUR: FINDINGS AND ANALYSIS

4.1. Sample Overview

This chapter summarises the findings of a mixed-methods assessment of the accessibility and safety of smart wheelchairs on Irish public transit. The poll was filled out by 56 people, including 10 wheelchair users, 7 professionals (such as physiotherapists and occupational therapists), 13 carers of wheelchair users, and 26 general commuters (those who utilise public transit). Notably, to concentrate on the viewpoints of users and observers, transport employees were purposefully excluded.

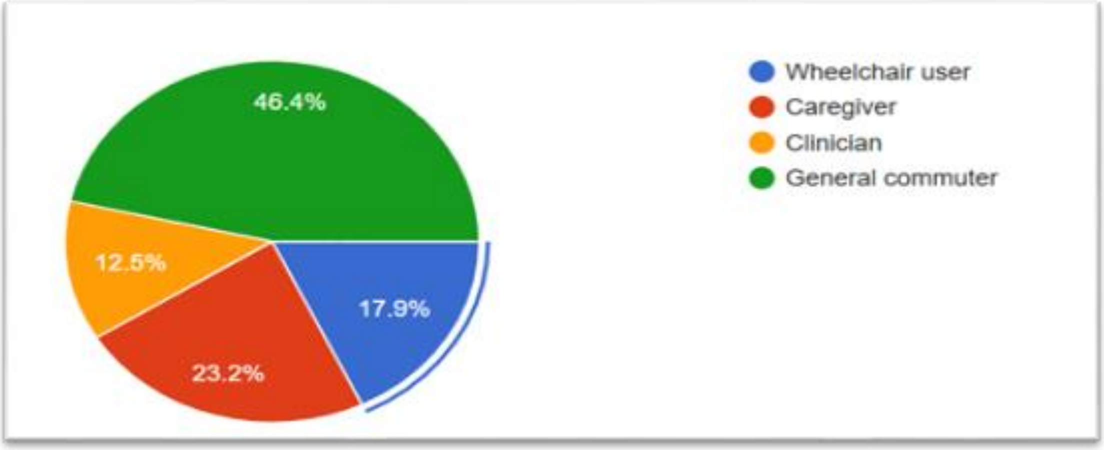


Figure 9: Stakeholders

Stakeholder group	%	n
General commuters	46.4	26
Caregivers	23.2	13
Wheelchair users	17.9	10
Clinicians	12.5	7

Table 3: Descriptive Results; Sample Composition (N = 56)

The obtained sample size is within acceptable ranges for exploratory analysis, while falling short of initial targets. The diversity of replies in survey research tends to stabilise as a sample size reaches about 30 respondents, resulting in declining returns from further data (Hague, 2021). The response variability curve flattens out after roughly 30 to 50 replies, as shown in Figure 10, suggesting that our sample size of 56 is probably adequate to capture the main trends even though it is relatively small. Due to the limitations of the study's duration and reach, as well as the usual difficulties in recruiting specialised demographics (such as wheelchair users and clinicians), the response rate was minimal. Every individual offered their explicit agreement to take part.

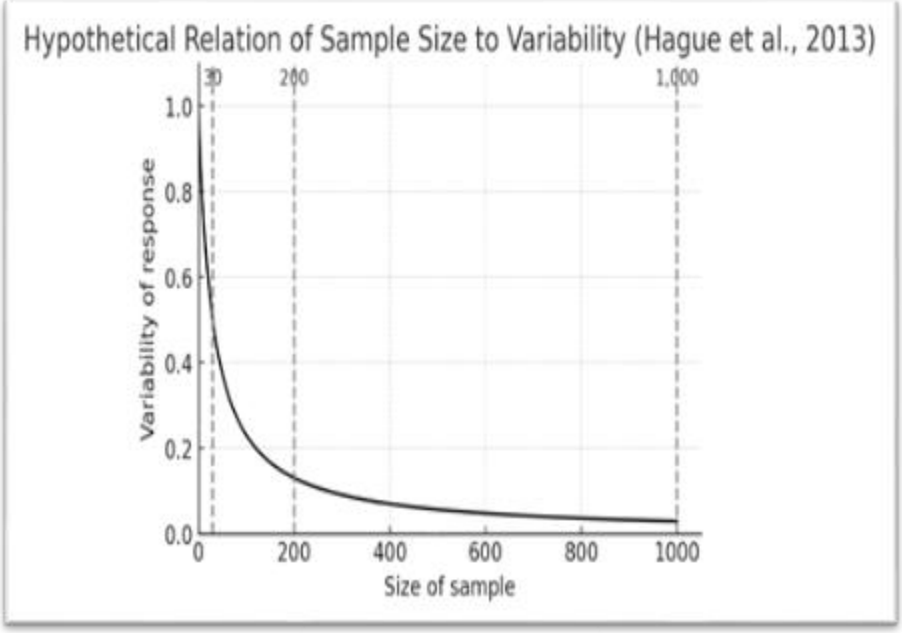


Figure 10: Conceptual relationship between sample size and response variability, adapted from Hague et al. (2013)

4.1.1.Frequency of Boarding Difficulties by Transport Mode

Respondents were asked how often they observe or experience difficulties when boarding or alighting with a wheelchair on various transport modes (bus, tram, train). Responses ranged from "Never" (1) to "Often" (4). The average frequency of reported boarding difficulties differed by transport mode. Participants who primarily relied on trams or trains reported difficulties almost “often” on average, whereas those using buses reported difficulties closer to “sometimes.”

Mode	%	n
Dublin Bus	78.6	44
Luas (tram)	60.7	34
Irish Rail	33.9	19
None	5.4	3

Table 4: Transport mode

Frequency	%	N
Daily	51.8	29
Weekly	39.3	22
Monthly	3.6	2
Rarely	5.4	3
Never	0.0	0

Table 5: Public Transport Use

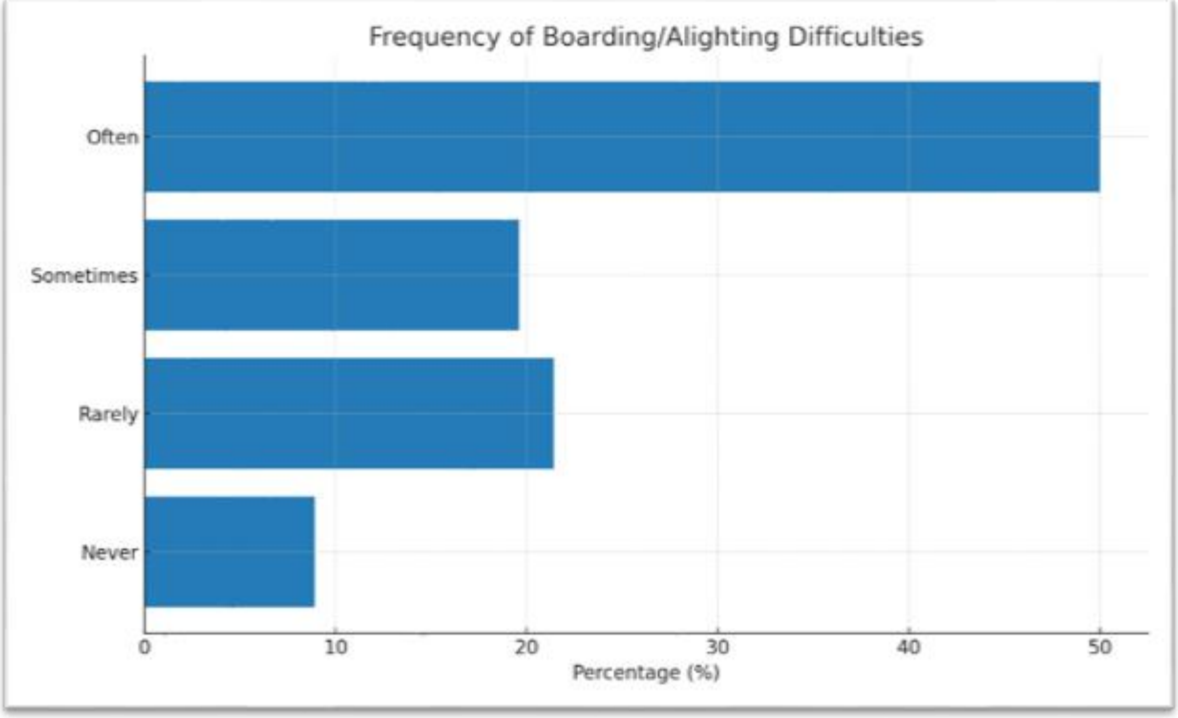


Figure 11: Frequency of Boarding Difficulties by Transport Mode

As shown in Figure 11, the mean difficulty rating for tram users was around 3.9 (between *Sometimes* and *Often*), and for train users it was 4.0 (approximately *Often*). In contrast, bus users reported a lower average difficulty of about 2.9 (between *Rarely* and *Sometimes*). This pattern suggests that boarding a tram or train tends to be more problematic for wheelchair users than boarding a bus, at least in the areas surveyed.

Primary Transport Mode	N (single-mode users)	Mean Difficulty Score*	Std. Deviation
Bus (Dublin Bus)	17	2.88 (≈ Sometimes)	0.99
Tram (Luas)	8	3.88 (≈ Often)	0.35
Train (Irish Rail)	2	4.00 (Often)	0.00

Table 6: Mean reported boarding difficulty by primary transport mode

To test the significance of these differences, a one-way ANOVA was conducted. The ANOVA confirmed that transport mode has a statistically significant effect on the frequency of difficulties, $F(2, 24) = 3.47$, $p = 0.047$. This indicates that the disparity in boarding experiences between buses, trams, and trains is unlikely due to chance. Specifically, the small number of respondents who predominantly use trains or trams tended to report difficulty almost every time they travel, whereas bus users reported difficulties somewhat less frequently on average.

Primary Transport Mode	N (single-mode users)	Mean Difficulty Score*	Std. Deviation
Bus (Dublin Bus)	17	2.88 (≈Sometimes)	0.99
Tram (Luas)	8	3.88 (≈Often)	0.35
Train (Irish Rail)	2	4.00 (Often)	0.00
ANOVA (mode effect)	**F (2, 24) = 3.47**	**p = 0.047**	–

Table 7: Analysis of Variance test (ANOVA Test)

However, when the same data were analysed using a chi-square test (treating the frequency categories as categorical rather than numeric scores), the difference between modes was not statistically significant ($\chi^2 = 5.55$, df = 6, $p = 0.136$). In other words, when looking at the proportion of respondents in each frequency category (Never/Rarely/Sometimes/Often) across modes, no clear association emerged.

Primary Mode	How often do you observe or experience difficulties when boarding or alighting with a wheelchair (e.g. gaps, steep ramps)?	Observed	Expected	Chi² Contribution
Bus	Never	2	1.36	0.301176
Bus	Often	8	10.2	0.47451
Bus	Rarely	6	4.08	0.903529
Bus	Sometimes	1	1.36	0.095294
Tram	Never	0	0.64	0.64
Tram	Often	7	4.8	1.008333
Tram	Rarely	0	1.92	1.92
Tram	Sometimes	1	0.64	0.2025

Table 8: Observed vs Expected Frequencies of Boarding Difficulties by Primary Mode of Transport

Test Statistic	Value
χ^2	5.55
Df	6
p-value	0.136
Significance	Not significant

Table 9: Chi-square Test Results for Boarding Difficulties by Mode of Transport

The difference between the ANOVA and chi-square results probably stems from how the data were handled: the chi-square was a more stringent test that looked for significant changes in categorical distributions, whereas the ANOVA, which used a numerical difficulty score, was sensitive to the trend that train and tram users tended towards the higher end of difficulty. It's possible that the chi-square lacked the power to identify a difference because there were only two people reporting train use, making the sample for train users tiny. However, the pattern points to more frequent troubles on trains and trams, which is consistent with anecdotal information that infrastructure problems, such as wider platform gaps and older vehicle designs, can present more difficulties on rail services.

Qualitative comments from the survey support this finding: for instance, one wheelchair user noted that "some train stops don't align well with ramps," leading to particularly difficult boarding. This quantitative pattern sets the stage for examining *why* these difficulties occur, which is addressed by looking at specific factors and qualitative insights later on.

4.1.2. Key Factors Contributing to Boarding Challenges

When asked about the factors that contribute most to wheelchair boarding problems, respondents could select multiple options (up to two). The most frequently cited issue was the steep ramp incline, selected by about 60.7% of respondents. This implies that a majority have encountered boarding ramps that are too steep, making it hard to push a wheelchair up or causing instability (especially in cases of higher-than-recommended ramp gradients).

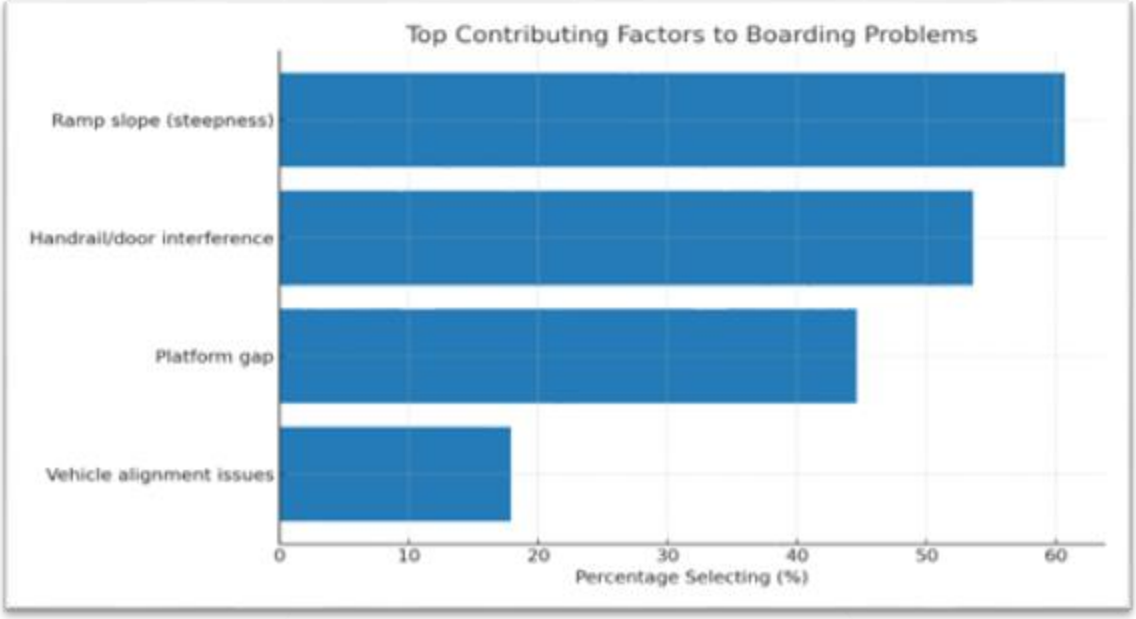


Figure 12: Top factors contributing to wheelchair boarding difficulties

Nearly as common were obstructions by handrails or doors, cited by 53.6%. Many buses and older vehicles have narrow entryways or awkwardly placed handrails that can snag or block wheelchair entry, a problem several participants noted in their comments. Platform gaps (horizontal distance between the vehicle and the station platform) were the next major issue, identified by 44.6% of respondents. A large gap requires a "leap" of the wheelchair or creates a risk of wheels getting stuck. Gaps are essentially a result of vehicle-platform misalignment, which in itself was also listed explicitly as "misalignment with platform" by 17.9% of respondents – a smaller percentage, possibly because some respondents treated platform gaps and misalignment as the same underlying issue. Taken together, nearly half of the respondents highlighted the lack of level alignment between vehicles and platforms (gaps or height differences) as a critical factor. These physical infrastructure issues (steep ramps and gaps) echo the context discussed in the introduction: many older transit systems in Ireland and elsewhere still have not achieved fully accessible gradients and minimal gap distances.

