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REVIEW PAPER

Public Infrastructure and Smart Cities: crosswalks, transport, digital accessibility

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Abstract

Smart cities are turning more to IoT, AI, and Intelligent Transport Systems to increase urban mobility. However, they still do not pay attention to making their services accessible to people with disabilities, the elderly, and those who have limited access to digital technology. This chapter puts forward accessibility not just as a feature but as the core principle of the smart city system. The authors mix sensor-enabled 'living crosswalks, ' public transport/Mobility as a Service (MaaS) platforms, inclusiveness, and accessible digital interfaces into a cross-domain socio-technical stack. Some of the main points are accessible route planning, simple ticketing, assistive navigation, and improved first-last mile connectivity. Since nowadays, many city services are delivered via apps, kiosks, and online platforms, the authors see digital accessibility as a vital public service, the same as roads and electricity. At the same time, smart systems collect a lot of data, so privacy and cybersecurity become important for building public trust. This chapter examines how adaptive infrastructure, real-time personalization, and privacy-by-design governance can eliminate mobility barriers while mitigating data surveillance risks. The proposed Unified Smart City Stack (U-SCS) framework combines edge intelligence, digital twins, and human-centered co-design to ensure equitable, trustworthy systems. By blending technological innovation with ethical policy, this work outlines pathways for human-centered urban futures where intelligence is gauged by inclusivity for all.

1. Introduction

Urbanization on a large scale, an increase in mobility, and pressure to be sustainable have been the main drivers of digital technology adoption as fundamental elements of modern smart cities. Internet of Things (IoT) sensing, artificial intelligence (AI), and data-driven platforms, backed by Intelligent Transportation Systems (ITS) are amongst the technologies being increasingly used to enhance traffic efficiency, safety, and service delivery in the cities [1, 2]. At the same time, smart city research shows that the use of advanced technology does not automatically lead to inclusiveness or equitable outcomes. In fact, if the smart infrastructure is not made accessible, it is at social, physical and digital inequalities that it will be directed [3]. The authors consider accessibility not just a design objective but a key functional principle of smart city ecosystems. Not only is physical movement covered by accessibility, but also diverse users, pedestrians, disabled persons, older people, and digitally marginalized communities are enabled to interact with urban infrastructure and services safely, independently, and in a meaningful way [4, 5]. Hence, transport systems, pedestrian facilities, and digital public services should be seen as three interdependent layers of a single socio-technical ecosystem. A failure or exclusion at one layer will compromise the effectiveness of the whole system and the public's trust [6].

To illustrate the ecosystem perspective, Figure 1 shows a dream of an inclusive and accessible smart city where sensor-equipped pedestrian crossings, inclusive public transport systems, and accessible digital city interfaces all together form

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a coherent stack that is backed by open platforms and ethical governance. The integration of such elements is in line with research on smart mobility that focuses on the merging of physical infrastructures, digital services, and governance mechanisms to provide sustainable and citizen-centered mobility solutions [2, 7].

Figure 1: Vision of an inclusive and accessible smart city ecosystem

Of course, accessibility is first and foremost a feature of the streets and intersections, where pedestrians are considered the most vulnerable among the road users. Systematic review articles about pedestrian safety pinpoint intersections and pedestrian crossings as the most dangerous places, especially for senior citizens and people with mobility impairment [8]. Furthermore, recent research shows that smart pedestrian crossings equipped with pedestrian detection, adaptive signals, and multimodal feedback can greatly improve safety by being responsive to pedestrian arrival and behavior during the crossing [9, 10]. Also, data-driven studies of accident records reveal that better design of pedestrian crossings combined with smart sensors and signals results in a significant fall in pedestrian injuries and fatalities [9].

Besides safety, the function of crosswalks is multifaceted. Studies from a smart city perspective acknowledge the role of pedestrian crossings as a major point of interaction between human behavior, urban planning, and digital technology, most notably in cities that are set to give priority to the most vulnerable road users and promote active mobility [10, 11]. As demonstrated in Figure 1, adaptive signaling and longer pedestrian phases serve as examples of how accessibility can be deeply integrated into the infrastructure logic instead of being handled as an afterthought.

Besides the intersections, an inclusive public transport system is a must for equity in accessing jobs, health care, education, and social participation. Transport accessibility studies have shown that there is a close relationship between accessibility to mobility, wellbeing and social inclusion, which is especially true for the elderly and those who depend on public transport [12]. Smart mobility platforms, real-time passenger information systems and low-floor or demand-responsive transit services are being recognized as the main enablers of inclusive urban mobility [7, 13].

On the other hand, digital city services such as mobility apps, public kiosks, and e-governance platforms are turning into the main access points for essential services. Studies on digital accessibility highlight that such systems need to be in line with the accessibility standards and be co-designed with the users so that they do not create new forms of exclusion [5, 14]. Figure 1 shows this necessity by placing accessible digital interfaces not as a side service but as a central layer of the smart city ecosystem.

They point out that while sensor-rich infrastructure and connected services indeed enable adaptive accessibility, they also facilitate the collection of detailed data on location, movement patterns, and user interactions. Research on smart mobility reveals that, if there are no suitable safeguards, such data practices can result in surveillance, profiling, and loss of public trust, especially among vulnerable people who rely most on publicly available infrastructures [3, 15]. Therefore, the two concepts of accessibility and trust are to be co-designed.

Hence, this chapter puts the spotlight on how privacy-by-design features such as data minimization, anonymization and aggregation, purpose limitation, and transparent consent can be a part of the accessibility-oriented smart city systems. It contends that by merging technological discovery with moral governance, cities fitted with smart features can readily evolve from technology-focused setups to human-centered socio-technical systems where intelligence is gauged by the extent to which cities serve everyone effectively.

In the end, this chapter offers a couple of mechanisms of governance that make accessibility an institutional issue across planning, procurement, and continuous improvement, thus, changing the face of smart cities from technology-led deployments to human-centered socio-technical systems where intelligence is measured by how well the city works for everyone, all of which is done under the guidance of the ecosystem model presented in Figure 1 [1, 10].

