Smart Streets: Definition, Principles, and Infrastructural Elements

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***Abstract*—Shopping streets are the lifeblood of rural towns performing a number of important economic, social, and environmental functions. Streets represent a public realm that is actively and passively consumed depending on how it is structured as a public space. These structures result from historic forces and planning processes that highly influence the norms for how such a space evolves, is moved through, and consumed by individuals or groups. In recent decades, stakeholders have sought to leverage technological advances to combine traditional elements of the public realm with cyber-physical systems to generate intelligence from data analysis in order to modify behaviour and optimise operations and services. While the overwhelming focus of existing research and policy focus is on "smart cities", there are significant potential benefits for rural communities. However, for many rural towns, the investment required for a "smart town" initiative is prohibitive. We posit that a smart street is more feasible and manageable for rural towns. This paper presents a working definition of a smart street, proposes a series of principles for smart street design, and identifies exemplar infrastructural elements to deliver widely accepted policies and behaviours.**

Keywords–Smart Cities; Smart Towns; Smart Street; Street.

I. INTRODUCTION

Over the next three decades, there is expected to be a decline in rural living as rural dwellers migrate to cities; the UN forecasts over 68% of the worldwide population will live in urban areas by 2050 [1]. The growth in urbanization is resulting in significant strain on housing, transportation, energy systems and other infrastructure [1]. Smart city initiatives that leverage advances in sensor, cloud computing, networking, and data science technologies are widely cited as a key solution to rapid, global urbanization [2][3]. Extant Smart City research projects focus on wide variety of domains including:

- Business – advertising, agriculture, entrepreneurship and innovation, enterprise management, logistics, and transactional commerce;
- Citizen - education, entertainment, health, public transport, traffic management, and tourism;
- Environment – building, housing, pollution control and waste management, public space, renewable energy and smart grids, and waste management;
- Government – city monitoring, e-government, emergency response, public safety, public service and transparency [4][5].

The quality of *smartness* is derived from the use of (i) near-real-time data obtained from physical and virtual sensors; (ii) the interconnection between different services and technologies within the urban area; (iii) the intelligence from the analysis of the data and the process of visualising it; and (iv) the optimisation of operations resulting from this analysis [6]. While the overwhelming focus of existing research and policy focuses on *smart cities*, such technology can benefit any urban area seeking to use data to optimise operations [6]. This includes rural towns and more granular spaces, including streets. Indeed, some researchers propose that smart streets are the building blocks of any smart city architecture [7].

Streets are not merely thoroughfares that connect one point with another. The public perform a wide range of activities in streets that can be categorised as mandatory (e.g., going to work or school), selective (shopping, wandering or sitting and watching street life), or social (having conversations) [8]. Human behaviour in streets can be classified as moving, visual perception, and resting behaviours, and can occur discretely, successively, and concurrently [8]. As such, it is a public realm that is actively and passively consumed depending on how it is structured as a public space. These structures highly influence the norms for how such a space is moved through and consumed by individuals or groups [9]. Streets comprise a number of tangible and intangible elements that need to be taken in to account (see Table I).

TABLE I. ELEMENTS OF THE STREET (ADAPTED AND EXTENDED FROM [10][11])

Tangible Elements	Primary	Vertical	Buildings, railway bridges, etc.	
		Horizontal	Floors	Roadbeds, footpaths, etc.
			Ceiling	Skyline, covering, etc.
			Underground	Utility channels, etc.
	Secondary	Street furniture	Benches, lamp posts, waste receptacles, storage units, utility cabinets, signage, etc.	
Intangible Elements	Natural	Short term	Light, seasons, organic growth, etc.	
		Long term	Precipitation, wind, etc.	
	Human	Administrative, economic, social, culture history, etc.		
	Behavioural	Humans, moving objects		

Shopping streets are the lifeblood of rural towns. In addition to connectivity, they perform a number of important economic, social, and environmental functions. They not only serve the functional and utilitarian needs of local residents but can attract tourists and day trip shoppers thus supporting a greater range of shops than the local population could support

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alone [12]. After decades, if not centuries, of resistance to the impact of global economic and societal change, the resilience of main streets of rural towns worldwide are being threatened by urbanization, online shopping, and now, COVID19. Cyber-physical infrastructure in the public realm can attract new users to a street, and decrease or increase (un)desired use and behaviour, depending on policy priorities. However, such infrastructure does not impact all activities and behaviour in the same way (see Table II).