Only one respondent (about 1.8%) indicated that "No problem" was observed, meaning virtually everyone sees some issue hindering smooth boarding. This underscores that boarding difficulties are pervasive, even if the exact causes vary by situation.

In summary, the quantitative data on contributing factors show that design and infrastructure limitations – specifically steep ramp angles, misaligned vehicles/platforms causing gaps, and narrow or obstructed entrances – are the dominant sources of difficulty. These findings quantitatively confirm the study's premise that despite advances in wheelchair technology, external environmental factors like vehicle and station design remain major barriers. Notably, these issues were reported not just by wheelchair users but also by caregivers and other observers, suggesting a broad recognition of the physical challenges in public transport settings.

4.1.3. Confidence and the Role of Assistance in Boarding

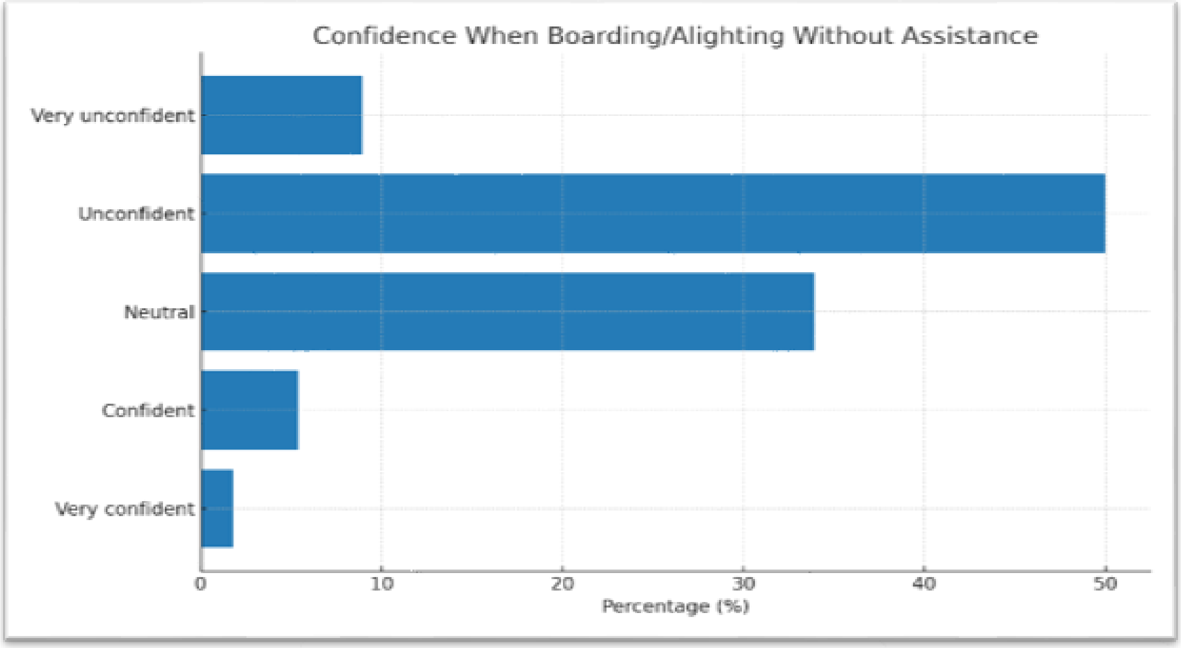


Figure 13: Confidence and the Role of Assistance in Boarding

Wheelchair users' (or those helping them) confidence level while boarding without assistance, and the importance they place on staff or companion assistance are other significant quantitative findings. To analyse this, a Likert scale was employed. In order to interpret the phrase "I feel confident boarding without assistance," respondents were asked to score their level of confidence on a scale that ranged from Strongly Disagree (1) to Strongly Agree (5). The findings indicate that users' confidence in their ability to attempt solo boarding is often poor. Regarding their confidence in getting into a car without help, almost half of the respondents (around 59%) disapproved or strongly disagreed. The majority were ambivalent, with only a very small minority (about 7% overall) agreeing that they are confident on their own. There was widespread disapproval of the idea of feeling confident on one's own, as seen by the confidence mean score of only 2.41 out of 5. Practically speaking, this indicates that solo boarding is uncomfortable for the average wheelchair user (or observer) under the current circumstances. This lack of confidence may result from the environmental barriers mentioned above; it makes sense that many users believe they cannot board securely without assistance when gaps, steep slopes, and other impediments are frequent.

Respondents strongly emphasised the importance of having staff or other assistance during boarding, which is consistent with the low level of independent trust. About 62–63% of respondents agreed or strongly agreed with the statement, "Staff assistance or guidance reduces boarding difficulties." Just about 5 percent disagreed, with the rest being neutral. To put it another way, almost two-thirds of participants agree that it is far easier to board a bus, train, or other employee who is willing to help or simply pay attention. This emphasises how crucial human support and appropriate training for transport employees are. (In fact, the literature raised concerns about staff members' inconsistent training and knowledge, and our qualitative findings also raised these issues.)

Question	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Mean Score**	**Standard Deviation**	**Interpretation**
Confidence boarding without assistance	8.9	50	33.9	5.4	1.8	2.412	0.797657	Moderate disagreement
Perceived safety improvement from sensors/audio alerts	16.1	1.8	12.5	23.2	46.4	3.82	1.441388	Neutral to slight agreement
Comfort with installing/using safety add-on system	0	3.6	25	64.3	7.1	3.749	0.634034	Neutral to slight agreement
Support funding/subsidising safety system	3.6	7.1	14.3	48.2	26.8	3.875	1.001686	Neutral to slight agreement
Likelihood to recommend system	1.8	3.6	1j0.7	51.8	32.1	4.088	0.852207	High agreement

Table 10: Likert scale analysis

A logistic regression analysis was conducted using a number of predictors to further investigate the factors that affect boarding difficulty: whether the respondent uses a wheelchair, whether they have mentioned ramp issues as a significant factor, and whether they indicated poor confidence (needing assistance). The result asked if the respondent said they have problems "often." Low confidence while boarding without help was the only statistically significant predictor of frequent boarding difficulty, according to the analysis. The likelihood of experiencing frequent difficulties was significantly higher for respondents who lacked confidence in their ability to board independently. In particular, the odds of reporting regular difficulties were increased by around 10.65 (OR ≈ 10.7, p = 0.001) if one had poor independent confidence. This finding is remarkable because it quantitatively highlights a self-reinforcing cycle in which people who are hesitant to board alone actually struggle more. This could be because they hesitate, position the wheelchair less optimally, or because their lack of confidence is a reflection of actual difficulties they expect. According to this theory, boosting users' self-esteem by training, supportive technology, or environmental improvements could directly lessen real challenges.

Predictor	B (Coef)	SE	Wald χ^2	*p*	Odds Ratio (OR)	95% CI for OR
Intercept (constant)	–1.488	0.667	4.99	0.026	–	–
Wheelchair User (vs others)	–1.453	0.962	2.28	0.131	0.234	0.036 – 1.541
Ramp Issue Cited (Ramp slope = yes)	0.433	0.711	0.37	0.543	1.54	0.382 – 6.215
Low Confidence (Needs assistance)	2.366	0.720	10.81	0.001**	10.65	2.600 – 43.646

Table 11: logistic regression predicting frequent boarding difficulties

On the other hand, in this model, reported difficulties were not significantly predicted by the respondent's kind of wheelchair use (as opposed to a carer or commuter) (p = 0.131). The coefficient suggested that wheelchair users themselves would have fewer challenges than carers or onlookers, which is interesting, but the sample size (only 10 wheelchair users) was too small to draw firm conclusions. Furthermore, the regression did not show that merely mentioning "ramp issues" as a top concern was an independent predictor of frequent difficulty (p = 0.543). This is probably because ramp steepness issues are common (many people mentioned them) and overlap with the confidence factor (steep ramps directly destroy confidence). Ultimately, these results point to confidence (or conversely, anxiety and need for assistance) as a critical piece of the puzzle in boarding safety. This insight complements the objective factors: even if infrastructure issues are addressed, perceived safety and confidence need to be improved to truly enhance the boarding experience.

4.1.4. Awareness of and Perceived Benefits of Smart Wheelchair Add-on Systems

Given the persistent challenges identified, the survey examined perceptions of technological solutions – specifically, sensor-based add-on systems for wheelchairs that could enhance safety during boarding (for example, systems with obstacle detectors, automatic braking on slopes, audio warnings for gaps, etc.). First, respondents were asked if they were aware of existing sensor-based wheelchair add-ons (such as commercially available products like the Braze Mobility blind-spot sensors or the LUCI smart wheelchair system).

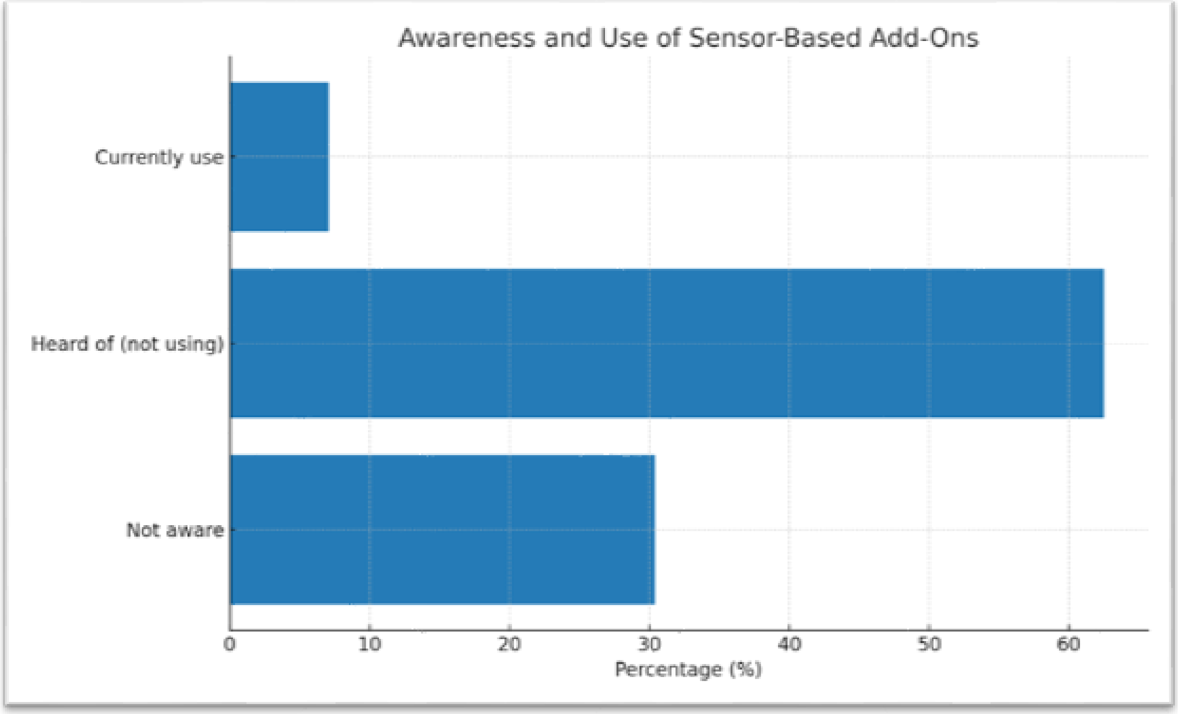


Figure 4.6: Awareness of and Perceived Benefits of Smart Wheelchair Add-on Systems

Awareness was modest: about 64.3% had heard of these systems (though they do not personally use one), and an additional small fraction (5.4%, just 3 respondents) actually use such a system on their wheelchair. The remaining ~30% had no awareness of these technologies prior to the survey. This indicates that while the concept of smart wheelchair enhancements is circulating (roughly two-thirds have at least some knowledge of it), actual adoption is still very low in our sample. Many wheelchair users and caregivers might not have had access or opportunity to try these add-ons, which is unsurprising given such products are relatively new and can be expensive.

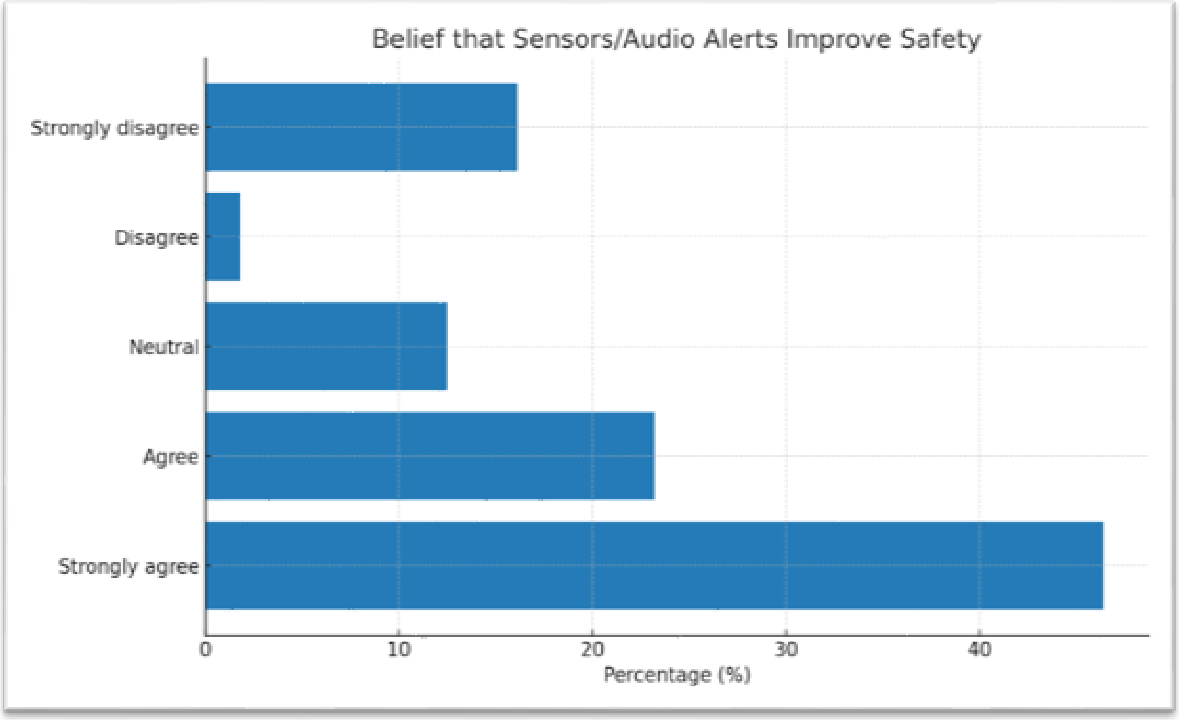


Figure 14: belief that adding sensor and audio alert technology would improve boarding safety.