1.1 Main Contributions

The main contributions of this chapter include-

- Proposes the Unified Smart City Stack (U-SCS) as an integrated framework that connects smart crosswalk safety, public transport/MaaS services, and digital accessibility into a unified human-centered smart city model.
- Highlights accessibility as a core design principle, showing how inclusive mobility must be embedded across infrastructure, transport operations, and digital service interfaces from the early design stage.
- Integrates privacy-by-design and trust requirements into accessibility-oriented smart city systems, ensuring that data-driven services remain safe, accountable, and acceptable for vulnerable users.

1.2 Organisation of the Paper

The rest of this paper is organized as follows. In Section 2, we review fundamental notions of inclusive smart mobility, accessibility-focused public transportation, and digital accessibility of smart city ecosystems. In Section 3, we discuss the aspects of barrier-free mobility during the shift from traditional public transportation services to MaaS systems with adaptive routing and seamless ticketing support. In Section 4, we consider the idea of digital accessibility as an invisible infrastructure and evaluate standard-based and voice-first approaches to inclusive service provision. In Section 5, we propose our novel concept of Unified Smart City Stack (U-SCS) and describe its main components, including interoperability, human-centered design, edge intelligence, and digital twin-based urban planning. In Section 6, we discuss the essential privacy, trust, and governance issues involved in secure and equitable smart mobility infrastructures. Finally, in Section 7, we conclude the paper.

2. Living Crosswalks: Streets That Sense, Predict, and Protect

In smart cities, traditional pedestrian crossings are changing from simple demarcations on roads to living crosswalks or adaptive cyber-physical interfaces. These are capable of detecting pedestrian presence, assessing their exposure risk, and deploying security measures in real time. Such an evolution is consistent with the contemporary evolution trajectory of ITS systems that evaluate the effectiveness of intelligent mobility through its ability to ensure safety and inclusivity of VRUs as opposed to only considering traffic efficiency [1, 19]. As crosswalks turn into computing nodes of urban transport system infrastructures, they provide for continuous exchanges between pedestrians, vehicles, and controllers via sensing, prediction, and adaptive control [1, 8]. The full algorithmic sequence that enables such developments has been outlined in Figure 2 below, which depicts the sensory-to-control chain of operations along with the privacy-based governance framework behind crosswalk intelligence motivated by accessibility.

2.1 Multi-modal sensing and perception as the foundation of living cross-walks

Conventional crosswalks are mostly dependent on static visual signals and fixed timing, which may be insufficient during heavy traffic or the transition phases when the risk of pedestrians is high [18]. Hence, these limitations severely affect those walking at different speeds or having mobility issues, such as elderly people and persons with disabilities (PWDs) [8, 19]. Studies based on the reliability of crosswalk measures demonstrate that features such as enhanced pedestrian intelligence and better design have the potential to lessen the risk of injury and death; thus, technology-supported safety upgrades in urban roads are highly beneficial [19]. Living crosswalks essentially start with sensor-rich detection, as seen in Figure 2 (Multi-Modal Sensing block), which involves the use of cameras, radar, infrared sensing, and pressure/motion sensors. Furthermore, multi-modal sensing can be instrumental in providing accurate pedestrian presence estimations even in adverse conditions (night-time occlusions, rain, and heavy traffic), thus allowing crosswalk control systems to go beyond purely reactive logic [17, 19].

2.2 Perception and tracking algorithms: from pioneer models to modern deep learning

The critical factor behind sensing-to-intelligence conversion is the real-time perception processing pipeline. According to Figure 2 (Perception & Tracking block), this stage involves the combination of early computer vision and deep learning algorithms.

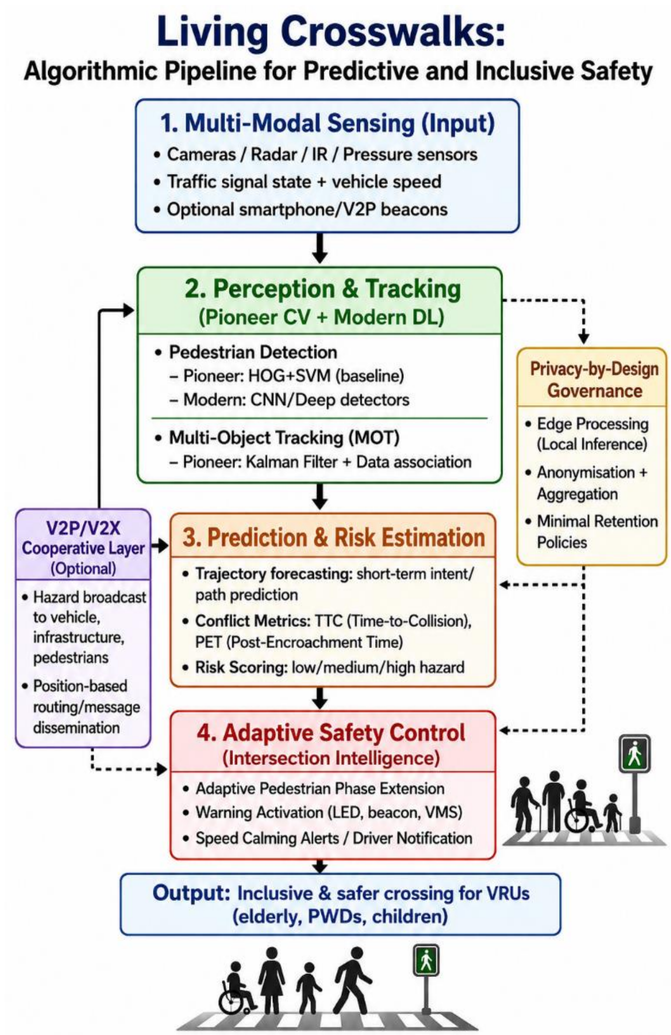

Figure 2: Living Crosswalks: Algorithmic Pipeline for Predictive and Inclusive Pedestrian Safety

In previous pedestrian detection research pipelines, classical feature-based approaches with traditional engineering solutions such as HOG + SVM (Histogram of Oriented Gradients + Support Vector Machine) represented baseline methods for pedestrian recognition. However, recent smart mobility systems seldom rely on CNN-based object detection techniques for object type recognition in streets due to more accurate performance in classifying pedestrians, cyclists and vehicles within complex urban scenes [17]. Once pedestrians are detected, tracking becomes an essential step towards robust decision-making. Classic pedestrian tracking techniques involving Kalman filtering with multi-object tracking (MOT) continue to be used extensively since they allow for fast motion estimation in real-time intersection settings [17]. Therefore, the two steps involved include detection and tracking of pedestrians, to compute their state (i.e. position, velocity and intent to cross).