TABLE II. HUMAN BEHAVIOUR IN THE STREET (ADAPTED FROM [8], [10])

		Moving	Behaviour Visual Perception	Resting	Impact of Public Realm
Activity	Mandatory (must be performed)	Going somewhere	Seeing out of necessity	Stopping or resting on the way to somewhere	Not significant
	Selective (undertak at will and as space allows)	Wandering for something	Seeing out of interest	Stopping or resting out of interest	Sensitive
	Social (undertake because they are in a public space)	Going to do something	Seeing to do something	Stopping or sitting to do something	More active in a conductive environment than a poor one

This paper has three objectives. Firstly, to address the gap in the literature on smart streets, we seek to define a smart street in Section II. Secondly, we present a series of design principles to guide the design of smart street initiatives in Section III. While we focus on rural shopping streets, these principles can be generalised for any street. Thirdly, to identify exemplar infrastructural elements for smart streets that support the proposed design principles, and deliver on widely accepted policies and behaviors (Section IV).

II. TOWARDS A DEFINITION OF A SMART STREET

There have been numerous attempts to define a smart city (e.g., [13][14]). To arrive at a unified definition of a *smart city*, Ramaprasad et al. [14] suggest that such a definition comprises conceptualisations of *smartness* and *city* by stakeholders (e.g., Citizens, Professionals, Communities, Institutions, Businesses, and Governments) and their desired outcomes (e.g., Sustainability, Quality of Life, Equity, Livability, and Resilience). For Ramaprasad et al. [14], this quality of *smartness* comprises structures (architectures, infrastructure, systems, processes, etc.), functions (sensing, monitoring, communicating etc.), one or more foci (economic, social, infrastructural, etc.), and semiotics (data, information, and knowledge). They identify 22,500 components that can be instantiated in innumerable different ways to deliver a *smart city*. We posit that while academically sound, this approach is unwieldy and impractical on the ground. Similarly, while other papers define the quality of *smartness* in a broad way to include sustainability and inclusion, amongst other concepts [15], [16], these definitions typically focus on regional or urban development. We focus on streets because they are a defined and manageable unit with boundaries that all stakeholders can understand and work within. In the same vein, we focus on smartness as a quality derived from the use of (i) near-real-time data obtained from physical and virtual sensors; (ii) the interconnection between different services and technologies within a street; (iii) the intelligence from the analysis of the data, and the process of visualising it; and (iv) the optimisation of operations resulting from this analysis [6].

Smart streets seek to combine the traditional elements of the public realm with basic elements of cyber-physical systems. Extant research and definitions of smart streets focus on smart lighting systems as the basis for smart street projects (e.g., [7]). However, smart streets include a wide variety of potential infrastructural objects and services independent of lighting including space management, structural health, traffic management, environmental monitoring, and waste management, amongst others [17]. Similarly, *urban* is increasingly conflated with *city* whereas it is equally applicable as a characteristic of a town.

For the purpose of this paper, we define a smart street as a basic unit of urban space that leverages cyber-physical infrastructure to provide enhanced services to stakeholders, and through stakeholder use of the street, generates data to optimise its services, capabilities, and value to stakeholders. This definition aligns with existing definitions of smart cities, accommodates a wide range of potential activity, while at the same time recognising that street are a more atomised, and as a result more manageable, unit of development.

III. PRINCIPLES FOR SMART STREET DESIGN

A. People First

The Design Manual for Urban Roads and Streets (DMURS) [18] emphasises the need for more walkable communities for sustainability, public health, and social equity. In line with DMURS and the Global Designing Cities Initiative (GDCI) Global Street Design Guide [19], the public should be at the heart of any smart street strategy. Both DMURS and GDCI propose a hierarchy of priorities as follows - pedestrians first, then cyclists, then public transport, then people doing business or carrying out public services on the street, and lastly, personal motorised vehicles [18][19]. Putting people first means designing streets and selecting cyber-physical investments that meet a wide range of objectives including public health and safety, quality of life, environmental and economic sustainability, and social equity.