Many people thought that adding sensors and voice alarms would increase boarding safety, even though very few had firsthand experience with sensor add-ons. Adding sensors and auditory alarms to a wheelchair would improve boarding safety, according to the participants' rating of agreement. Based on the responses, as shown in Figure 14, roughly 75% of the respondents agreed to some degree, with more than 50% strongly agreeing. While the majority were neutral, only a tiny minority (about 12% total) disagreed. With an average agreement rating of about 4.0 out of 5, there is general hope that technology might improve safety. In practical terms, most people think that a smart add-on would help prevent accidents or make boarding easier, for example, by warning of a gap or stopping a wheelchair before it goes off a steep edge. This positive perception was shared not just by tech-aware individuals but broadly, even among those who hadn’t heard of such systems before (it appears the idea itself is intuitively seen as beneficial).

It's important to note, too, that despite the high level of enthusiasm, a sizable percentage (about one in eight respondents) expressed uncertainty or scepticism. Ten to twelve percent of respondents did not think sensors would be helpful, and some (approximately eleven percent in our sample) strongly disagreed with the effectiveness of such add-ons. These objections suggest that not everyone views technology as a panacea, either because of worries about its dependability or the nature of the issues (for instance, a sensor may detect a gap but not physically fill it). The qualitative findings will show that some participants did express worries about false alarms or ineffectiveness in challenging real-world situations.

4.1.5. Design Preferences and Adoption Willingness for the Safety Add-on

To delve deeper into how a smart "boarding safety" system should function and whether people would actually use it, the survey included questions on preferred features, willingness to adopt, and overall attitudes toward such an add-on module. Participants could choose which types of alerts or features they believed would improve boarding safety the most (choosing up to two). Four main alert modalities were presented: visual indicators (like flashing lights), audible tones/beeps, spoken voice alerts, and vibrations (haptic feedback).

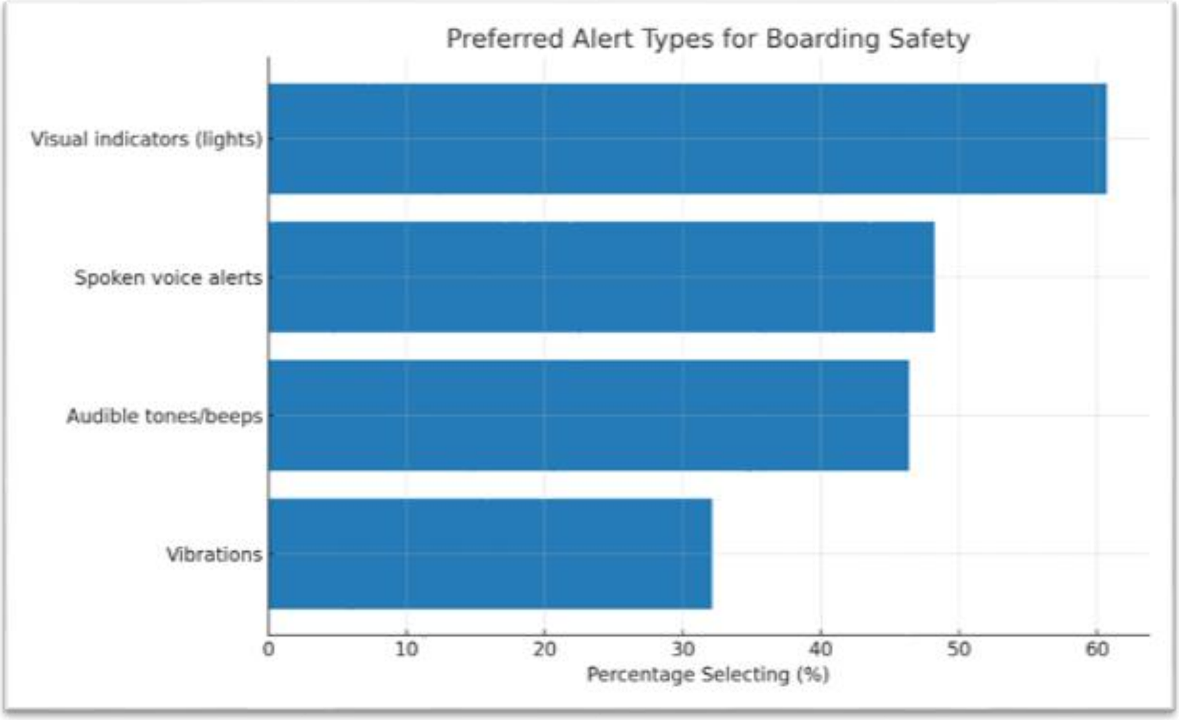


Figure 15: Preferred alert types for a hypothetical wheelchair boarding safety add-on system

As can be seen from the choices (Figure 15), no single option fully dominates and multisensory feedback is crucial. With almost 60.7% of respondents choosing visual signs, this was the most preferred option. A wheelchair or ramp's flashing lights or other visual cues are often seen to be an effective way to draw attention, such as warning the user or those close of a potential hazard. Spoken voice warnings came in second (48.2% of respondents had chosen them). Some people may find voice alarms more instructive or difficult to ignore than a basic beep. For example, they could say something like "Caution: gap ahead." The next most common voice notifications were beeps or audible tones (46.4%); they are more straightforward noises that can be combined with other messages.

Although vibration feedback was the least popular option (32.1%), almost one-third of respondents still believed that vibrations (such as those in the wheelchair's seat or joystick) would be beneficial. The conclusion is that, in accordance with accessibility best practices (which encompass both hearing and vision modalities), a combination of visual and auditory alerts is thought to be the most effective. Notably, a sizable portion of users favour vibrations; this is probably the case when noise is present or the user may have vision or hearing difficulties. Therefore, creating a system with several alert modes (and user choice options) would take into account the respondents' diverse preferences.

Beyond alert types, participants were asked to rate their agreement with several statements regarding a potential add-on system for boarding safety. These statements probed their willingness to use and trust the system, concerns about drawbacks, and support for recommending or funding it.

Statement about add-on system	Mean (1–5)	% Agree*	% Neutral	% Disagree*
I would use a modular add-on system that costs under €500.	3.74	57%	20%	23%
I would trust the system to accurately detect boarding hazards.	3.54	66%	13%	21%
I would be concerned about false alarms from the system.	3.58	66%	18%	16%
I would recommend this system to others (wheelchair users or public transport staff).	4.00	70%	9%	21%
I would support public funding for widespread adoption of such systems.	3.96	66%	11%	18%

Table 12: Respondents' attitudes toward adopting a wheelchair boarding safety add-on

Several conclusions can be drawn from these attitude tests. First, 57% of respondents said they would use the system if it cost less than €500, only 23% disagreed, indicating a pretty substantial willingness to utilise it if it is affordable. The average score of 3.74 indicates that money is a significant factor; €500 seems to be a threshold that many people find acceptable for these safety enhancements. As will be described later, cost sensitivity also surfaced qualitatively as a worry, demonstrating that affordability is crucial for adoption.

Second, just a small percentage of respondents expressed mistrust (disagreement that they would trust the system), but around two-thirds (66%) would trust the system to accurately detect hazards. Neutral were the others. This demonstrates cautious optimism: although some people appreciate the concept, others are holding out for proof that it won't overlook challenges or issue false alarms. Almost same percentage (66%) also voiced concern about false alarms, which is telling. In actuality, the mean agreement for "concern about false alarms" (3.58) is marginally higher than the midpoint, indicating that respondents generally tended to be concerned. In practice, many users are afraid of systems that cry wolf (beep excessively at non-issues), which might make them irritable or cause them to disregard them. False positives can undermine user trust, which is similar to what has happened with other sensor systems. Users had a balanced perspective, both optimistic about the technology and cognisant of its possible drawbacks (oversensitivity or technological issues), as seen by the respondents' simultaneous expressions of trust and concern.

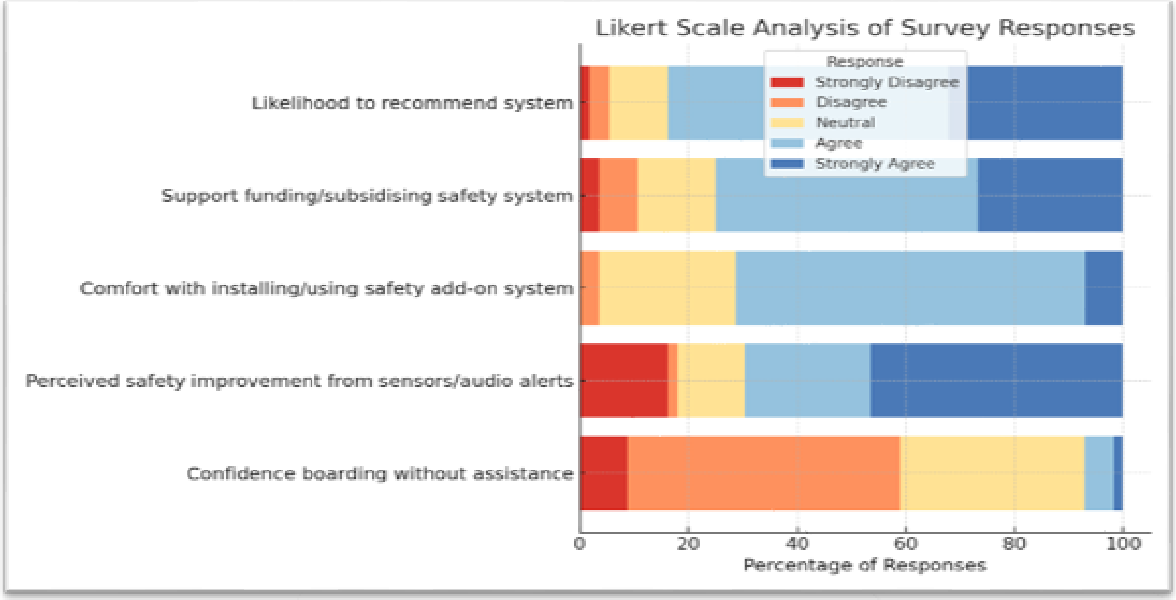


Figure 16: Likert scale analysis of survey response (Graphical Representation)

A resounding majority (70%) agreed that they would suggest the system to others, while only 21% were unwilling to do so. This suggests that after being individually persuaded, they believe it will benefit the community as a whole, which is encouraging if the product works. Similarly, there was strong support (66% in favour vs. 18%) for public funding or subsidies. Participants understand that in order for these safety devices to be widely used, they could require organisational or governmental support, particularly to help individuals who cannot afford even a few hundred euros. The mean score for supporting funding was 3.96, close to “Agree,” reflecting that sentiment. This finding resonates with the idea that enhancing accessibility is a public good. Respondents likely feel that institutions should help pay for measures that improve safety and inclusion.

Lastly, another question enquired how comfortable the responder would feel if they were given easy instructions to install the add-on module on a wheelchair. This was because some people may find it difficult to install, particularly if they lack technical knowledge or dexterity. When asked if they would feel comfortable or extremely comfortable doing it themselves, almost 70% said they would. The majority (one respondent in our sample) expressed that they would feel "not at all comfortable" with installation, while about 25% expressed no opinion. According to this, most users or carers believe that a modular add-on is feasible to create, provided that it is made to be user-friendly. Indeed, ease of use was a recurring theme in the qualitative feedback – people want a “plug-and-play” solution that doesn’t require advanced skills to attach or operate.

In summary, the quantitative findings on technology adoption are quite positive: most participants are willing to embrace a smart safety add-on, especially if it’s affordable and proven reliable. They desire multi-modal alerts (visual, audible, etc.) and appear ready to recommend and even advocate for funding for such technology. At the same time, they will be wary of false alarms and will expect the system to justify their trust by performing accurately. This balanced stance provides clear guidance for developers and policymakers: focus on reliability and cost, and adoption will likely follow.

4.2. Qualitative Findings

The survey included open-ended questions (e.g., “In your own words, what improvements or features would most increase adoption of this safety system?” and “Any other suggestions or concerns related to improving wheelchair boarding in public transport?”). These questions elicited rich qualitative feedback, which was analyzed using thematic analysis (Braun and Clarke, 2006; Maguire and Delahunt, 2017). Eleven key themes emerged from the responses, each highlighting a different aspect of user needs or concerns.

Theme	Codes	Example Quote(s)	Frequency (mentions)
Ease of Use & Accessibility	One-touch controls, voice activation, intuitive signage, app for carers, quick operation, universal compatibility	"One-touch operation or voice-activated controls for users with limited dexterity."	14
Safety & Reliability	Obstacle/blind-spot detection, misalignment sensors, automatic braking, waterproofing, stable boarding	"Features that detect a blind spot and beep to alert the wheelchair user of the hazard."	16
Cost & Affordability	Low price, trial option, affordable for small operators, cost-benefit justification	"If the system was cheaper or had some kind of trial option, more people would definitely give it a try."	11
Customisation & User Comfort	Adjustable alerts, vibration option, mute mode, sensitivity settings	"Customisable alert tones and the option to mute alerts when not needed… for users with sensory sensitivities."	7
Integration with Wheelchair & Infrastructure	Works with different wheelchair types, fits existing ramps, multi-lingual or symbol-based	"Making the alert system multilingual or symbol-based may help users with cognitive or language barriers."	8

Staff Support & Training	Skilled assistance, prompt boarding/alighting help, specific powered wheelchair handling training	“Transport staff need more training in handling powered wheelchairs, especially when there are alignment or locking issues.”	13
Automation & Technology	Automated ramps, driver/staff notification system, hazard sensors, automatic securement	“Sometimes the ramp is available but the driver doesn’t notice me. A system that alerts staff I’m waiting would be amazing.”	10
Infrastructure & Design	Better ramp–stop alignment, wider ramps, consistent ramp height, priority space near entrance	“Alignment of the stops are not well with ramps.”	12
Maintenance & Reliability of Systems	Regular inspections, repair responsibility clarity	“Proper maintenance of the system.”	5
Public Awareness & Empathy	Passenger education, campaigns to encourage patience	“Some older passengers get irritated… There needs to be more public awareness and empathy.”	6
Reporting & Feedback Systems	Easy ways to report problems and suggest improvements	“Make it easy for users to report issues or improvements.”	3

Table 13: Thematic analysis of open-ended responses

The most frequently mentioned themes were related to technical features (safety/reliability of the system, ease of use) and human/infrastructure factors (staff support, infrastructure design). We will discuss each theme in turn:

4.2.1. Ease of Use & Accessibility (mentioned by 14 respondents)

Participants emphasized that any safety add-on must be extremely easy to use, especially given that many wheelchair users have limited dexterity or cognitive load when traveling. Features like "voice-activated controls" and "one-touch controls" were proposed by respondents to make it easier to use the system without tinkering with intricate settings. In addition, they suggested user-friendly displays or signage and possibly a related smartphone app that would allow carers to keep an eye on or manage the system. One carer commented that the system should enable "quick operation, [be] universal in compatibility" so that it may be smoothly implemented on any wheelchair, indicating that speed and simplicity were crucial. "Voice-activated controls or one-touch operation for users with limited dexterity" is a quotation that exemplifies this idea. Reducing the amount of work needed to use the technology is crucial because if it's too complex, it could work against you instead of for you. Therefore, it is essential to have a simple and universal design that is compatible with wheelchairs and all users.