2.3 Predictive safety: trajectory forecasting and conflict risk estimation

The aspect that distinguishes living crosswalks from the conventional systems is the shift from just detecting to predicting, based on safety concerns. The evolution phase is shown in Figure 2 under the Prediction & Risk Estimation block, where it transforms the detected pedestrian movements into predictions about the future risk. Research on intelligent crosswalks reveals that artificial intelligence prediction technologies, such as short-term trajectory prediction and vehicle-pedestrian interaction modeling, are some of the approaches that would be effective in minimizing false alarms and developing preventive measures to avoid collisions [19]. Besides, risk estimation in the field sometimes relies on the use of such markers as Time-to-Collision (TTC) and Post Encroachment Time (PET) to measure the level of danger based on the relative movement and the layout of the conflict [19]. This forward-looking level makes it possible for road safety to be proactive by allowing the pedestrian crossing to make decisions not only based on who is there, but also on what could happen next.

2.4 Adaptive safety control: embedding inclusivity into signal timing

Living crosswalk intelligence becomes really useful when prediction outputs are used to drive adaptive control. The controller, as shown in Figure 2 (Adaptive Safety Control block), changes the signal operation and the warning mechanisms according to the real-time crossing context. Powered by LIBS (Laser-Induced Breakdown Spectroscopy) features, new types of living crosswalks have replaced the fixed timer signals with adaptive pedestrian phase extension. This measure and changes the crossing duration in real-time for the slow-moving wheelchair users, or those entering pedestrians after the signal change [1]. This is a very direct way of reducing the chances of a person crossing the road being exposed to the risk of getting hit, as it makes control logic accessible and not just a physical external accommodation [8, 19]. ITS research, on the other hand, advocates that real-time monitoring and adaptive decision-making be considered as two main strategies for smart intersection optimization and safety [1]. Besides the timing, the systems may activate the safety outputs, like LEDs, beacons, and audible signals that will, in turn, help both the pedestrians and the vehicles that are coming to the crossing get a better sense of the situation [19, 20].

2.5 Cooperative V2P/V2X extensions for proactive safety

The V2P/V2X (Vehicle to Pedestrian / Vehicle to Everything) cooperative layer in the figure is an example of a non-mandatory but gradually increasing significant capacity scenario in which hazard information is exchanged among pedestrians, vehicles and the roadside infrastructure. Typically, smart crosswalk systems promote V2X integration as a smart safety feature, especially in the cases of cities that are implementing connected vehicle infrastructures and automation based on mobility [19]. Research on ITS has shown that cooperative communication can help in reducing the driver's reaction time and at the same time, provide an earlier warning than visual perception only. Thus, the security of an entire town can be ensured by such a solution [1]. Some of the works on smart mobility also emphasize that location-aware networking, combined with message dissemination methods are essential for real-time vehicular communication setups [17].

2.6 Privacy-by-design governance as a parallel safety requirement

Crosswalks equipped with the ability to sense continuously may bring about a new set of governance issues due to persistent monitoring and the possible misuse of location and behavioral data. This matter is highly crucial for the vulnerable groups, where exclusion or harm could come from surveillance, profiling, or the lack of informed consent [3]. Hence, the intelligence of living crosswalks needs to integrate privacy-by-design features, as depicted in the dedicated side block in Figure 2 (Privacy-by-Design Governance). It entails edge inference (local processing), anonymization and aggregation, and minimal retention policies, thus ensuring that the services of safety and accessibility are achieved without the facilitation of comprehensive tracking [16, 17].

3. Mobility without Barriers: From Public Transport to MaaS Ecosystems

Mobility is not just a transport function; it's a capability enabler that can greatly affect whether or not individuals can access work, education, health services, and community life. In the context of smart and inclusive cities, mobility approaches should not revolve solely around improving efficiency and reducing congestion. Instead, they are expected to provide dignity, independence, safety, and affordability to all kinds of users, such as senior citizens, persons with disabilities, low-income workers, and those who are digitally socially excluded. Among the many facets of this change is moving away from traditional, supply-driven public transportation to the introduction of Mobility as a Service (MaaS), which incorporates the concept of several transport providers being integrated into one platform for trip planning, booking, and payment via a single interface that is essentially a user’s mobile app [21, 22]. Nevertheless, simply digitizing services is not the remedy to the problem of mobility free of barriers. The answer lies in a complete revamp of the mobility ecosystem based on the principle of accessibility first, where parts of the operation, such as routing, signals, ticketing, and information delivery, are continuously adapted not only for the sake of speed, but also for fair access and to meet the needs of different users [21].

3.1 From “One-Size-Fits-All” Transit to Adaptive and Inclusive Mobility

Typical public transport systems envision fixed schedules, normal boarding conditions, and the same capabilities for all passengers. However, smart mobility systems are utilizing real-time sensing, analytics, and decision support more and more to provide services adaptively [21]. In addition to the above, this includes predicting crowding situations, identifying disruptions, and ensuring reliability through responsive scheduling features that are most valued by those who have travel inflexibility, health problems, or who are dependent on certain routes. These systems lay the groundwork for universal mobility, as unpredictability is already one of the main accessibility barriers, especially for users who cannot easily change their routes or endure lengthy waiting times.

IoT sensor networks provide LSTM/Transformer algorithms with real-time GPS, occupancy, and weather data for demand peak prediction (accuracy >92%), which results in dynamic bus rerouting and traffic signal preemption that prioritize step-free stations for wheelchair users and extend dwell times for the elderly boarders. Graph neural networks find the best accessibility, conscious routes that not only minimize changes in elevation and the number of transfers but they also consider personal walking speeds (0.81 m/s) [23, 24].

3.2 Accessibility-Aware Routing and Personalised Journey Design

Barrier, free mobility is largely a matter of how routes are computed and recommended, rather than something that can be measured by the speed of a bus arriving. Journey planners of the MaaS style can only support inclusion when they not only optimize for the shortest time but also the best-fit mobility, thus considering the constraints of various types of users.