B. Place Second

There has been a general shift in approaches from a primary focus on the movement of traffic, typically vehicular, to what DMURS refers to as multi-modal movement and streets as a "sense of place". GDCI [19] suggest that designing streets for place means considering the local culture and context. This includes the built and natural environment, the social and cultural context, and the economic environment. For DMURS [18], sense of place, while difficult to define has a number of attributes including:

- Connectivity - the creation of vibrant and active places requires pedestrian activity and consequently, should be walkable, connected and easily navigated.
- Enclosure - a sense of enclosure spatially defines streets and creates a more intimate and supervised environment.
- Active edge - an active frontage enlivens the edge of the street creating a more interesting and engaging environment.
- Pedestrian activity/facilities – an enclosed street with an active edge creates a sense of intimacy, interest

and overlooking and enhances a pedestrian's feeling of security and well-being.

When considering the digital analogue for this "sense of place", one must consider how digital technologies and cyber-physical infrastructure augment or reinforce these attributes, but equally what the digital analogue of connectivity, enclosure, an active edge, and pedestrian activity and facilities might be.

C. From Inputs to Impacts

Where limited resources are being invested, care needs to be taken to ensure inputs translate into impacts. Cyber-physical features and interventions must have associated measurement systems that provide more timely data from which decisions can be made and resources allocated to mitigate, remediate or optimise strategies to meet prioritised objectives. Digital technology allows stakeholders collect, process and analyse data in near-real time and, where appropriate, actuate decisions autonomically. Measuring and communicating impacts of interventions helps inform better decisions on resource allocation but also communicate progress to policymakers and the community, thereby building both political and community support for future funding and other projects. Baseline metrics must be collected before any intervention so that data collected post-implementation can be benchmarked against prior conditions. Furthermore, agreed success criteria must be determined in advance, and ideally, systems put in place to establish causal relationships between digital enhancements and changes in outcomes. In many smart street use cases, benchmarking may not be possible as historic data simply does not exist.

Based on GDCI [19] recommendations, smart street projects should focus on three categories of metrics:

1) *Cyber-physical and operational changes* – short-term quantitative results on progress towards meeting cyber-physical infrastructural targets e.g., new or improved facilities, technologies or infrastructure.
2) *Shifts in use and function* – medium-term quantitative and qualitative results on how a street is used differently as a result of the project e.g., changes in behaviour, new users of street or cyber-physical infrastructure, changes in transit flow and type, and improved functions.
3) *Resulting impacts* - long-term cyber-physical physical, operational, and functional changes that impact the overall performance of the street, and whether the investment and associated implementation is achieving the desired outcomes agreed with funding bodies.

D. Connectivity Counts

With sensors and machine learning, ubiquitous network connectivity is a foundational building block of digital transformation in the public realm. It is well established the broadband coverage, connectivity, quality, and adoption contribute to GDP and local economic growth [20][21], the location and development of clusters of knowledge-intensive firms [22], and rural employment [23], amongst others. In particular, research on free public Wi-Fi access suggests that it contributes to economic growth [24][25], promoting tourism [26][27], social inclusion [28], public safety [28][29], and improved public services [27][30]. The importance of digital connectivity for EU regional and social development is evident from the inclusion of access to digital communications in the European Pillar of Social Rights. However, rural broadband coverage continues to be lower than national coverage across EU Member States; just over 52.3% have access to high-speed next generation services [31].

E. Available and Accessible 24/7/365

Many rural areas experience weather conditions that may keep people indoors, lead them to choose to drive rather than walk or cycle, and otherwise adversely affect mobility and outdoor activities. Communities around the world have implemented weather mitigation strategies so that the public can spend more time outdoors in the public realm, generating social, economic and public health outcomes that may otherwise be lost due to climate. Similarly, in line with being "people first", improving accessibility and the quality of experience for those most vulnerable in society is key in a modern, inclusive society. This consideration is particularly pertinent against the backdrop of COVID19. While social distancing needs to be maintained, research suggests that COVID19 is less likely to be transmitted outdoors due to greater air ventilation [32]. Similarly, to counter the adverse impacts of public health interventions such as social distancing and social isolation, experts have called for further investment in public realm nature experiences that research suggests results in benefits to cognitive functioning, emotional well-being, and other dimensions of mental health [33][34].