4.2.2. Safety & Reliability (16 respondents)

Many respondents raised questions about whether the system actually improves safety in practice as well as specific safety aspects that would make it effective. Among the features mentioned are automatic braking to stop the wheelchair if a dangerous situation is detected (e.g., rolling backwards on a steep ramp or nearing a platform edge), misalignment sensors to detect when the wheelchair is not properly aligned with a ramp or when there is a gap, and obstacle detection (especially covering blind spots that a wheelchair user might not see when backing up or approaching a bus ramp). Additionally, reliability came up. For example, making sure the system is sturdy and waterproof (because it will be used outdoors in Irish weather).

Another factor was stability upon boarding: participants wanted a system that could, for instance, work with the vehicle or the wheelchair's suspension to keep the chair steady. This subject is best shown by the following remark from one participant: "Features that detect a blind spot and beep to alert the wheelchair user of the hazard." This indicates a need for active hazard alerts, demonstrating that consumers seek for concrete safety advantages such notifications for hidden hazards or dangerous openings. All things considered, this topic emphasises that although people are drawn to technology, they won't trust it unless it can be shown to improve safety and be relied upon in practical situations. Users place a high value on reliability since any malfunction or failure to notice a hazard could have dire repercussions.

4.2.3. Cost & Affordability (11 respondents)

Cost was a persistent practical issue. Although the quantitative portion set a hypothetical price of less than €500, which was deemed acceptable by a small majority, many emphasised that the system must be inexpensive or have funding support in order to be widely used. Some proposed offering a trial or rental option so that transit operators or passengers may test the system out before making a financial commitment. Some noted that small transportation providers (such as community transport services) might not have large budgets, thus offering subsidies or proving a clear cost-benefit analysis would be beneficial. A poignant statement: "More people would definitely give the system a try if it was less expensive or offered a trial option." This makes it clear that cost is still a barrier to adoption; no matter how useful a system is, it won't be widely adopted if it is too costly. In essence, participants are requesting assistance from outside sources (grants, insurance, and public programs) to lessen the financial burden on individuals or a fair market price.

4.2.4. Customization & User Comfort (7 respondents)

Giving users authority over how the system interacts with them is central to this concept, which aims to respect individual preferences and comfort levels. Respondents recommended that alarm settings be able to be changed, such as the ability to change the tone, have vibrations instead of noises, or regulate the level for audio alerts. Certain users may prefer a soft vibration to a loud beep, particularly if they are in a quiet setting like a train car or have sensory sensitivity issues. For situations where a user would not require help (such as a normal, familiar trip), the option to mute or temporarily disable the device was also proposed. Another suggestion was sensitivity settings, which would allow you to adjust the sensors' sensitivity so that, for instance, they only sound an alarm for serious dangers or not at very tiny bumps.

One quotation that exemplifies this subject is: "Customisable alert tones and the option to mute alerts when not needed… especially for users with sensory sensitivities." It is clear from this that there is no one-size-fits-all solution; in order to be generally accepted, the system must for customisation. Here, users are comfortable both physically (not startled or irritated) and psychologically (feeling in control and able to customise the system to suit their needs). This theme is complementary to the "ease of use" concept in that they both imply that the perfect system is plug-and-play and adaptable.

4.2.5. Integration with Wheelchair & Infrastructure (8 respondents)

Participants pointed out that the add-on system needs to work in unison with the current transit system and wheelchairs. This implies that it should not require a particular kind of wheelchair to function and should be compatible with a variety of wheelchair types, including manual and power chairs, as well as varied sizes. It should also work with different types of ramps and cars. The system should be able to manage both, for instance, if a bus and a train have separate ramp mechanisms. Integration and connectivity with infrastructure was another intriguing aspect; some people saw the system interacting with the car or station.

For instance, one suggestion was to make the system multilingual or symbol-based in its interface or warnings so that users with different languages or cognitive abilities could use it. Another was that it could effectively integrate the wheelchair's system with the larger transit system by alerting the driver or station staff when a wheelchair user is trying to board. One participant stated that "users with cognitive or language barriers may benefit from a multilingual or symbol-based alert system." In addition to the wheelchair hardware, the system should be able to accommodate the different user community (language, cognition), as this quotation highlights. For the user and environment, integration essentially refers to both physical and communicative compatibility.

4.2.6. Staff Support & Training (13 respondents)

Many responses raised the human element, particularly the function of transport workers, in addition to the equipment itself. A sizable portion of respondents demanded improved wheelchair boarding assistance and staff training. If train conductors or bus drivers are informed and willing to help when needed, even the best technology will function more smoothly. Participants want employees who are adept at using ramps and lifts, know how to securely fasten wheelchairs, and are alert—for instance, spotting a wheelchair user waiting at a stop and quickly deploying the ramp.

"Transport staff need more training in handling powered wheelchairs, especially when there are alignment or locking issues," was one incisive statement. This is a situation that many users encounter: service members may be eager to help but may not know how to do so or may not be familiar with particular wheelchair functions, which could cause delays or even accidents. The main takeaway from this is that skilled staff support cannot be replaced by technology. Instead, the two should work in tandem. For example, a smart alert system may inform staff to a user's boarding, but staff members should react promptly and properly. Respondents clearly demand consistent excellence in this area and value when employees perform their jobs properly (which ties back to known issues of inconsistent staff training highlighted by bodies like the NDA, 2020).

4.2.7. Automation & Technology in Transportation (10 responders)

A few participants expanded their recommendations to include more automation in public transportation to help with boarding. Automated or enhanced ramps (e.g., ramps that deploy more smoothly or change their angle to lessen steepness) and systems where the vehicle or station sends out notifications in line with the wheelchair's alarms were among the ideas. One particular concept was a system for alerting drivers or staff. For instance, if a wheelchair user is at a bus stop, a signal may be sent to the bus driver (perhaps activated by the wheelchair user's device or app) to ensure that they stop and help.

In order to reduce time and increase safety, another idea was automatic securement, which would use technology to lock the wheelchair in position once it was on board without the need for awkward physical belts. These answers are essentially envisioning a smarter travel system in which the car and the wheelchair have complementary technology. "There are instances when the ramp is available, but the driver doesn't notice me," said one participant. It would be great if there were a mechanism that told employees I was waiting. This quotation demonstrates a typical annoyance (being ignored) and how technology could address it (by alerting the driver). The automation theme focuses on considering the larger system, including how to improve buses, trams, and other modes of transportation in addition to wheelchairs. It is forward-looking, suggesting that our prototype ideas could be part of a larger smart transport ecosystem.

4.2.8. Infrastructure & Design (12 respondents)

The physical infrastructure of mobility is the main emphasis of this theme, which both echoes and provides answers for the quantitatively defined problems. The respondents advocated for improved ramp and stop design, including less steep and wider ramps, more uniform platform heights that match vehicles, and making sure that wheelchair places on cars are close to the entry and roomy enough. Some have pointed out that some of the current designs are ineffective, such as bus stops with excessively low curb heights or ramps that are too small. The statement, "Alignment of the stops [is] not well with ramps," is straightforward but powerful. (This was probably caused by a respondent pointing out bus stops that weren't aligned.)

In essence, participants contend that many boarding issues would be eliminated if the infrastructure were constructed or renovated in accordance with appropriate standards. However, until that ideal is reached, at least design any new interventions (technical or procedural) with these physical concerns in mind. This includes standardising factors like the gap and step height (such that sensor systems might not even be as necessary). The fact that this theme is so prevalent (12 references) serves as further evidence that accessible environments must be created in addition to smart wheelchairs. It serves as a crucial reminder that our study's focus on a wheelchair add-on only tackles one aspect of the issue; respondents are obviously aware of the wider picture and call for concurrent infrastructural changes.

4.2.9. Maintenance & Reliability of Systems (5 respondents)

The maintenance of any adopted solution was the subject of a smaller but noteworthy collection of remarks. Whether the equipment is the vehicle's ramps or lifts or an add-on module, users are concerned about who will maintain it. Regular inspections and unambiguous accountability for repairs are emphasised. For instance, who has responsibility for a safety add-on system's failure or malfunction—the user, the manufacturer, or transportation agencies? They added that maintenance is essential, otherwise the best-laid plans fail because many accessibility elements on public transportation, such as lifts on buses, frequently malfunction. One participant summed up what should be a top priority in any deployment with the words, "Proper maintenance of the system." The theme here is that consistency and reliability over time matter. It’s not enough to have a great system on paper; it needs to work day in and day out. Users fear scenarios where everyone gets an add-on device, but after a year, half of them are non-functional due to lack of servicing, or transit staff ignoring upkeep of their part of the system. This practical perspective reminds us that any implemented solution must have a maintenance plan to ensure longevity and trust.

4.2.10. Public Awareness & Empathy (6 respondents)

Wheelchair users encounter a number of social as well as technological obstacles. Several respondents reported instances in which other travellers, possibly irritated by the additional time required, were impatient, impolite, or unhelpful when a wheelchair user was boarding. As a result, public education and the development of patience and empathy became a central subject. Among the suggestions are public awareness initiatives to educate other travellers on the value of accessibility and the justifications for any delays or modifications. People should be made aware, for instance, that waiting a few minutes while a wheelchair boards securely is a basic politeness and not a reason to complain.

According to one reply, "When wheelchair users take their time boarding, some older passengers become agitated." More empathy and public awareness are required. This quotation emphasises how some people may mistakenly blame the wheelchair user for "delaying" the trip because they do not fully comprehend the difficulties involved. Accordingly, respondents believe that influencing public opinion is a component of the solution; infrastructure and technology can be helpful, but for travel to be truly inclusive, a thoughtful setting is also required.

4.2.11. Reporting & Feedback Systems (3 respondents)

Finally, some participants recommended ways to improve the way that problems are reported, and feedback is gathered. They want simple methods to report issues with boarding or make suggestions for enhancements, such as an app, a hotline, or direct feedback to transportation officials. Even after initial deployment, this theme, which is the least discussed, focuses on making sure that the user's voice is heard. When a new ramp style or add-on module is implemented, for example, there ought to be a channel where users can communicate whether everything is functioning well or if they run into any new problems. A participant said, “Make it easy for users to report issues or improvements,” indicating that continuous improvement and user feedback loops are important. Essentially, rather than assuming a solution will work perfectly from the get-go, there should be a mechanism to learn from real-world use and adapt accordingly.

To sum up, the qualitative results offer a complex picture of what interested parties anticipate from enhanced wheelchair boarding security. The topics cover everything from particular technological aspects (sensors, automation, warnings) to human considerations (training, empathy) and systemic problems (maintenance, cost, infrastructure). Any successful solution needs to be comprehensive, combining dependable technology with user-centred design, infrastructure that supports it, skilled employees, and an informed public. Along with providing insight into why those figures are what they are, the insightful remarks and recommendations from participants also support the quantitative trends (for example, worries about false alarms are consistent with the quantitative finding that 66% of people are concerned about them). For example, the strong support for multi-modal alerts in quant is echoed by qualitative calls for customizable visual/auditory signals; the importance of staff help is echoed by calls for better training, and so on. These points will be further integrated in the discussion below.

4.3. Summary of Findings and Analysis

In summary, the results and analysis show that while the transportation ecology is gradually getting better, wheelchair users still face several obstacles. Smart wheelchair technology has potential and is well-received by the community, but it needs to be implemented in a supportive environment, which includes improved infrastructure, knowledgeable other passengers, and trained staff. The study's findings are consistent with the idea that a mix of engineering, design, policy, and educational initiatives is needed because no single innovation is a cure-all. By tackling both the "soft" (people and infrastructure) and "smart" (technology) components, we can get closer to providing wheelchair users with safe, respectable travel experiences. This research contributes a data-driven evaluation of the current gaps and offers a user-informed direction for bridging those gaps, thus helping transit authorities, designers, and advocates prioritize interventions that will have the most impact on making public transportation genuinely accessible for all.

4.4. Discussion

A thorough grasp of the difficulties and possible solutions for enhancing wheelchair boarding safety in public transport is offered by the combination of the quantitative and qualitative results. The study topics and the previously defined larger context are taken into consideration while interpreting these findings in this section. We go over the limits or surprising findings, the implications for design and policy, and how the evidence addresses the study's goal. Although the results generally support the main idea that wheelchair technology advancements alone have not completely removed enduring obstacles in the transit environment, they also point to practical methods to make travel safer and easier.

4.4.1. Persistent Barriers and the Need for Environmental Improvements

Our original finding that many transit systems are not yet universally accessible is supported by the most obvious result, which is that problems with the physical infrastructure continue to be a major source of boarding difficulties. The majority of respondents cited steep ramps and platform gaps as important challenges, which align with established design constraints (IWA, 2020). For example, older train or tram stations sometimes have significant gaps, and many buses still have ramps that are higher than the advised slope. Our results demonstrate that these problems are not merely theoretical; they frequently result in actual challenging situations or near-accidents.

The research pointed out that Ireland's older transport system regularly falls short of contemporary accessibility norms (Mwaka *et al.*, 2023), and our survey participants often mentioned these issues (e.g., "alignment of stops not well with ramps"). The inference is that a key component of the answer is infrastructural improvements (wider, less steep ramps; standardised platform heights; gap reduction). This is in line with earlier demands by advocacy organisations to replace or repair antiquated facilities (IWA, 2020). Even the smartest wheelchair is limited in its capabilities without such advancements; a sensor may alert users to a gap, but the gap will still exist physically. Therefore, it is suggested that transportation authority’s promote assistive technologies and expedite infrastructure improvements.

4.4.2. Human Factors – Confidence and Assistance

The human element of accessibility is highlighted by this study, particularly the significance of staff support and user confidence. Low confidence in independent boarding is a substantial predictor of frequent issues (OR ~10.7), according to the quantitative results. It implies that in addition to physical restrictions, psychological and experiential factors—such as fear of falling or lack of practice—are involved. Researchers Poli and Malagas (2024) have identified a gap in the literature by pointing out the absence of information on the relationship between user perceptions (confidence, fear) and actual accessibility outcomes. This fills that gap. We show that those perceptions are significant: Increasing self-assurance could directly lower the number of events.

This could be accomplished by providing wheelchair users with training programs that teach them safe boarding skills, possibly in conjunction with transit officials, or by exposing them to the vehicle gradually in controlled environments to foster familiarity. The majority of our participants, however, value staff support, which is in line with earlier findings. According to the qualitative feedback, which calls for improved staff training ("staff need more training in handling powered wheelchairs"), issues can occasionally develop not only because of the infrastructure or the wheelchair but also because of staff members who malfunction in the lift or bus positioning.

Training on ramp operation and handicap awareness has been implemented by several transit agencies, but the results indicate that it is not consistent. The implications for transport operators are obvious: frequent, practical training for conductors and drivers on how to help people with disabilities can have a significant positive impact on safety. Furthermore, our research indicates that regulations such as providing a second staff person to aid wheelchair boarding at busy train stations should be taken into consideration, as user confidence is significantly increased when assistance is guaranteed. These findings support the research goal that a strong human support system is necessary and that technology (smart wheelchairs) is insufficient on its own. Together, a self-assured user and a capable employee can overcome obstacles that neither could on their own.