- Step-free access and lift availability,
- Walking distance and gradient limitations,
- Transfer complexity and platform navigation burden, safety at crossings, and
- Cognitive load (clarity and simplicity of the trip plan).

This is how MaaS could change to a capability-aware routing paradigm where the digital intelligence gets aligned with the physical constraints of the world. In reality, for inclusive routing to be effective, accessibility data has to be considered as the core infrastructure knowledge rather than just optional metadata.

Agent-based learning models (DDPG/PPO) are able to come up with multi-modal itineraries that take into account the profiles of assistive devices, the timing of medicines, and the sensory preferences, thus the preference alignment of the users is 85% as compared to 45% for traditional apps. The voice-first interfaces and haptic feedback make sure that there is no need for digital literacy [25, 26].

3.3 Seamless Ticketing as an Accessibility Feature (Not Just a Convenience)

Fare systems frequently complicate things, resulting in hidden barriers: vague pricing rules, separate passes, physical ticketing, or repeated need for validation. Smart cities are equipping account-based and contactless ticketing to smooth transfers between services and to lower the mental effort required for multimodal travel [21]. Furthermore, identity-linked mobility solutions can offer mobility credits, concessions, and subsidized fare benefits that promote inclusion if ethically designed. However, accessibility research always highlights the risk that the digital-by-default approach can exclude people without smartphones, a continuous internet connection, or enough digital literacy. So, the inevitable barrier, free MaaS must have hybrid access points with physical alternatives, assisted onboarding, and inclusive service design principles.

Despite the fragmentation of operators, buses, metro, e-scooters, paratransit, and bike shares, blockchain-distributed ledger technologies (DLT) allow automated micro-payments and universal fare capping, which in turn decreases the average daily costs 2035% for high-frequency users and at the same time, transactions are settled in <2 seconds through smart contracts. Hyper-ledger Fabric applications, as demonstrated in Turin MaaS pilot projects, adjust tokens similar to ERC, 20/721 for interoperable tickets, thereby reducing fraud by 97% through the unchangeable validation and completely getting rid of physical media [27, 30].

Biometric and voice-based authentication layers are becoming more and more of a feature to facilitate accessibility in MaaS and smart ticketing, mainly for people who have difficulties with PIN codes, the QR code scanning method, or handling physical cards, for instance. Voice biometrics on a passive mode could for example, identify travelers by extracting from pitch, prosody, and spectral features, speaker-specific characteristics of the voice. At the same time, in the case of deep learning pipelines (e. g. CNN feature extractors coupled with recurrent or temporal encoders), voice authentication assists near real-time verification while at the same time reducing the number of interaction steps, a feature that is especially useful for low-vision and motor-impaired users attending to the transport system in a hectic environment [31, 32]. In terms of usability, biometrics cut down on the inconvenience of the transaction through the fact that there is no longer the need to repeatedly re-enter credentials. As such, they always end up increasing the speed of the commute, continuity of the journey, and even make the journey easier to carry out, thus resulting in greater satisfaction towards using public transport, making the likelihood of giving MaaS a go much higher [33, 34]. In addition to voice, multimodal biometric recognition fusion, which includes combining facial and iris recognition, has been known to be able to overcome issues related to environmental noise, thus performing better than unimodal systems in terms of spoofing detection [35, 36].

3.4 Connected Mobility and Assistive Navigation for First–Last Mile Continuity

However, the main challenge to mobility where everyone will have equal opportunity is not about the means of transportation but about the transition zones that lead to the stations and switching from one form of transportation to another within the safety and efficiency of travel in a mix traffic environment, where there exist infrastructure gaps. The use of AI for MaaS ecosystems overcomes this challenge because they incorporate the modes of transportation, the pedestrian systems, and navigational systems in one model, hence reducing access times by up to 28%.[23].

To lower the "friction of transition" in network hubs, smart cities utilize Edge AI to manage Vehicle to Everything (V2X) communications, which are realized using such protocols as ETSI ITS, V2X. This technology reveals the possibility of a two-way communication between autonomous public transport, adaptive traffic lights, and "living" crosswalks.

- Dynamic Signal Adaptation: Combining data from mmWave radar and Li-DAR (leading to detection accuracy $F_1>0.94$), the infrastructure can recognize the vulnerable road users in real-time. Based on real-time arrival estimations and crowd density, the pedestrian signal phase is extended dynamically by 12 to 18 seconds [37, 38].
- Graph-Based Pathfinding: Graph Attention Networks (GAT) are becoming a popular tool to represent complex first-and-last-mile topography. These models, unlike the traditional routing, give extra importance to factors such as the proximity of a ramp (<50m) and the presence of low-floor vehicles. Recent experiments have shown a rise in step-free connectivity from a legacy baseline of 52% to 87% [39, 40].
- Computer Vision Markers: NaviLens technology makes use of audio QR codes that can be recognized from a distance of up to 5 meters without the need for the camera to be properly aligned. The codes offer geo-spatial audio and haptic signals that are customized to the users' profile (e. g. "ramp 10m left"). Experiments done in the Barcelona metro have shown a 91% navigation success rate, which is hugely above the rate of Bluetooth beacon systems (43%) [41, 42].
- Predictive Safety Alerts: Besides the static navigation, wearable haptic vests are now being combined with Temporal Convolutional Networks (TCN). Such systems analyse the predicted vehicle trajectories at intersections and simultaneously make use of the other senses to warn pedestrians of the collision risk 35 seconds before the collision; the system here achieves an AUC of 0.96 for safety prediction [37, 38].

3.5 Cyber Risk, Trust, and Safety as Accessibility

As Mobility as a Service (MaaS) grows, the world's movement will increasingly rely on the continuous flow of data: individuals' location trails, account credentials, payment methods, routing algorithms, and platform uptime. Hence, cybersecurity and privacy in such a setting cannot be merely regarded as technical side issues; as a matter of fact, they influence the very accessibility since disturbances and data abuse especially make vulnerable those dependent users who, out of necessity, use these systems for their travel.