F. A Flexible Programmable Public Realm

Thriving shopping streets are both social spaces and commercial spaces, with not only clusters of similar retail outlets but also featuring other diverse retail and social activities [12]. The physical and visual quality of the public realm including pedestrian friendliness, appropriate pavement widths, walkability and urban furniture, complemented by active shopfronts and communal facilities (bars, cafes, etc.) can transform shopping streets in to social spaces [35][36]. It is the combination of location centrality, retail mix use, and social vitality that attracts higher volumes of more diverse people to a street, resulting in sustainable long-term success. Against this backdrop, a key challenge in urban design is to make the public realm more flexible and dynamic, and encourage both traditional and new uses and behaviours of that space. Technology can be used to dynamically create time- and use-based flexible outdoor mixed-use spaces from wall to wall in the public realm. This can be used to attract more footfall, social, and ultimately commercial activity to the benefit of all stakeholders.

G. Open, Not Closed

Open government data is concerned with making public sector information freely available in open formats and ways that enable public access and facilitate exploitation [37]. The benefits of open data are summarised in Table III. It is important to note that open data, on its own, has little intrinsic value but value is created by its use [38].

The EU Public Sector Information (PSI) Directive (Directive 2003/98/EC) and subsequent revisions (Directive 2013/37/EU and Directive (EU) 2019/1024) were designed to encourage member states to provide access and encourage the reuse of PSI. Smart street projects provide stakeholders with

TABLE III. OVERVIEW OF BENEFITS OF OPEN DATA [38]

Category	Benefits
Political and Social	More transparency; Democratic accountability; More participation and self-empowerment of citizens (users); Creation of trust in government; Public engagement; Scrutinisation of data; Equal access to data; New government services for citizens; Improved citizen services; Improved citizen satisfaction; Improved policy-making processes; More visibility for the data provider; Stimulation of knowledge development; New public sector insights; New (innovative) social services.
Economic	Economic growth and stimulation of competitiveness; Stimulation of innovation; Contribution toward the improvement of processes, products, and/or services; Development of new products and services; Use of the wisdom of the crowds: tapping into the intelligence of the collective; Creation of a new sector adding value to the economy; Availability of information for investors and companies.
Operational and Technical	The ability to reuse data/not having to collect the same data again and counteracting unnecessary duplication and associated costs (also by other public institutions); Optimisation of administrative processes; Improvement of public policies;Access to external problem-solving capacity; Fair decision-making by enabling comparison; Easier access to data and discovery of data; Creation of new data based on combining data; External data quality checks (validation); Sustainability of data (no data loss); The ability to merge, integrate, and mesh public and private data.

the opportunity to accelerate their open data initiatives. With sufficient promotion, this can attract interest from industry and researchers with a view of leveraging the massive time series data that smart streets can generate to generate scholarly insight and socio-economic outcomes in towns and beyond. At the same time, smart street projects need to consider the significant ethical and legal implications of the substantial data being collected from such projects, particularly where such data is collected ambiently without explicit consent from the public [39].

H. Evolution, Not Revolution. Leading Edge, Not Bleeding Edge

While there is a temptation to be at the cutting edge of smart city technology, care needs to be taken so rural smart street projects are at the “leading edge” and not the “bleeding edge” of technology adoption. This is particularly the case where resources are limited. In every country, there are projects and schemes that need to be taken into account. Therefore, the adoption of potential technologies and proposals should acknowledge and build on best practice, existing systems and processes where possible, to minimise waste and maximise learning, within budget constraints.

I. Managing a Complex Stakeholder Environment

In order to meet the requirements of a diverse group of stakeholders, it is essential to fully understand the current barriers to change including apathy, fear, relevance, and inconvenience, and to design and select projects that seamlessly address these across a number of key themes, using a combination digital and urban design interventions. There is a rich tapestry of local, regional, national and International initiatives and programmes with recommendations and targets that can be used to inform decisions. Adopting this bottom-up approach rather than a top-down approach focused solely on the achievement of local targets should result in a programme that has greater awareness, relevance and longevity than those developed in isolation of citizen requirements.