4.4.3. Technology as a Promising Complement (with Caveats)

The general positive attitude of participants towards sensor-based safety accessories supports the study's investigation of this technology. A comparable percentage stated they would support and even help finance the introduction of these devices, and almost 75% think they can increase safety. The awareness that technology could bridge some of the gaps left by human capabilities and infrastructure is reflected in this enthusiasm. Sensors, for instance, may operate as a proactive brake and a second pair of eyes by spotting obstacles or warning of unsafe gaps sooner than a human could. Sensor systems have been shown to reduce certain accidents in controlled trials in the literature (Leblong *et al.*, 2021).

Instead of presenting lab results, our study offers real-world user viewpoints and highlights two crucial cautions: false alarms and trust. They will trust the system if it turns out to be intelligent enough to avoid raising false warnings, as evidenced by the fact that two-thirds of respondents both trust it and worry about false alarms. Qualitative statements about guaranteeing dependability ("proper maintenance of the system," "no false alarms") emphasise that if a device starts beeping unnecessarily (for instance, because of rain on the sensor or every sidewalk bump), users may turn it off or ignore it, negating its safety benefit. This is a well-known problem in technology adoption discussions: how to increase real positives and decrease false positives.

For those who build such systems, machine learning and calibration may be crucial; perhaps the system can learn the peculiarities of a given route or let users adjust sensitivity. It's significant that some respondents raised worries about stigma ("false alarms… and stigma; importance of optional modes" was mentioned). If an alert is overly frequent or gives the impression that the user is "setting off alarms," it may cause embarrassment or unwanted attention. To make the technology both socially and operationally acceptable, design discretion (e.g., a private vibration vs. a public loud warning in some circumstances) should be taken into account.

4.4.4. Integration of Quantitative and Qualitative Insights (Mixed-Methods Perspective)

Our quantitative and qualitative results can be used to provide a more comprehensive response to the study questions. Quantitatively, we saw that more than half of the respondents regularly experience problems on specific modes (trains/trams); qualitatively, we discovered that these issues are commonly caused by particular variables, such as uneven platform alignment. Additionally, we discovered numerically that only about 7% of users felt comfortable boarding by themselves. Qualitatively, we heard the emotional toll that this number took, as users expressed worry and anxiety, and one even highlighted "emotional stress from delays" when things go wrong.

As a result, the numbers become more meaningful because fear is a part of the lived experience rather than merely nuisance. Another integration point: individuals expressed that they want multi-sensory input (lights, noises, vibrations) and flexibility, which describes how they want such sensors to assist. Sensors and warnings also received a thumbs up in terms of numbers (mean agreement ~3.94). These connections were amply demonstrated by the joint display (quant–qual integration table) produced during analysis. The cost and integration themes, for instance, explain why someone might hesitate even though they are technically comfortable with installation. One row, for instance, indicated that 71.4% of respondents were comfortable with installation (quant), and it was connected to the theme that affordability, reliability, and compatibility drive willingness (qual).

58.9% of respondents valued staff support (quant), according to another row, and they connected it to the demand for timely, well-trained staff (qual). The strands' consistency gives our conclusions more assurance because the results are solid when they come from independent data sources (Evans et al., 2011). Additionally, it indicates that our survey attained saturation on important topics; the fact that no one mentioned anything significantly different from the survey alternatives on their own demonstrates that our combined method effectively captured the primary areas of interest.

Theme	Quantitative Evidence	Qualitative Insights	Representative Quote
Low confidence in independent boarding	50% disagreed they felt confident; Mean Likert score **2.42**	Confidence drops with steep ramps, platform gaps, and door obstructions; emotional stress from delays	“Sometimes the ramp is available but the driver doesn’t notice me. A system that alerts staff I’m waiting would be amazing.”
Ramp slope and alignment issues	Steep ramps cited by **60.7%**; misaligned stops by **44.6%**	Poor alignment creates tipping hazards; infrastructure not standardised	“Some stops don’t align well with ramps. It would help if the system also alerted staff for support.”
Value of sensor-based safety systems	69.6% agreed sensors/audio alerts improve safety; Mean score **3.94**	Desire for multi-sensory feedback (lights, sounds, vibrations); alerts should be customisable	“Customisable alert tones and the option to mute alerts… especially for users with sensory sensitivities.”
Preferred alert types	Visual (60.7%), spoken (48.2%), audio tones (46.4%), vibration (32.1%)	Accessibility must cover vision, hearing, and cognitive impairments	“Making the alert system multilingual or symbol-based may help users with cognitive or language barriers.”
Adoption willingness	71.4% comfortable with installation; strong funding support	Affordability, reliability, compatibility across wheelchair types is key	“If the system was cheaper or had some kind of trial option, more people would give it a try.”

Staff role in safety	Assistance rated valuable by **58.9%**	Need for prompt, well-trained staff at both boarding and alighting	“Transport staff need more training in handling powered wheelchairs, especially when there are alignment or locking issues.”
Public awareness and empathy	N/A (not directly measured in Likert items)	Older passengers sometimes get frustrated; need education campaigns	“Some older passengers get irritated when wheelchair users take time to board. There needs to be more public awareness and empathy.”
Prototype reception	Positive scenario-based ratings; increased confidence reported	Concerns over false alarms, alert volume, and stigma; importance of optional modes	“It’s good as it is, but add voice alerts when boarding.”

Table 14: joint display: integration of quantitative and qualitative findings

4.4.5. Implications for Design of the Add-on System

An ideal "smart wheelchair boarding aid" is outlined in the user comments. It should be inexpensive (a few hundred euros or with subsidies), simple to set up and operate (plug-and-play, one-touch activation), and offer multimodal alerts (visual and auditory, with the option of vibration). It must be dependable (waterproof, sturdy sensors) and intelligent enough to prevent false alerts or, at the very least, let the user adjust it. Customers want to be able to adjust the volume, select the sort of alert, and turn it off when not in use, thus customisation is crucial. In terms of integration, it need to work with any wheelchair and preferably be able to speak with cars (for example, a future enhancement could be that when the wheelchair sensor detects a misaligned ramp, it signals the vehicle to adjust if possible, or alerts the driver).

In order to accommodate all users, it is important to make voice alerts multilingual or use simple tones and icons. This is because some users or bystanders may not understand English voice alerts, which is why symbol-based communications are suggested. The high level of interest in voice alerts suggests adding a speaker that can say messages. Privacy and dignity should also be taken into account; the system should support the user without making them feel special or childlike. For example, depending on the situation, a soft light or vibration may occasionally be better than a loud statement. These subtleties are crucial for directing the subsequent stages of design and are directly derived from user voices in our data. Engineers and designers can use our checklist, which is derived from actual stakeholders, to assess prototypes.

4.4.6. Policy and Training Implications

From a policy standpoint, the results support a multifaceted strategy to increase accessibility. Infrastructure, training, and subsidies should all receive investment rather than just one aspect (such as purchasing devices). This mandate might be used to campaign for government grants or transportation agency budgets to cover these systems for individuals who cannot afford them, as two-thirds of participants are willing to have public dollars spent on accessibility technology. Additionally, a large percentage of our respondents were commuters or carers rather than wheelchair users themselves, indicating that these problems are acknowledged by the community as a whole.

For instance, if regular commuters acknowledge delays and seek improvements, there may be more public support for accessibility initiatives than one may think. This community awareness can be used to advocate for changes. In addition to technical solutions, the inclusion of public awareness campaigns implies that education programs (such as politeness campaigns or educational posters regarding wheelchair boarding etiquette) could enhance the social environment for accessibility. Also, considering the combination of challenges and poor confidence, maybe transit agencies should provide wheelchair users with orientation sessions (some cities have 'try the bus' days where people with disabilities can practise getting on a parked bus with staff help, to build confidence). These initiatives, when paired with our suggested alert system, might significantly lower anxiety and boost self-reliance.

4.4.7. Evaluation of the Hypothesis and Contribution to Knowledge

The basic hypothesis of this research was that because of external factors affecting the architecture and operations of public transit, sophisticated wheelchair technology has not completely resolved enduring accessibility issues. The results provide substantial support for this theory. Even while participants are aware of smart technologies and are generally positive about them, we found that they still frequently experience boarding issues, primarily because of infrastructure and uneven support. Although modern wheelchairs with advanced sensors and braking (such as those mentioned in earlier studies) are useful, our findings indicate that they occasionally actually run into obstacles when they are in the presence of a poorly constructed car or an untrained attendant.

A real-world example raised in our background (the Dublin Luas tram incident in 2024 where a sensor-equipped wheelchair got stuck in a gap) is a case in point, and our data echoes that scenario: respondents reported platform gaps and also voiced that sensors would be great, but only if the gap issue is managed. Thus, the study contributes empirical evidence from Ireland (complementing work in other countries like the UK by Velho, 2019) to illustrate that technology must be complemented by environmental and human-factor solutions.

Additionally, by using a mixed-methods approach, we were able to record not just the issues but also their causes and potential practical solutions. As the literature review points out, not many research has connected quantitative information on incident frequency with qualitative information on user experiences in the context of Irish public transport, making this a noteworthy contribution. This link has been supplied. For instance, we now know both numerically that "trains are hardest to board" and qualitatively that "trains have large gaps at certain stations causing that difficulty"—a relationship that was previously primarily anecdotal.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

This study demonstrates that boarding is still hampered by enduring infrastructure problems, particularly steep ramp inclines and vast platform gaps, especially on trains and trams, but buses provide comparatively fewer challenges. Which design and safety constraints have the biggest effects on Irish public transport? This topic is immediately addressed by these findings, which translate to Objective 1. This is consistent with the systematic review by Unsworth et al. (2021), which shows that ramp access and manoeuvrability continue to be persistent obstacles in practical situations (Unsworth *et al.*, 2021).

Two key elements that stood out were staff support and user confidence. In line with Velho's (2019) results that transit usage is restricted by fear and negative emotions, low confidence in solo boarding strongly predicted boarding difficulties (OR 10.7). This immediately answers the study question on autonomy and support that is related to Objective 3 (Velho, 2019).

Respondents favoured multimodal alerts, affordability, customisation, and dependability when it came to technology, and they viewed sensor-based add-ons as a promising advancement. These observations address Objective 2, which is to evaluate assistive features. Comparable research indicates that integrating technology with environmental and psychological support improves independence (Mwaka et al., 2024).

Beyond technological solutions, there was substantial support for non-technical measures such as maintenance systems, feedback pathways, and public empathy campaigns. This met Objective 4 and answered the issue about practical enablers for accessibility. Calls for inclusive design and user-centred policy are more general and echo these.

It was surprising to learn that wheelchair users reported fewer challenges than commuters and carers. This could be because of adaptation or underreporting, which is a topic that needs more research. Overall, the results support the initial theory that more extensive environmental and societal constraints cannot be addressed by sophisticated wheelchair technologies alone. An integrated strategy, better infrastructure, human-centered support, sympathetic public sentiments, and responsible technology is needed to achieve truly inclusive transit.

5.1. Limitations

It's critical to recognise the limits of this research while analysing the findings. First, although it is enough for this study, the sample size (N=56) is modest and does not accurately represent all wheelchair users in Ireland. Just 10 responders (18%) were wheelchair users, specifically. Though knowledgeable, the remaining individuals were not the major users themselves, such as carers or observers. For example, carers may overestimate difficulties out of worry, while commuters may not be aware of all the internal struggles a wheelchair user has. This could add bias. The data from various respondent groups, however, was generally consistent.

However, by collaborating with disability organisations to conduct targeted interviews or a broader poll, Braun's research should aim to include additional perspectives from real wheelchair users. Second, conducted our investigation in a particular environment, which was mainly Irish urban transit with some rural responses. Regions with differing transportation design may yield different results (for instance, cities with newer infrastructure may not have the same frequency of ramp and gap difficulties).

Nevertheless, several of the findings may have generalisable implications (e.g., the concern over false alarms or the demand for multi-modal notifications). The reliance on self-reported data is another drawback. Neither boarding incidence measurements nor prototype field testing were done.

Consequently, a discrepancy between what people say and what they would actually do may exist. A prototype add-on might be tested with a small group of wheelchair users in authentic boarding scenarios to monitor genuine usage patterns and collect comments, which could either support or contradict the findings of our survey.

Lastly, even though the qualitative analysis is comprehensive, it is open to the researcher's interpretation. Another researcher might categorise themes slightly differently from what this research did, despite the best efforts to be methodical (using coding and counting mentions). However, the primary concerns (pricing, ease, safety, etc.) are clearly seen in the unfiltered remarks

5.2. Suggestions for Further Research

Using a combination of repeated surveys, ecological momentary assessment (EMA), and real-time incident logging from on-chair sensors and smartphones, a longitudinal mixed-methods approach should track the same participants across time and across routes. This complies with best-practice mixed-methods guidelines and captures trend and context effects that a cross-sectional snapshot would miss (Campbell *et al.*, 2012).

Simultaneously, use a staged or cluster/stepped-wedge rollout across depots to field-test a boarding safety prototype (sensor/alert module) in real service, utilising on-device analytics and blinded adjudication of "events." Manage device risk and ethics in accordance with ISO 14155 and report the observational elements to STROBE and any interventional elements to CONSORT.

REFERENCE

Alam, A. and Mohanty, A. (2023) ‘Educational Technology: Exploring the Convergence of Technology and Pedagogy through Mobility, Interactivity, AI, and Learning Tools’. *Cogent Engineering*, 10(2). DOI: 10.1080/23311916.2023.2283282.

Almoshaogeh, M. *et al.* (2025) ‘A Review on Disability-Inclusive Public Transportation: Current Barriers and Prospects’. *IEEE Access*, 13, pp. 75769–75786. DOI: 10.1109/access.2025.3564225.

Arora, T. *et al.* (2023) ‘Classification of Methods to Reduce Clinical Alarm Signals for Remote Patient Monitoring: A Critical Review’. In *Cloud Computing in Medical Imaging, Healthcare Technologies and Services*. pp. 1–25.

Bennett, R. and Vijaygopal, R. (2024) ‘Exploring Mobility and Transportation Technology Futures for People with Ambulatory Disabilities: A Science Fiction Prototype’. *Technovation*, 133, p. 103001. DOI: 10.1016/j.technovation.2024.103001.

Boyd, R.J., Powney, G.D. and Pescott, O.L. (2023) ‘We Need to Talk about Nonprobability Samples’. *Trends in Ecology & Evolution*, 38(6), pp. 521–531. DOI: 10.1016/j.tree.2023.01.001.

Braun, V. and Clarke, V. (2006) ‘Using Thematic Analysis in Psychology’. *Qualitative Research in Psychology*, 3(2), pp. 77–101. DOI: 10.1191/1478088706qp063oa.

Brierley, J.A. (2017) ‘The Role of a Pragmatist Paradigm When Adopting Mixed Methods in Behavioural Accounting Research’. *International Journal of Behavioural Accounting and Finance*, 6(2), p. 140. DOI: 10.1504/IJBAF.2017.086432.

Campbell, M.K. *et al.* (2012) ‘Consort 2010 Statement: Extension to Cluster Randomised Trials’. *BMJ*, 345(sep04 1), pp. e5661–e5661. DOI: 10.1136/bmj.e5661.

Cui, J. *et al.* (2022) ‘IoT Wheelchair Control System Based on Multi-Mode Sensing and Human-Machine Interaction’. *Micromachines*, 13(7), p. 1108. DOI: 10.3390/mi13071108.