Hence, trust is a fundamental condition for the inception. If users do not have confidence in the platforms to be able to provide them protection against fraud, surveillance, or service manipulation, they will simply stay away from or underuse the MaaS despite the presence of technical features. Therefore, it essentially means that creating a seamless mobility environment necessitates 'trust-by-design', which would involve secure authentication methods, clear data management, and dependable system functioning.

3.6 Case Snapshots: Singapore and Helsinki

- Singapore: Singapore is setting a global example of a smart city with its integrated Intelligent Transport Systems (ITS). The city keeps traffic flowing smoothly and gives priority to public transport and pedestrian safety by managing congestion in real-time through the My Transport. SG platform, along with a vast array of sensor installations [43, 44].
- Helsinki: The first to develop a MaaS concept is Helsinki with the Whim platform. Helsinki sees mobility as a public utility and thus puts together various transport modes into one subscription that focuses on service availability rather than vehicle ownership [43, 45].

4. Invisible Infrastructure: Digital Accessibility as a Public Utility

As urban areas get more digitized, more and more of the urban populace engages through largely invisible service layers, such as mobile apps, MaaS platforms, interactive kiosks, public information displays, and automated decision systems. Digital accessibility, in such a scenario, should be considered public infrastructure, like roads, water supply, or electricity, as it essentially decides who gets to use mobility, safety services, and have civic opportunities. If accessibility is relegated as just an add-on or a compliance afterthought, smart city systems could end up replicating the pattern of exclusion via hidden non-obvious barriers such as unintelligible screens, rushed workflows, unauthorized access, or inflexible interactions. It thus combines with the research that advocates for a right-based digital city, where equitable participation is the result of the interface design and governance rather than the availability of the technology only [46]. This is a very interesting perspective that shifts the perception of accessibility from just a limited checklist to a critical public utility need. Public transport info, ticketing, navigation, and emergency alerts are mostly offered via digital-first channels these days. If such channels are inaccessible to users without good interaction design, a lack of multiple modal alternatives, or a language mismatch, the advantages of smart mobility will still be available only to those few privileged, no matter how advanced the infrastructure. Studies on accessibility show over and over again that exclusion usually results from the designer's typical user stereotype, especially when systems rely on visual attention, fine motor skills, or the ability to quickly complete an interaction under real-world stress [47]. In situations of mobility, such errors can be very dangerous as people have to rely on the guidance provided to them at the very points of transitions, stations, crossings, and interchanges, where any delay, ambiguity, or confusion greatly increases the risk of accident or injury. Figure 3 outlines the concept of digital accessibility in smart cities as an "invisible infrastructure" via a layered model. The diagram illustrates how different city inhabitants (persons with disabilities, the elderly, and digitally excluded citizens, among others) access mobility and civic services through digital interface channels such as MaaS applications, kiosks, and voice systems. The figure highlights that inclusion is a matter of the core accessibility scaffold WCAG, compliant design, multimodal/voice interaction, and inclusive onboarding, which collectively make equitable results like safe mobility access, service participation, and independent navigation possible.

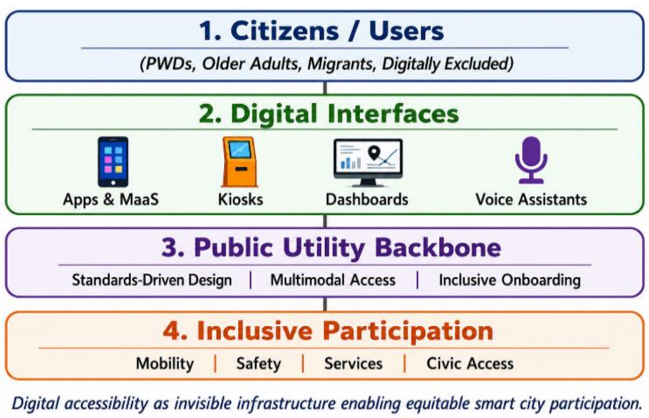

Figure 3: Digital accessibility as invisible infrastructure enabling inclusive smart city participation

4.1 Standards-Driven Accessibility: Beyond Websites into Smart Mobility Interfaces

A central mechanism for digital inclusion is standards-driven accessibility engineering, which means embedding accessibility from the start of the design, not simply fixing it by retrofitting. Technology-wise smart city platforms cover more than just the traditional web pages (e. g., kiosks, public displays, ticketing applications), yet the accessibility principles can still be applied: perceivability, operability, and robustness are the necessary requisites for equitable service access. Studies on accessibility evaluation methods show that a systematic guideline-driven assessment lowers the risk of critical services becoming unintentionally inaccessible due to diverse sensory, physical, or cognitive needs [47].

Practically, smart city scenarios have a lot of implications: user interfaces equipped with features such as scalable text, high contrast, predictable navigation, forgiving input, screen-reader-friendly, and non-visual access modes can lessen the difficulty of interaction for elderly people, persons with disabilities, and digital novices, among others. Besides, these must be viewed as equity mechanisms rather than mere usability enhancements because they decide if citizens will be able to perform their own core activities, e.g. finding platforms, making payments, or reacting to service alterations on time.

4.2 Voice-First and Multimodal Interaction: Expanding Access Through Natural Interfaces

Several smart city systems are progressively adding voice first and multi-modal interaction to their suite of features, mainly to lessen their reliance on vision, literacy, and complicated gestures navigation. In the case of outdoor public spaces where people’s attention is easily distracted and their hands are busy most of the time voice interfaces serve as a means quickly obtaining navigation instructions, getting the latest information on services, and making inquiries for help, especially for the visually impaired and travelers with motor disabilities. Traditional multimodal interaction studies have shown that allowing conversational modes reduces task difficulty and enables more natural communication between humans and systems when these modes handle interruptions, ambiguity, and environmental noise appropriately [48].

However, strictly voice-driven systems could generate novel failure scenarios (voice-recognition errors, privacy concerns in public areas, and fewer opportunities to correct the situation, to name just a few). In this case, the multimodal redundancy approach would be the most beneficial for a smart city ecosystem, where voice control is combined with visual tactile interfaces, and straightforward procedures in case of emergency. This philosophy aligns well with the conversational interface studies that emphasize the necessity to build systems with realistic assumptions rather than idealistic ones [49].