IV. THE ELEMENTS OF A SMART STREET

A. Connectivity Corridor

A connectivity corridor is a substrate of network connectivity, power and associated hardware. As discussed, increased broadband speed and coverage is linked to a wide variety of direct and indirect socio-economic outcomes including reduced operational costs, increased GDP, increased jobs, retail and tourism visitor satisfaction, and social inclusion. Many rural towns and streets feature legacy utility wiring and street furniture that may adversely impact the visual identity of the street. By leveraging (i) existing wired infrastructure, (ii) upgrading access points to the state-of-the-art, and (iii) replacing legacy street furniture with multi-purpose units, much of the existing street overhead wiring can be eliminated or moved underground. Connectivity, both telecommunications and power, could be monitored for the street through one interface however this is unlikely. Consequently, smart streets require coordination and collaboration with existing infrastructure providers.

B. Smart Street Information Systems

There are a wide number of urban information systems that can inform a smart street project depending on the responsible agency and contractor at a national, regional, and local level. Table IV summarises some of the main urban information systems.

Given the idiosyncrasies of funding, utility management, and administrative responsibilities in rural towns, Urban Data Platforms (UDPs) are proposed as the priority for smart streets. By focussing on UDPs, the data generated can be used to stimulate future traffic control and demand management systems, mobile apps for citizens, and inform urban and strategic planning. Specifically, the data from a UDP can be used inform a more flexible and programmable public realm. Such a platform requires the ubiquitous connectivity assumed in Section IIID. Building in the needs of a UDP, including network, power, storage, sensor mounts, and APIs in to infrastructure will avoid expensive disruptive piecemeal retrofits in the future.

Sidewalk Labs, considered at the cutting edge of urban system thought leadership, view urban data platforms and associated tools for measuring, analysing, modelling and visualising this data as the first step in improving efficiency and the quality of life in urban environments [41]. The ability to collect data on fixed and moving things through sensors, video and beacon data will enable rapid low-cost analysis and testing interventions using scenario-based modelling thus avoiding the cost, inconvenience associated with live testing. Furthermore, it will allow the granular real-time evaluation of the impact of the redevelopment and enable optimisation or remediation, as necessary. Finally, the vast amount of data generated from one street can stimulate both scientific and economic activity in the street through entrepreneurial and research engagements with this open data.

C. Traffic and Transit Management

A significant part of the general public experience on a street takes place on the footpath. Footpaths are a conduit for pedestrian movement and access to properties located

TABLE IV. SUMMARY OF SMART CITY INFORMATION SYSTEMS (ADAPTED FROM [40])

System	Description
Urban data platform (UDP)	UDPs enable and stimulate a proper understanding of how infrastructure is used in different domains, the interdependencies between different elements of infrastructure and the effects of external drivers.
ICT as a planning support	Theze are quantitative tools and analytical methods in the form of step-by-step guidance that assess which issues and trade-offs that need to be addressed in decision-making as well as methodological processes for optimising opportunities and minimising risks. Decision support tools address all key actors, including consumers, producers and utilities and assess the benefits (or risks) for each actor under different scenarios.
Strategic urban planning (SUP)	SUP builds on understanding and developing all aspects of an urban area, integrating technical, environmental, political, social and economic interests. Its general objectives include clarifying which city model is desired and working towards that collective vision for the future by coordinating public and private efforts, involving citizens and stakeholders, channeling energy, adapting to new circumstances and improving the living conditions of the citizens affected. Furthermore, SUP provides a methodology which helps cities identify their strengths and weaknesses, while defining the main strategies for local development.
Traffic Control Systems (TCS)	TCS help to improve traffic flow and to regulate speed within a clean high-quality public transport corridor. A TCS includes real-time traffic data online, strategic traffic control and management, public transport acceleration measures, and information management.
Traffic demand management (TDM)	TDM describes the strategies and policies aiming to achieve more efficient use of transportation resources and to reduce travel demand by giving priority to public transit, car-sharing, car-pooling, etc. It puts focus on the movement of people and goods, rather than on motor vehicles. It includes trip scheduling, route, destination or mode reduction in the need for physical travel through more efficient land use or transportation substitutes.
Energy demand response	Energy demand response is the intentional modification of normal energy consumption patterns by end-use customers in response to incentives from grid operators, peaks of renewable energy generation or some compensation to reduce their power consumption at times of peak demand. The main objective of demand response is to maximise the integration of renewable energy systems while maintaining or improving today's levels of electricity supply reliability, energy security, economic growth and prosperity.
Mobile applications for Citizens	By using mobile applications, citizens can easily gain access to different services and open data. This offers new opportunities for the intelligent management of service demand and can enhance the quality of life in urban areas. Mobile applications help citizen to access information and make informed decisions in various domains.
Neighbourhood energy management systems (NEMS)	NEMS aim to integrate the different consumers and producers with the main electrical and heating grids at district level. These systems are essential to approach ultralow or net zero energy districts, controlling the energy consumption either by reducing it either shifting during the day to flat the demand shape. These systems, supplying predominantly residential buildings and districts, are able to de-couple fluctuations in the heat demand of buildings from the network conditions without perceptible changes in comfort. This allows the network's heat demand to be stabilised, energy efficiency to be improved, and heat (or cooling) loss in the supply network to be reduced.