Cui, J. *et al.* (2025) ‘Research on Outdoor Navigation of Intelligent Wheelchair Based on a Novel Layered Cost Map’. *Actuators*, 14(2), p. 46. DOI: 10.3390/act14020046.

Digital Culture Network. (2024) *What Is the Social Model of Disability and How Can You Use It to Improve Digital Accessibility?*. Available at: https://digitalculturenetwork.org.uk (Accessed: 22 August 2025).

Evans, B.C., Coon, D.W. and Ume, E. (2011) ‘Use of Theoretical Frameworks as a Pragmatic Guide for Mixed Methods Studies: A Methodological Necessity?’ *Journal of Mixed Methods Research*, 5(4), pp. 276–292. DOI: 10.1177/1558689811412972.

Favey, C. *et al.* (2021) ‘Development of a New Negative Obstacle Sensor for Augmented Electric Wheelchair’. *Sensors*, 21(19), p. 6341. DOI: 10.3390/s21196341.

Frost, K.L., Bertocci, G. and Smalley, C. (2015) ‘Ramp-Related Incidents Involving Wheeled Mobility Device Users During Transit Bus Boarding/Alighting’. *Archives of Physical Medicine and Rehabilitation*, 96(5), pp. 928–933. DOI: 10.1016/j.apmr.2014.12.013.

Gebresselassie, M. (2023) ‘Wheelchair Users’ Perspective on Transportation Service Hailed Through Uber and Lyft Apps’. *Transportation Research Record: Journal of the Transportation Research Board*, 2677(5), pp. 1164–1177. DOI: 10.1177/03611981221140369.

Gillespie, A., Glăveanu, V. and De Saint Laurent, C. (2024) *Pragmatism and Methodology: Doing Research That Matters with Mixed Methods*. Cambridge: Cambridge University Press Available at: https://doi.org/10.1017/9781009031066 (Accessed: 18 July 2025).

Grigioni, C. *et al.* (2024) (arXiv:2403.08984) DOI: 10.48550/arXiv.2403.08984.

Hague, P. (2021) *Market Research in Practice: An Introduction to Gaining Greater Market Insight*. 4th edn. Kogan Page Available at: https://www.perlego.com/book/3028370/market-research-in-practice-an-introduction-to-gaining-greater-market-insight-pdf.

Hamdan, S., Ayyash, M. and Almajali, S. (2020) ‘Edge-Computing Architectures for Internet of Things Applications: A Survey’. *Sensors*, 20(22), p. 6441. DOI: 10.3390/s20226441.

Hireche, R., Mansouri, H. and Pathan, A.-S.K. (2022) ‘Security and Privacy Management in Internet of Medical Things (IoMT): A Synthesis’. *Journal of Cybersecurity and Privacy*, 2(3), pp. 640–661. DOI: 10.3390/jcp2030033.

Hossan, A. *et al.* (2025) ‘On the Capacity of V2X Communication Networks to Support the Delivery of Emerging C-ITS Services: A Case Study on an Irish Motorway’. *Information*, 16(7), p. 563. DOI: 10.3390/info16070563.

Hou, L. *et al.* (2024) ‘An Autonomous Wheelchair with Health Monitoring System Based on Internet of Thing’. *Scientific Reports*, 14(1). DOI: 10.1038/s41598-024-56357-y.

iFLYTEK. (2017) *AI Smart Home Demonstration on Zhihu*. *Zhihu*. Available at: \url{https://www.zhihu.com/ (Accessed: 22 August 2025).

International Electrotechnical Commission. (2020) ‘IEC 62366-1:2015/Amd 1:2020 - Medical Devices — Part 1: Application of Usability Engineering to Medical Devices, Amendment 1’.[International Standard] Available at: https://webstore.iec.ch/publication/63497.

IWA. (2020) ‘Transport Accessibility Report: Issues in Irish Public Transit for Disabled Individuals’.

Johnson, E. *et al.* (2023) *ARE WE THERE YET?* Transport For All.

Kaushik, V. and Walsh, C.A. (2019) ‘Pragmatism as a Research Paradigm and Its Implications for Social Work Research’. *Social Sciences*, 8(9), p. 255. DOI: 10.3390/socsci8090255.

Kim, Yane. *et al.* (2023) (arXiv:2312.01285) DOI: 10.48550/arXiv.2312.01285.

Layton, N. *et al.* (2022) ‘When the Wheelchair Is Not Enough: What Capabilities Approaches Offer Assistive Technology Practice in Rural Argentina’. *Societies*, 12(6), p. 158. DOI: 10.3390/soc12060158.

Leaman, J. and La, H.M. (2017) ‘A Comprehensive Review of Smart Wheelchairs: Past, Present, and Future’. *IEEE Transactions on Human-Machine Systems*, 47(4), pp. 486–499. DOI: 10.1109/THMS.2017.2706727.

Leblong, E. *et al.* (2021) ‘SWADAPT1: Assessment of an Electric Wheelchair-Driving Robotic Module in Standardized Circuits: A Prospective, Controlled Repeated Measure Design Pilot Study’. *Journal of NeuroEngineering and Rehabilitation*, 18(1), p. 140. DOI: 10.1186/s12984-021-00923-2.

Lecrosnier, L. *et al.* (2020) ‘Deep Learning-Based Object Detection, Localisation and Tracking for Smart Wheelchair Healthcare Mobility’. *International Journal of Environmental Research and Public Health*, 18(1), p. 91. DOI: 10.3390/ijerph18010091.

Lim, S. and D’Souza, C. (2021) ‘Wheeled Mobility Use on Accessible Fixed-Route Transit: A Field Study in Environmental Docility’. *International Journal of Environmental Research and Public Health*, 18(6), p. 2840. DOI: 10.3390/ijerph18062840.

Martinez, J. (2022) ‘Riders With Disabilities Sue MTA To Close The Gap Between Subway Train And Platform’. *Patch*, 26 October. Available at: https://patch.com/new-york/new-york-city/riders-disabilities-sue-mta-close-gap-between-subway-train-platform (Accessed: 22 August 2025).

Mathis, K. and Gowran, R.J. (2023) 'A Cross-Sectional Survey Investigating Wheelchair Skills Training in Ireland'. *Disability and Rehabilitation: Assistive Technology*, 18(7), pp. 1221–1228. DOI: 10.1080/17483107.2021.2001058.

Medical Device HQ. (2024) 'The Illustrated Guide to Risk Management for Medical Device and ISO 14971'. *MedicalDeviceHQ*. Available at: https://medicaldevicehq.com/articles/the-illustrated-guide-to-risk-management-for-medical-devices-and-iso-14971/ (Accessed: 22 August 2025).

Meligy, R., Ahmad, A.R. and Mekid, S. (2024) 'An IoT-Based Smart Wheelchair with EEG Control and Vital Sign Monitoring'. In *ECSA-11*. ECSA-11. Basel Switzerland: MDPI, p. 46. DOI: 10.3390/ecsa-11-20489.

Memon, M.A. *et al.* (2024) 'PURPOSIVE SAMPLING: A REVIEW AND GUIDELINES FOR QUANTITATIVE RESEARCH'. *Journal of Applied Structural Equation Modeling*, 9(1), pp. 1–23. DOI: 10.47263/JASEM.9(1)01.

Menon, A. 'HD Recall of Reactive Behavior through Multi-Modal Sensor Fusion'.

Metropolitan Transportation Authority. (2023) *MTA Launches Pilot of Automatic Wheelchair Securement Device on Buses*. Metropolitan Transportation Authority (MTA) Available at: https://new.mta.info/press-release/mta-launches-pilot-automatic-wheelchair-securement-device-buses (Accessed: 7 September 2025).

Mitchell, A. (2018) 'A Review of Mixed Methods, Pragmatism and Abduction Techniques'. 16(3).

Mitra, S. (2006) 'The Capability Approach and Disability'. *Journal of Disability Policy Studies*, 16(4), pp. 236–247. DOI: 10.1177/10442073060160040501.

Mwaka, C.R. *et al.* (2024) 'Barriers and Facilitators of Public Transport Use among People with Disabilities: A Scoping Review'. *Frontiers in Rehabilitation Sciences*, 4. DOI: 10.3389/fresc.2023.1336514.

Naeem, M. *et al.* (2023) 'A Step-by-Step Process of Thematic Analysis to Develop a Conceptual Model in Qualitative Research'. *International Journal of Qualitative Methods*, 22, p. 16094069231205789. DOI: 10.1177/16094069231205789.

National Disability Authority. (2020) 'ANNUAL REPORT Annual Report 2019'. *ANNUAL REPORT*.

Nejati, M. and Argall, B.D. (2016) 'Automated Incline Detection for Assistive Powered Wheelchairs'. In *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. 2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN). New York, NY, USA: IEEE, pp. 1007–1012. DOI: 10.1109/ROMAN.2016.7745232.

Nguyen, J.S., Su, S.W. and Nguyen, H.T. (2013) 'Experimental Study on a Smart Wheelchair System Using a Combination of Stereoscopic and Spherical Vision'. In *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. 2013 35th Annual International Conference of the IEEE Engineering in Medicine and

Biology Society (EMBC). Osaka: IEEE, pp. 4597–4600. DOI: 10.1109/EMBC.2013.6610571.

Nichols, E. (2024) ‘ISO 14971 Risk Management for Medical Devices: The Definitive Guide’. Available at: https://www.greenlight.guru/blog/iso-14971-risk-management (Accessed: 19 July 2025).

O’Donoghue, D. (2015) ‘Wheelchair-User Left Alone on Locked, Dark Train in Dublin Station’. *Irish Examiner*, 12 May.

Oliver, M. ‘Social Model of Disability’. *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Social_model_of_disability (Accessed: 18 July 2025).

Ozdenizci, O. *et al.* (2019) (arXiv:1907.09540) DOI: 10.48550/arXiv.1907.09540.

Padfield, N. *et al.* (2022) ‘A Comprehensive Review of Endogenous EEG-Based BCIs for Dynamic Device Control’. *Sensors*, 22(15), p. 5802. DOI: 10.3390/s22155802.

Pan, J. and Li, Y. (2018) ‘27 Hybrid Brain–Computer Interfaces and Their Applications’. Available at: https://www.researchgate.net/publication/340087401.

Pearlman, J. ‘COMMONWEALTH OF PENNSYLVANIA DEPARTMENT OF TRANSPORTATION’.

Pokyse, E. *et al.* (2024) ‘Implementation of Smart Wheelchair with Obstacle Avoidance’. *LAUTECH Journal of Engineering and Technology*, 18(3). DOI: 10.36108/laujet/4202.81.0321.

Polenakis, I. *et al.* (2024) (arXiv:2406.06154) DOI: 10.48550/arXiv.2406.06154.

Ramaraj, V. *et al.* (2024) ‘Development of a Modular Real-Time Shared-Control System for a Smart Wheelchair’. *Journal of Signal Processing Systems*, 96(3), pp. 203–214. DOI: 10.1007/s11265-022-01828-6.

Siribunyaphat, N. and Punsawad, Y. (2023) ‘Brain–Computer Interface Based on Steady-State Visual Evoked Potential Using Quick-Response Code Pattern for Wheelchair Control’. *Sensors*, 23(4), p. 2069. DOI: 10.3390/s23042069.

Smith, E.M. *et al.* (2019) ‘“A Chance to Try”: Exploring the Clinical Utility of Shared-Control Teleoperation for Powered Wheelchair Assessment and Training’. *American Journal of Occupational Therapy*, 73(6). DOI: 10.5014/ajot.2019.032151.

Smith S, C. (2024) ‘“It Makes Me My Own Person”: The Impact of Assistive Technologies on the Lives of People Living with a Disability in Ireland.’ *Rehab Group*, p. 40.

Song, M. *et al.* (2022) ‘An EEG-Based Asynchronous MI-BCI System to Reduce False Positives with a Small Number of Channels for Neurorehabilitation: A Pilot Study’. *Frontiers in Neurorobotics*, 16. DOI: 10.3389/fnbot.2022.971547.

Stjernborg, V. (2019) ‘Accessibility for All in Public Transport and the Overlooked (Social) Dimension—A Case Study of Stockholm’. *Sustainability*, 11(18), p. 4902. DOI: 10.3390/su11184902.

Sun, L. *et al.* (2024) ‘Privacy Barriers in Health Monitoring: Scoping Review’. *JMIR Nursing*, 7, p. e53592. DOI: 10.2196/53592.

Thakur, M., Sharma, S. and Vaegae, N.K. (2018) ‘NEXT GENERATION WHEELCHAIR USING MULTIMODE SMART SENSOR MODULE’. *IAEME Publication*, 9(7), pp. 155–162.

Unsworth, C. *et al.* (2021) ‘A Systematic Review of Public Transport Accessibility for People Using Mobility Devices’. *Disability and Rehabilitation*, 43(16), pp. 2253–2267. DOI: 10.1080/09638288.2019.1697382.

Ušinskis, V. *et al.* (2025) ‘Sensor-Fusion Based Navigation for Autonomous Mobile Robot’. *Sensors*, 25(4), p. 1248. DOI: 10.3390/s25041248.

Velho, R. (2019) ‘Transport Accessibility for Wheelchair Users: A Qualitative Analysis of Inclusion and Health’. *International Journal of Transportation Science and Technology*, 8(2), pp. 103–115. DOI: 10.1016/j.ijtst.2018.04.005.

Wasti, S.P. *et al.* (2022) ‘The Growing Importance of Mixed-Methods Research in Health’. *Nepal Journal of Epidemiology*, 12(1), pp. 1175–1178. DOI: 10.3126/nje.v12i1.43633.

Wikipedia contributors. (2025a) ‘Edge Computing’. *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Edge_computing (Accessed: 22 August 2025).

Wikipedia contributors. (2025b) ‘European Accessibility Act’. *Wikipedia*. Available at: https://en.wikipedia.org/wiki/European_Accessibility_Act (Accessed: 22 August 2035).

Wikipedia contributors. (2025c) ‘Inclusive Design’. *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Inclusive_design.

Wikipedia contributors. (2025d) ‘PRM TSI’. *Wikipedia*. Available at: https://en.wikipedia.org/wiki/PRM_TSI (Accessed: 22 August 2025).

World Health Organization. and World Bank. (2011) (62783) *WORLD REPORT ON DISABILITY*. Geneva Available at: https://www.who.int/publications/i/item/9789241564182 (Accessed: 17 July 2025).

Xu, Y. *et al.* (2025) (arXiv:2501.09680) DOI: 10.48550/arXiv.2501.09680.

Yee, K. (2023) *Meet the Maker: Robotics Student Rolls Out Autonomous Wheelchair With NVIDIA Jetson*. *NVIDIA*. Available at: https://blogs.nvidia.com/blog/kabilan-kb-autonomous-wheelchair/?utm_source=chatgpt.com (Accessed: 18 July 2025).

Yousfi, E., Jacquet, T. and Métayer, N. (2025) ‘Automated Vehicles and People Living with a Disability: Opportunities, Challenges, and Future Directions for Sustainable Mobility’. *Sustainability*, 17(13), p. 5941. DOI: 10.3390/su17135941.