For inclusive MaaS and transport hubs, voice-first interaction should work as an access route to accessibility, not as the sole route. Users must be able to choose interaction modes that are in harmony with their needs and surroundings.

4.3 Bridging the Digital Divide: Affordability, Literacy, and Inclusive Onboarding

Even if interfaces are perfectly accessible from the technical point of view, mass inclusion will rely on people's ability to actually use and keep access to the services. Phone ownership, Internet connection, or a high level of trust in digital identity/payment methods are the necessary conditions for the digital divide to disappear. The studies of digital participation in smart cities say that the provision of fair smart city services needs not just the focus on interface design but also the governance decisions that determine the access conditions, public accountability, and participation rights [46]. Therefore, the use of inclusive onboarding is an essential level of an invisible infrastructure. Support methods, e.g. interactive registration, straightforward support, low-cognitive-load "guest mode" access, and human digital hybrid support, alleviate the exclusion that is caused by fear of making mistakes, low digital confidence, or being unfamiliar with app-based mobility. From the point of view of accessibility engineering, it is not merely the objective that a compliant interface should be provided, but rather users should be enabled to stay at real-world usage even under the usual conditions such as time pressure, stress, device limitations, unfamiliar environments, which is a classic issue in accessibility evaluation research [46].

4.4 Cities and Inclusive Digital Services: From Innovation to Institutionalization

Successful cities in ensuring inclusive smart services mostly seem to consider accessibility as a fundamental institutional demand rather than a feature or an extra. This implies that accessibility becomes a part of procurement, evaluation of the lifecycle, and co-design governance, rather than being added as a late-stage upgrade. Studies on urban digitalization are increasingly depicting inclusion as a civic condition associated with participation, representation, and rights rather than as a merely technical attribute [46].

In essence, digital accessibility peaks once it has been distributed through various platforms such as apps, kiosks, and displays, across different forms of interaction such as text, audio, and tactile, and throughout various stages of travel planning, paying for services, navigating the journey, and dealing with disruptions. In the case where digital mobility services are provided as utilities, they contribute to the empowerment of all citizens by ensuring that smart mobility becomes available for all rather than for the few digitally well-endowed.

5. Proposed Framework: The Unified Smart City Stack (U-SCS)

In the face of rapid developments in smart crosswalks, intelligent transport systems (ITS), and digitally mediated public services, a large number of smart city projects are still limited to functional silos. Single subsystems may be very efficient when working separately, but their total value is greatly diminished if interoperability, governance, and user experience are not harmoniously combined. To resolve this issue of fragmentation, this paper suggests using the Unified Smart City Stack (U-SCS) as a conceptual model that brings together (i) physical safety infrastructures (such as smart crosswalks), (ii) inclusive mobility systems (public transport and MaaS), and (iii) digital accessibility layers (accessible interfaces, assistive interaction, and on boarding) within a single human-centered operating model. U-SCS sees designing for accessibility as a system-level design principle that permeates the interfaces between infrastructure, data, and decision making across the urban eco-system, not a mere downstream compliance requirement.

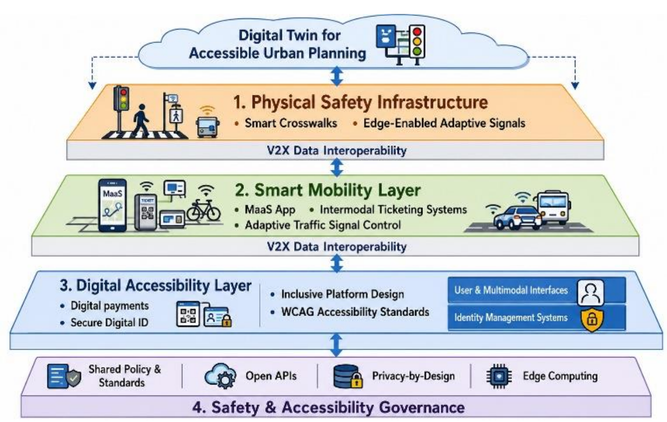

Figure 4: Layered architecture of the Unified Smart City Stack (U-SCS) for inclusive and interoperable smart mobility

Figure 4 depicts the Unified Smart City Stack (U-SCS) as a multi-tiered architecture that merges digital twins for planning, physical safety infrastructure (smart crosswalks and adaptive signals), smart mobility services (public transit and MaaS), and a digital accessibility layer, which is enabled by interoperability and governance. The vertical stream demonstrates how data interoperability and shared standards link all the layers to supply safer, more inclusive, and human-centered smart city services. [50, 51]

5.1 Interoperability: Open APIs, Data Standardization, and Shared Governance

Interoperability is the technical and institutional basis of a U-SCS, or urban smart city system. Smart crosswalks Mobility as a Service (MaaS) platform, and digital city services create different data streams, e. g. pedestrian detection events, vehicle trajectories, ticketing transactions, service disruptions, and user interaction logs. If these datasets stay separate, the city-wide intelligence becomes fragmented and thus, the coordinated optimization and real-time responsiveness is limited. Hence, U-SCS focuses on using open APIs, standardized data models, and harmonized integration mechanisms for cross-system coordination between sensing infrastructure, transport controllers, and accessibility services. [52, 17]

Moreover, this interoperability can enable safety, critical interactions, e. g. Vehicle to Infrastructure (V2I) and Vehicle to Pedestrian (V2P) messaging, to be part of a single unified service layer which then supports adaptive signals, accessibility aware route planning and responsive pedestrian protection at scale. At the same time, U-SCS also admits that technical connectivity alone cannot solve everything. [1, 17] Besides a shared ICT platform-integrated urban system need shared governance, the transport authorities, urban planners, ICT departments, and social welfare stakeholders have to coordinate around common inclusion and safety objectives. If things are not aligned in this way, even smart interventions that are well-designed are at risk of ending up as isolated pilots rather than becoming scalable public utilities. [53-56]

5.2 Human-Centered System Design: Journey Mapping, Co-Design, and Feedback Loops

Human-centered design is integrated into U-SCS as one of its core layers because mere technical integration cannot ensure fairness. Journey mapping during the planning phase assists cities to conduct a full analysis of their mobility journeys, identifying the areas of friction that arise due to the integration of physical and digital aspects. These include instances of inaccessibility, disorientation, or dangerous crossing points along the path of travel [50, 57, 58].