APPENDICES

Appendix A – Online Survey (Google Form)

Smart Wheelchair Safety and Accessibility in Public Transport: A Data-Driven Evaluation of Design Limitations and Real-World Challenges

My name is **Akshaya Radhan Puthoor**, and I am a postgraduate student at **Griffith College Dublin**, currently completing my **MSc in Medical Device Technology and Business**.

You are invited to take part in a research study that explores the safety, usability, and real-world accessibility of **smart and powered wheelchairs** in **public transport settings across Ireland**. This study forms part of my MSc dissertation.

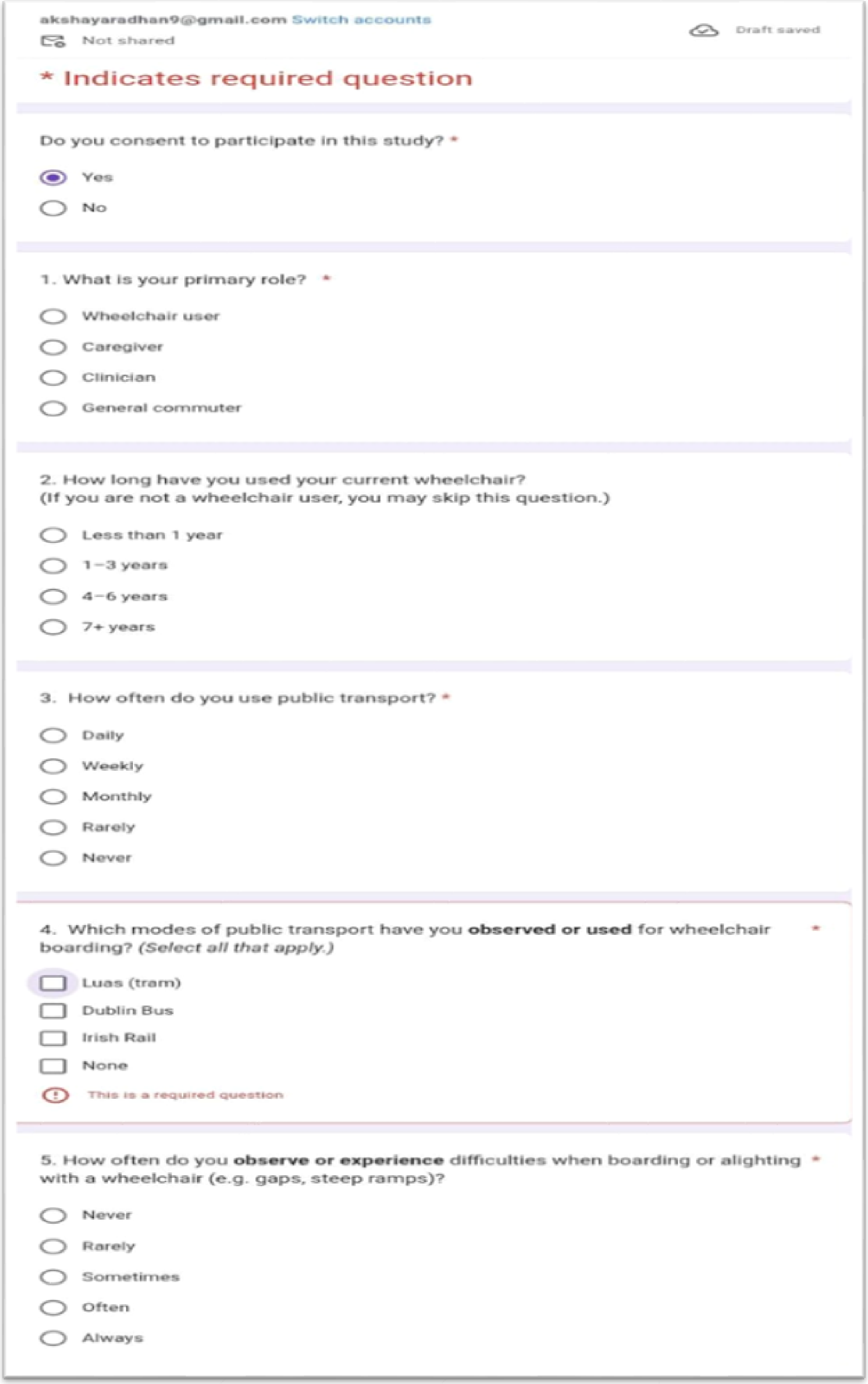
The purpose of this research is to gather insights from wheelchair users, caregivers, healthcare professionals, transport staff, and regular commuters. It aims to understand the challenges faced during boarding or alighting from buses, trains, or trams, as well as perceptions of current assistive technologies like obstacle sensors or audio alerts. Your input will help identify design improvements, accessibility gaps, and practical strategies for making transport systems safer and more inclusive for all users.

The survey will take approximately **10–12 minutes** to complete. It includes a combination of multiple-choice, scaled, and optional open-ended questions. Participation is entirely voluntary, and you are free to withdraw at any time without providing a reason.

All responses will be **anonymous** and treated confidentially, in full compliance with **GDPR** and the ethical standards of Griffith College. No identifying information (such as your name or IP address) will be collected unless you voluntarily provide it for follow-up or further participation.

If you have any questions, concerns, or would like to know more about the study, please feel free to contact me at: **akshayaradhan.puthoor@student.griffith.ie**

Thank you for considering your participation. Your perspective will contribute meaningfully to a better, safer, and more accessible future for wheelchair users in Ireland's public transport system.



* Indicates required question

Do you consent to participate in this study? *

● Yes
○ No

1. What is your primary role? *

○ Wheelchair user
○ Caregiver
○ Clinician
○ General commuter

2. How long have you used your current wheelchair?
(If you are not a wheelchair user, you may skip this question.)

○ Less than 1 year
○ 1–3 years
○ 4–6 years
○ 7+ years

3. How often do you use public transport? *

○ Daily
○ Weekly
○ Monthly
○ Rarely
○ Never

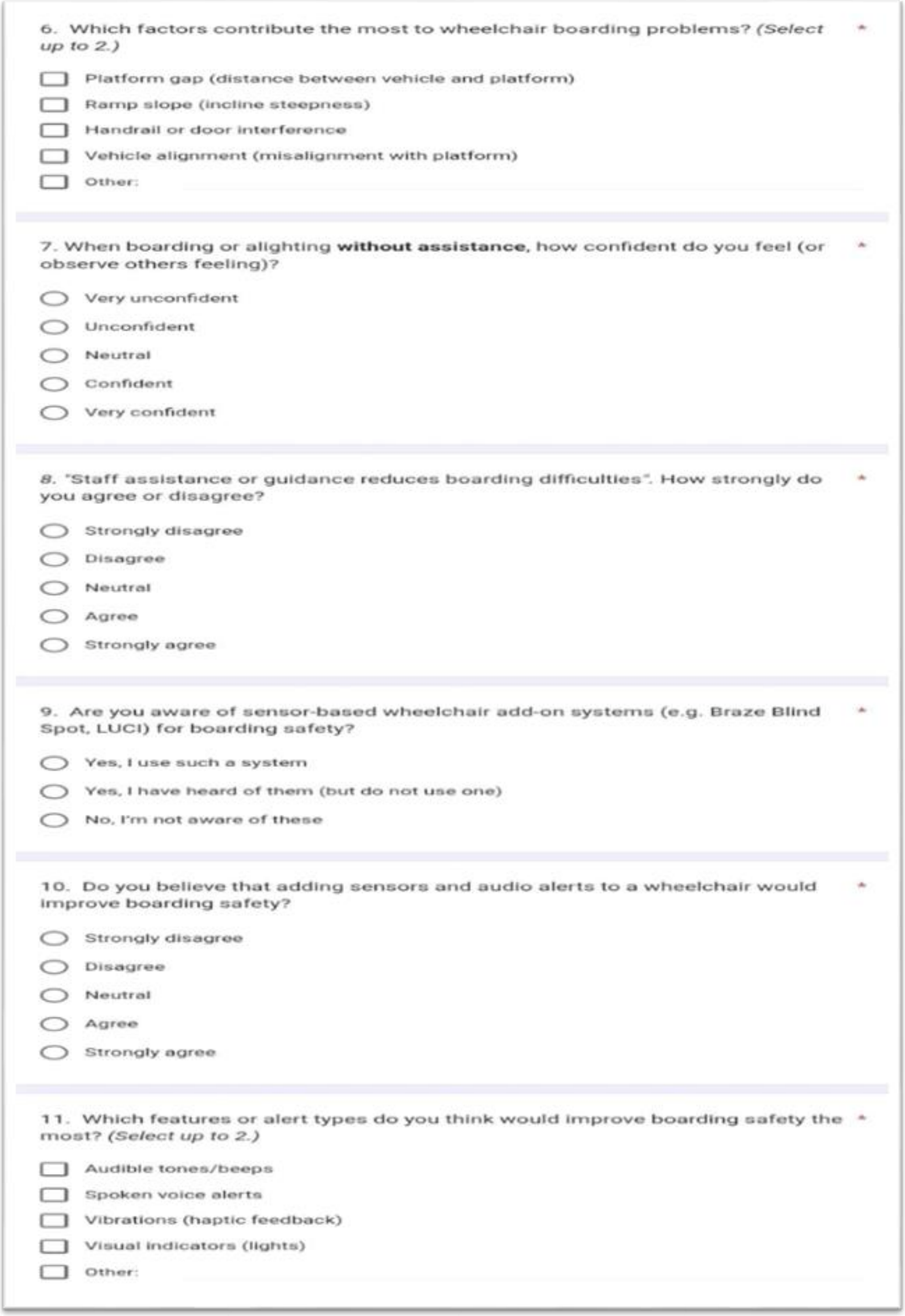
4. Which modes of public transport have you **observed or used** for wheelchair boarding? *(Select all that apply.)* *

☐ Luas (tram)
☐ Dublin Bus
☐ Irish Rail
☐ None

This is a required question

5. How often do you **observe or experience** difficulties when boarding or alighting with a wheelchair (e.g. gaps, steep ramps)? *

○ Never
○ Rarely
○ Sometimes
○ Often
○ Always



6. Which factors contribute the most to wheelchair boarding problems? *(Select up to 2.)* *

☐ Platform gap (distance between vehicle and platform)
☐ Ramp slope (incline steepness)
☐ Handrail or door interference
☐ Vehicle alignment (misalignment with platform)
☐ Other:

7. When boarding or alighting **without assistance**, how confident do you feel (or observe others feeling)? *

○ Very unconfident
○ Unconfident
○ Neutral
○ Confident
○ Very confident

8. "Staff assistance or guidance reduces boarding difficulties". How strongly do you agree or disagree? *

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

9. Are you aware of sensor-based wheelchair add-on systems (e.g. Braze Blind Spot, LUCI) for boarding safety? *

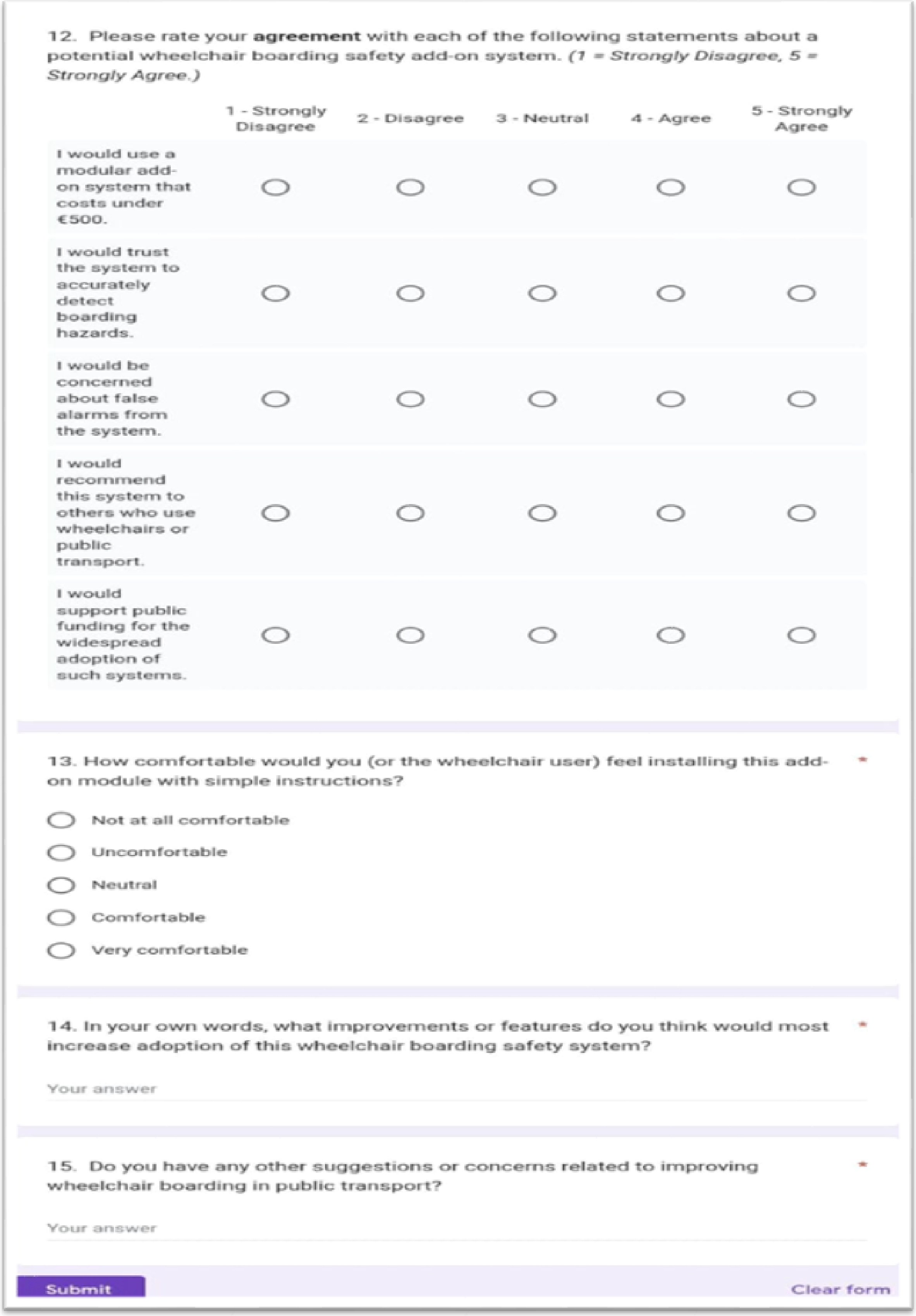
○ Yes, I use such a system
○ Yes, I have heard of them (but do not use one)
○ No, I'm not aware of these

10. Do you believe that adding sensors and audio alerts to a wheelchair would improve boarding safety? *

○ Strongly disagree
○ Disagree
○ Neutral
○ Agree
○ Strongly agree

11. Which features or alert types do you think would improve boarding safety the most? *(Select up to 2.)* *

☐ Audible tones/beeps
☐ Spoken voice alerts
☐ Vibrations (haptic feedback)
☐ Visual indicators (lights)
☐ Other:



12. Please rate your **agreement** with each of the following statements about a potential wheelchair boarding safety add-on system. *(1 = Strongly Disagree, 5 = Strongly Agree.)*

	1 - Strongly Disagree	2 - Disagree	3 - Neutral	4 - Agree	5 - Strongly Agree
I would use a modular add-on system that costs under €500.	○	○	○	○	○
I would trust the system to accurately detect boarding hazards.	○	○	○	○	○
I would be concerned about false alarms from the system.	○	○	○	○	○
I would recommend this system to others who use wheelchairs or public transport.	○	○	○	○	○
I would support public funding for the widespread adoption of such systems.	○	○	○	○	○

13. How comfortable would you (or the wheelchair user) feel installing this add-on module with simple instructions? *

○ Not at all comfortable
○ Uncomfortable
○ Neutral
○ Comfortable
○ Very comfortable

14. In your own words, what improvements or features do you think would most increase adoption of this wheelchair boarding safety system? *

Your answer

15. Do you have any other suggestions or concerns related to improving wheelchair boarding in public transport? *

Your answer

Appendix B: Ethics Committee Form

Innopharma
education

GRIFFITH COLLEGE

Ethics Application & Declaration Form

DISSERTATION TITLE: **Smart Wheelchair Safety and Accessibility in Public Transport: A Data-Driven Evaluation of Design Limitations and Real-World Challenges**

RESEARCHER’S NAME: AKSHAYA RADHAN PUTHOOR

PROGRAMME OF STUDY: MSc in Medical Device Technology & Business

SUPERVISOR'S NAME: SHAUNA COEN

DECLARATION:

The information in this application form is accurate to the best of my knowledge. I undertake to abide by the principles outlined by Innopharma /Griffith College's ethics policy in my research dissertation. I confirm that I have completed a full ethics assessment for my research dissertation as per the college guidelines. I will not begin my primary research until such approval from my supervisor and/or ethics Committee has been obtained.

I pledge to carry out my research according to the Innopharma/Griffith College academic integrity standards. Any results presented in my dissertation will be from my own, original research, I will reference and/or acknowledge any material or sources used in its preparation and I will not plagiarise the work of anyone else.

For Student:

STUDENT SIGNATURE: Aksh

DATE: 03-07-2025

The research contained within this research dissertation proposal has been approved.

[i]For Supervisor:

Ethics Committee Approval Required: Yes ☒ No ☐

SUPERVISOR SIGNATURE:

DATE: 07-Jul-2025

For Ethics Committee (if required): Ethics Committee Approval Given:
Yes ☐ No ☐

ETHICS COMMITTEE MEMBER SIGNATURE:

DATE:

NOTE: Supervisors are responsible for ensuring their students fill in this form correctly and that all ethical areas have been considered.

SECTION 1: DESCRIPTION OF RESEARCH STUDY

1.1 Purpose and objectives of research

The purpose of this research is to evaluate the accessibility, safety, and performance of smart wheelchairs in Irish public transportation systems. Despite rapid advances in assistive technology, such as shared-control algorithms, obstacle-avoidance sensors, and SLAM navigation, smart wheelchairs still face several challenges in dynamic environments, including buses, trams, and trains. Inadequate infrastructure led to a smart wheelchair getting stuck in the Luas incident in 2024, serving as a reminder that technology alone cannot address poor environmental design or a lack of staff support.

This study aims to bridge these gaps by using a mixed-methods approach to examine sensor reliability, boarding challenges, and user confidence in smart wheelchair technology. Including a range of stakeholder groups, including people who use wheelchairs, healthcare professionals, and transportation workers, will yield data-driven insights and direct recommendations for design improvements and policy interventions.

Objectives of the research are:

- To investigate common design and safety challenges of smart wheelchairs in Irish transport settings.
- To evaluate user experiences and incident data related to docking and boarding.
- To assess real-world performance of assistive features (e.g. sensors, locks).
- To identify design enhancements based on compliance with ISO/EU standards.
- To capture stakeholder perspectives on barriers and potential solutions

1.2 Research methodology:

An online survey will be the main tool used to collect data for this study. A structured questionnaire comprising multiple-choice, binary (yes/no), Likert scale, and "select all that apply" question forms will be developed based on the study's objectives. The survey will be revised in response to feedback after the academic supervisor reviews the initial draft for clarity and adherence to methodological and ethical standards.

The completed survey will be made available using Google Forms, a user-friendly and safe online platform that works with mobile devices and screen readers. The poll link will be shared via advocacy and professional networks, such as the Disability Federation of Ireland, the Irish Wheelchair Association, and pertinent LinkedIn groups for staff members working in hospitals and public transport.

Purposeful sampling will be used to recruit participants, with a focus on smart/electric wheelchair users, physiotherapists and occupational therapists, and employees of public transport (such as Luas, Dublin Bus, and Irish Rail). Participants will be encouraged to forward the link to peers who fit the inclusion criteria, especially those who reside in under-represented or rural areas, in order to promote snowball sampling.

Before the survey begins, participants will read a participant information sheet that explains the study's goals, confidentiality, and data security procedures. We will use the internet to get informed consent. During a specified data collection session, you can finish the self-administered survey whenever you want.

SECTION 2: POSSIBLE ETHICAL ISSUES

Answer 'yes' or 'no' to the following questions.

SUBJECT MATTER

Does the research proposal involve:

Research into specific company activities that would be deemed sensitive or confidential	No
Research into politically and/or racially/ethnically and/or commercially sensitive areas	No

Sensitive, personal, professional, or corporate issues	Yes

RESEARCH PROCEDURES

Does the research proposal involve:

Research that might damage the reputation of companies or participants	No
Research that may negatively affect the reputation of Griffith College/Innopharma	No
Use of personal records without consent	No
Use of company data without consent	No
The offer of any inducements to participate	No
Audio or visual recording without consent	No
Using a language other than English	No

PARTICIPANTS

Does the research proposal involve:

People who are not competent and/or fluent in English	No
Does your research group include any of the following vulnerable groups	Yes

(Adults with psychological impairments; Adults with learning difficulties; Adults under the protection/control /influence of others (e.g. in care/prison); Relatives of ill people (e.g. parents of sick children); Hospital or GP participants recruited in a medical facility; persons under the age of 18)

If you have answered NO to ALL questions, please go straight to Section 4.

If you have answered YES to ANY question in SECTION 2, you must fill in SECTION 3.

SECTION 3: STEPS TAKEN TO AVOID ETHICAL ISSUES

[Only fill in this section if you answered YES to ANY of the questions in Section 3. For example, if you answered yes to including participants who are not fluent in English, you might put forward a plan that offers your survey in two languages to take this into account. Another example could be a study where the researcher wants to include information about the care received by children with a long-term condition but it would not be ethical to approach the children directly but it might be acceptable to instead ask parents questions about their child's care. If these plans are acceptable to your supervisor, you may not need to apply for ethical approval from the Ethics Committee].

3.1. If your ethics relate to ***Subject Matter***, outline your action plan to work around any sensitive issues.

Intimate and possibly distressing tales about subjects like unsuccessful boarding attempts or safety incidents may be shared by participants. To ensure their welfare, no personal information will be collected, and all enquiries are voluntary. One of the resources available to participants if they require assistance or feel uneasy is the Irish Wheelchair Association helpline.

3.2. If your ethics relate to ***Research Procedures***, outline your action plan to deal with possible ethical issues in your research procedures.

No personal documents, audio or video recordings, or inducements would be needed because the study would be conducted using an anonymous, self-administered online survey on Google Forms. The academic supervisor reviews the questions to make sure they are clear, objective, and free of leading statements or technical jargon.

3.3. If your ethics relate to ***Participants***, outline how you will protect vulnerable persons or those who do not have English as their first language.

People who use wheelchairs, a group identified as vulnerable by the Belmont Report, are study participants. To uphold respect for persons, each participant is provided with an easily accessible Participant Information Sheet, and they are required to tick a box to indicate their agreement. They can skip any question or depart at any moment. Since no children, individuals with disabilities, or non-native English speakers are involved, participation is fully informed. This design strikes a balance between beneficence, or minimising harm, and justice, or guaranteeing fair, voluntary inclusion.

SECTION 4: ABOUT YOUR PARTICIPANTS

4.1. Outline your participant profile and why you have chosen them for this study.

People who frequently utilise public transport, drivers, platform helpers, adults in wheelchairs, and medical professionals such as physiotherapists and occupational therapists will all be part of my target audience. Participants must have used or aided with wheelchair boarding on Irish buses, trams, or trains during the last six months. Purposive sampling guarantees the selection of "information-rich cases" that are directly related to assessing the usefulness and safety of smart wheelchairs in typical travel situations. This research collects a range of practical viewpoints on assistive technology, design enhancements, and boarding concerns by involving users, carers, clinicians, and personnel.

4.2 How do you plan to gain access to/contact/approach your participant(s)?

I'll use a combination of purposive and snowball sampling methods to find participants. The Irish Wheelchair Association network, healthcare forums (like OT/PT associations), LinkedIn groups, and a transport staff email list will all be used to send out invitations. Snowball sampling will be encouraged by asking respondents to share the survey with their eligible peers. By using this technique, I can expand reach and data richness ethically and efficiently by targeting a specific, relevant audience and increasing the number of participants through trustworthy networks.

SECTION 5: INFORMATION, CONSENT AND CONFIDENTIALITY

5.1 **Participant Information Letter (PIL) for participants**

Please confirm below that your information letter covers:

Description of the research topic and method	Yes
Details of what participation will involve	Yes
Rights to anonymity	Yes
Confidentiality	Yes
Rights to withdraw from the research	Yes
The contact details of the researcher and supervisor (if necessary)	Yes

5.2 **Informed Consent Form (ICF) for participants**

[Informed consent is required for most research. For online surveys, it is sufficient to get the participant to tick two boxes at the beginning of the survey – one to state they understand the research and one to give consent. In all other research e.g. interviews, phonecalls, a signed consent form is required. If the data is gathered online e.g. zoom, a signed consent form can be scanned and sent to the researcher. A template ICF is available in Moodle. The signed ICFs, along with the surveys, audio files or interview notes etc. must be stored in the primary

data folder on moodle and can be accessed by Innopharma staff for the purposes of verifying the authenticity of the research carried out and the data collected].

Please indicate below if your research requires a signed consent form by selecting the relevant option only:

No: my research study involves an online survey only and/or does not require signed consent

SECTION 6: STORAGE OF DATA

[Please ensure that you are abiding by GDPR and the national Data protection laws https://www.hrb.ie/funding/gdpr-guidance-for-researchers/gdpr-and-health-research/).

The student is responsible for storage of data and this will be handed over to the college in an electronic format as part of the thesis submission i.e. primary data and completed ICFs where applicable will be added to the primary data folder on moodle. The rationale is to keep data ***as long as it is still useful*** *and there is an intention to use it further* ***for research*** *so if this is not the case then this can be stipulated here and a shorter retention period given.]*

6.1. How will you store the research data and for how long? How will you manage data protection issues?

All research data will be stored electronically in a secure, password-protected OneDrive folder authorised by Griffith College. Only the researcher and academic supervisor will have access. Identifiable personal data will not be collected; responses will be anonymised through coding before analysis and reporting. Data will be retained for one year after study completion, in line with Griffith College's records retention policy, which mandates that personal data be kept only as long as necessary. After this period, all electronic files—both cloud and local—will be permanently deleted. Throughout the study, GDPR principles will be followed, including data minimisation, storage limitation, and integrity and confidentiality. Secure file transfer protocols and restricted access will safeguard the data. Only aggregated, anonymised results will be published, ensuring that individual participants cannot be identified. These processes will be communicated in the Participant Information Letter to maintain transparency.

SECTION 7: NON-DISCLOSURE AGREEMENT & STUDENT CONSENT

7.1 **Non-Disclosure Agreement (NDA)**

Will the final dissertation contain any information pertaining to any source what would warrant the use of a Non-Disclosure Agreement (NDA) e.g. industry-based research? -

No

7.2 **Student consent**

If a Non-Disclosure Agreement (NDA) is not required, does the student consent to allow their completed dissertation to be held/published by Innopharma/Griffith College?

Yes

SECTION 8: RECORDING AND RETENTION OF DISSERTATION VIVA

8.1 **Viva Recording**

The Dissertation viva will be recorded. This recording may be used to facilitate assessment by Innopharma staff, a third reader if necessary, and/or if requested by the external examiner for the Programme. The recording will be held in line with current GDPR guidelines and will not be made publicly available.

SECTION 9: DOCUMENT CHECKLIST

NOTE: Applicants must attach the following documents in electronic format to the appendix.

Which documents are added to the appendix? Please tick N/A if not applicable:

9.1 Participant Information Letter (PIL) for participant	Yes
9.2 Informed Consent Form (ICF) for participant	N/A
9.3 Questions/survey for interviewees/focus groups etc *(can be in draft form)*	Yes
9.4 Any other documents e.g. Non-Disclosure Agreement	N/A

I confirm that this application is complete and all required documents are included in the appendix.

For Student:

STUDENT SIGNATURE:

Aksh

DATE: 03-07-2025

Participant Information Letter

SMART WHEELCHAIR SAFETY AND ACCESSIBILITY IN PUBLIC TRANSPORT: A DATA-DRIVEN EVALUATION OF DESIGN LIMITATIONS AND REAL-WORLD CHALLENGES

My name is Akshaya Radhan, and I am a researcher at Griffith College, Ireland, currently studying my master's in Medical Device Technology & Business. I am conducting a research project to understand how smart wheelchair design features, such as sensors, collision-avoidance systems, and docking mechanisms, interact with real-world public transport infrastructure in Ireland, and to identify improvements that can enhance safety and independence for wheelchair users. If you agree to participate, you will be invited to complete a survey, which will be sent to you as a Google Form. Completing the survey will take approximately 10-15 minutes of your time.

Since you are familiar with Irish public transport and smart/electric wheelchairs, I am inviting you to participate in this study. Your opinions are important, regardless of whether you are a wheelchair user who regularly takes buses, trams, or trains, a medical professional who advises or instructs patients on powered wheelchairs, a transport worker who assists wheelchair users, or an average traveller who observes accessibility issues. With your help, we can more accurately evaluate how well-suited the current smart-wheelchair technologies are for real-world transit situations and pinpoint areas where acceptance, usability, and safety could be enhanced.

There is no obligation to participate. You are free to decline to participate in this study in any way or to not respond to any of the survey's questions. Additionally, you are free to leave the study at any time without facing any repercussions.

If you need to withdraw, please contact:

- Akshaya Radhan Puthoor
- Phone: 0894904217
- Email: akshayaradhan.puthoor@student.griffith.ie

There are minimal risks associated with participating in this study. You are free to withdraw from the study till 7 days after completion of the research, after which the response will be used for the research.

Confidentiality and Data Protection:

All your information will be kept confidential. Your name and any other identifying information will be removed from the final responses and any reports generated from this research. The survey data will be stored securely on a password-protected OneDrive and will be deleted 1 year after completion of the research.

Results outcome

The primary outcome of this research will be the completion of my Master's thesis at Griffith College. The thesis will be accessible through the college library and may potentially be made available electronically through online repositories. All dissertation research projects, and their content, will be made accessible in the college library and could potentially be made available in online e-journals

For additional details regarding the study's objectives, methodology, ethical considerations, participation requirements, potential risks and benefits, data handling, or results dissemination, please contact:

Supervisor Name: Shauna Coen

Mail: shauna.coen@griffith.ie

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[i]