U-SCS also put into practice the concept of inclusion via codesigns, which is based on the principle of "Nothing About Us Without Us" among others. This guarantees that senior citizens, people with disabilities, and the digitally excluded have a say in the system requirements, user experience, and service priorities right from the start and are not just adjusted to the next-to-last solutions. [53, 54]. To maintain performance and equity over time, U-SCS employs continuous feedback loops built with sensors, citizen reporting tools, and service analytics. In this framework, feedback is not confined to post deployment evaluation; it is a structural element of the systems intelligence that enables iterative improvement. Thus, pedestrian hesitations at crossings, disfavoured MaaS services, or repeated navigation failures can be uncovered and made use of to continuously update infrastructure design, information provision, and policy decisions. [56, 59]

5.3 Edge Intelligence: Real-Time Decisions Without Cloud Dependency

A key technical characteristic of U-SCS depends on edge intelligence that is strategically leveraged to support low-latency decisions which are highly sensitive to safety. Street-level smart crosswalk controllers, traffic lights that change based on the flow and direction of vehicles, and assistive navigation systems require real-time calculation, for instance, changing pedestrian phases, enabling alerts, giving priority to public transport, or identifying unusual movement patterns. Edge intelligence, by carrying out these functions on the spot, enhances responsiveness and at the same time lessens the reliance on the cloud being connected all the time, thus leading to the system's uptime loss or failure of service being able to continue functioning. [1, 17]. Additionally, from an accessibility and governance standpoint, edge-enabled U-SCS also helps privacy through design. Very personal data (for example, pedestrian presence or movement) can be handled at the source and thus only generalized or pseudonymized results are sent upstream. On one hand, this lessens the surveillance risk and on the other hand, it ensures the safety of operations that is indispensable for public confidence in widely deployed sensing environments. [53, 56]

5.4 Digital Twins for Planning Accessible Infrastructure Upgrades

Besides handling real-time changes, U-SCS also considers the use of digital twins as tools for anticipating and planning. In U-SCS, digital twins aren't just about traffic optimization; they are designed to offer an explicit integration of accessibility, conscious evaluation metrics, e. g. sufficiency of crossing time, availability of step free routes, transfer burden, and reliability in the face of disruption. [17]. Consider that planners could evaluate the impact of adaptive pedestrian timing on the elderly, the effect of curb reallocation on wheelchair users or the result of interchange redesign on the continuity of navigation across the first and last mile. This way, they can make decisions that are focused on equity and are measurable, comparable, and can be easily justified to all stakeholders [53, 56].

5.5 Future Trends: Augmented Wayfinding, Predictive Maintenance, and Secure Civic Identity

U-SCS lays down a base for innovations that merge physical safety and digital accessibility on a deeper level. For example, Augmented Reality (AR) wayfinding can provide navigation directions that are aware of the user's environment, thus giving extra assistance to users with cognitive impairments, low vision, or those who are not familiar with complicated transport settings. [58, 60]
At the same time, predictive maintenance which uses machine learning on sensor data collected over a long period, can identify situations like signal faults, ruts in the road surface, broken tactile paving, or elevators that don't work on time before they become safety hazards or accessibility problems. With this, urban accessibility management is no longer about reacting to repairs but about ensuring reliability proactively. [52]. Moreover, U-SCS allows safe access to deeply integrated services via privacy-preserving digital identity means, such as decentralized identity and blockchain-informed models that are still coming. If these systems are transparently governed, they can reduce the number of times a person needs to prove who they are when moving between transport, civic services, and participatory platforms while keeping the user in control of their private data. This layer of trust is becoming more and more necessary as smart city services get interconnected, identity-mediated, and constantly data-driven. [55, 56]

6. Privacy-by-Design Governance for Accessible Smart Cities

As smart cities depend more and more on sensor-rich infrastructure, real-time analytics, and interconnected digital platforms, privacy governance becomes closely linked with the issues of accessibility and public trust. Systems that are aimed at making the city safer for pedestrians, public transport works smoothly, and digital services will, by their nature, have to process data about human presence, movement, and behaviour. If such systems are not equipped with safeguards, they can become a surveillance city which will lead to a loss of public trust and as a result, the most vulnerable groups who rely on public infrastructure will be affected the most [2, 12]. Hence, privacy-by-design governance is a must have for the accessible smart cities of the future and it is a way of guaranteeing that technology intelligence uses the capabilities of individuals without violating their rights to freedom.
Several recent studies on smart crosswalks and intelligent mobility systems have revealed that trust is the very basis for the adoption of these systems. If the users feel that the sensing and data gathering are done in a way that is not clear or is too excessive, then even the best accessibility interventions may face rejection or may be used at a very low level [15, 16]. In short, privacy governance is not just a matter of compliance with the law but also a prerequisite for the operation of inclusive smart city systems.

6.1 Data Minimization by Infrastructure Type

One of the fundamental privacy-by-design principles is data minimisation, which means only collecting what is strictly necessary for a clearly defined public purpose. In smart cities that are accessible, this principle should be applied differentially with respect to various infrastructure layers.
The main goal of smart crosswalks is pedestrian safety. Hence, systems should concentrate on detecting presence, direction, and speed instead of acquiring identifiable personal

characteristics. Edge-based processing allows for immediate safety responses like adaptive signal timing or driver alerts while raw image or biometric data is being eliminated at source [11, 12]. Recent smart crossing deployments demonstrate that such architectures can maintain high safety performance while significantly reducing privacy risk [15, 17].

In public transport and MaaS systems, the data collected generally serves routing, scheduling, ticketing, and service optimisation. Along with a limited user-level data allowance for personalisation or concessionary access, extreme monitoring of individual travel histories raises the risks of profiling and exclusion, especially for dependent users [2, 8]. Research on integrated mobility platforms has shown that accessibility improvements are not related to higher data granularity, which further supports the argument for minimal purpose bound data use [16].

Accessibility features like voice interaction or assisted navigation for digital kiosks and civic portals should be able to work without the need for ongoing identity tracking. Session-based interactions and anonymous access modes are good ways to guarantee that essential services can be used without forcing users to give up personal information [4, 10].

Minimization, as a concept, helps to underline the idea that accessibility should not be accompanied by the highest possible data extraction level. This is true for all types of infrastructures.

6.2 Retention Policies and Access Control

Privacy governance covers not only the data collected but also the period for which they are retained and the aspects of access control. Retention policies should be in line with the operational requirements: data that is potentially related to safety may be kept for a very short time so as to be able to verify the incident, while the aggregated mobility data may be kept for a relatively longer time for the purposes of planning and evaluation [7, 12]. On the other hand, keeping detailed movement data forever simply exposes one to unnecessary risks without providing any real benefits in terms of data accessibility.

Access control measures are just as important. Implementing role-based permissions, encrypting data, and physically separating operational and analytical datasets reduces the chances of the data being used in an unauthorized manner. Transparent governance arrangements set forth who among the public agencies or private operators can have access to the data, under which conditions, and for what purposes a matter of great concern especially for people who have been historically subjected to over-surveillance [2, 10]. Studies of smart mobility infrastructure deployment suggest that clear governance of data access greatly fosters institutional accountability and public trust [16].

6.3 Anonymization, Aggregation, and Re-Identification Risks

Anonymization and aggregation are standard measures used for protecting data in smart city environments. For instance, aggregated pedestrian counts, traffic flows, and service usage metrics can be used to support planning and optimisation without exposing individual identities directly [12]. Nevertheless, research is increasingly uncovering the risk of re-identification by combining multiple datasets, especially in densely populated urban areas where distinctive mobility patterns may exist [1, 12].

Where accessibility focused systems are concerned, the danger is even greater. Mobility patterns of persons with disabilities or older adults are generally quite distinctive and thus these groups may be indirectly identifiable if the data is inadequately anonymised [10]. Literature on smart sensing infrastructures highlights the need for industry-wide coarse-grained aggregation, local processing, and continuous reassessment of anonymization techniques as analytical capabilities become more advanced [15, 17]. Hence, privacy-by-design governance must be flexible in its response, being aware that safeguards that are currently effective may become insufficient in the future.

6.4 Consent Models in Public Spaces

Acquiring proper consent in public spaces is fraught with difficulties, whereas in private- digital services user can always decide simply to change the app and not interact with the service whereas in the case of a pedestrian or a transit user, the person simply cannot avoid interacting with the hardware and software installed in the environment. Therefore, there is a move towards layered consent and notice models. On the one hand, clear physical signage, digital disclosures and explanatory materials available in the vicinity help the public to understand the data collection and purpose of processing in order to be aware even if such a situation deprives them of the opportunity to give an explicit consent [4, 12].

Under the situation that it is possible, the opt-out features should be available, i.e., the mode that makes the service non-tracked or the anonymous access option, especially in the case of non-safety services [2]. However, the point is that the consent addressing features ought to be the very features that are accessible; hence, in an effort to guarantee that the different groups of users comprehend the message, the implementation of plain language, multi-modal communication, and multilingual formats is essential [4, 10]. A study of users' trust in smart environments has revealed that users' trust in smart environments is influenced by transparency and perceived choice, which also affect their agreement to the use of data, even when the option to disallow is not readily available [16].

6.5 Procurement Rules and Continuous Auditing

Governance of privacy-by-design cannot only depend on after-the-fact supervision. Procurement policies are a key component of embedding accessibility and privacy requirements from the start. Public authorities are able to enforce compliance with accessibility standards, data minimization principles, and security certifications when purchasing smart crosswalks, ITS platforms, or digital services [7, 9]. These kinds of requirements shift the responsibility to the source, making it so that vendors internalize ethical and legal obligations instead of externalizing risk to cities and users.

Regular auditing helps to increase accountability. For instance, periodic assessment of data practices, algorithmic behavior, and system security can uncover unintended biases, vulnerabilities, or departures from the stated accessibility objectives [1, 12]. Data from smart infrastructure implementations shows that regularly auditing, rather than a one-time certification, is the key to continuously aligning technological evolution, regulatory frameworks, and public expectations [15, 16].

7. Conclusion

This chapter strengthens a major change of focus in urban development nowadays: a city does not get smart just by installing high-tech gadgets but by making sure that the technologies used respect and promote human dignity, safety, and inclusion. The success of a smart city hinges on purposely integrating accessibility, trust, and interoperability in the physical infrastructure, mobility systems, digital platforms, and governance models. Whether it is living crosswalks, adaptive transport networks, digital accessibility layers hidden from view, or privacy-by-design governance, the discussion constantly indicates that cities are most efficient when their design is centered on the real needs and capabilities of humans rather than on technological potentials only. An important point is that accessibility should be regarded as basic infrastructure and deeply rooted from the very beginning of design, not only for street-level safety systems and MaaS-based mobility services but also for digitally accessible public interfaces, because later installation of accessibility features tends to make things more complicated and may unintentionally lead to exclusion.

It further discusses how integration leads to a bigger impact than isolated innovation since crosswalk intelligence, public transport, ticketing, and city digital services provide the highest value only when they are organized through interoperable architectures, shared standards, and coordinated governance. Here, the suggested Unified Smart City Stack (U-SCS) presents a well-organized plan that integrates pedestrian safety infrastructure, smart mobility layers, and digital accessibility into one operating model that can extend inclusion beyond pilot projects. On the other hand, the chapter validates that a human-centred design approach is fundamental: journey mapping, co-design, and continuous feedback loops make certain that smart systems are a reflection of the lived experience, thus they become more user-friendly and public trust is even enhanced, especially for older adults, persons with disabilities, and digitally marginalised communities. Trust, which is the overall condition for adoption, comes up as an issue at every level. That is why privacy-by-design practices such as data minimisation, proportional retention, anonymization safeguards, and transparent consent become not only desirable but mandatory elements of truly inclusive smart environments. In short, the chapter points to the main areas of research in the future such as ethical pedestrian, scale IoT which respects privacy while ensuring safety, accountable AI that refrains from embedding bias into mobility decisions, and resilience, driven planning by means of edge intelligence and digital twins that can maintain accessibility at a high level even under the impact of climate change, demographic shifts, and changes in the way people travel.

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