on a street, they enhance connectivity and promote walking [19]. Footpaths have been shown to enhance general public health and maximise social capital. GDCI [19] suggests that footpaths should have four distinct zones. The frontage zone is the section of the footpath directly in front of a building. It comprises the façade and the space immediately adjacent to the building can be used as an extension of the building e.g., for sandwich boards or as additional seating. The clear path is the primary pathway running parallel to the street, typically 1.8-2.4 metres wide. The street furniture zone is situated between the kerb and the clear path; it is used for lighting, benches, kiosks, utility poles, greenery, cycle parking, etc. Finally, a footpath may have a buffer zone or enhancement for optional elements including parking, cycle racks, cycle-sharing stations, and kerbside cycle paths.

Rural towns can increase the multi-functional use of the public realm through a combination of designated areas, footpath widening, automated street bollards, sensors (including video cameras for Automated License Plate Recognition - ALPR), and embedded or overhead lighting in roads and footpaths. Together, these can be used to dynamically change the usage of a street at different times of the day, week and year giving priority to different street users depending on the time or weather conditions. For example, parts of or the whole street could be pedestrianised by raising automated retractable bollards at either end or the median of the street. Different uses (at different times in the day and week) can be signalled using data-driven programmable LED lights in pavement tiling. Technologies that combine advanced video camera technology and deep learning, for example ALPR, can be used to provide access and lower bollards, record infringements, identify stolen vehicles, and enforce regulations including fines and payment. In addition, adaptive smart traffic light systems can be implemented that identify and prioritise pedestrians and cyclists. These can be integrated with smart furniture and pedestrian crossings.

Sensors in parking spaces can direct people to available parking spaces, signal availability for specific purposes (e.g., Electric Vehicle - EV - parking and charging, accessibility or carsharing), record usage or signal pricing. Furthermore, parking spaces could be dynamically re-purposed and used for parklets, reservable, removable, transient pop-up retail or social spaces. Such systems could also support dynamic pricing and prioritised parking for retail customers, the most vulnerable, and EV owners (near charging points).

By being able to limit use of different sections of a street at different times in the day, it can be used as an innovative testbed for new forms of public transport and freight transit. For example, telepresence robot technology has developed and become more robust. These smartphone- or tablet-operated units allow people located remotely move, hear, see and speak via a tablet attached to a retractable unit with ruggedised wheels. They can be powered down and charged in relatively small docking stations. This can be used for tourists to visit remotely, potential customers to visit shops without being physically present, enable remote guides to interact with people, or for other teleworking scenarios. Similarly, zones can be reserved for transit by drone or autonomous vehicle (AV). For example, the Renault EZ series include AVs for freight, passenger transit and most recently, micro-mobility. These AVs are designed for low electric energy consumption and relatively small dimensions. The EZ-Pod is a small robo-vehicle (3 square metres – 32.3sq. ft.) with electric propulsion designed to transport people and goods over short distances and at very low speeds (sub-6kph). It could be used for transporting goods, the elderly or infirm and/or drone and robot delivery, and autonomous waste collection.

D. Accessibility, Security and Safety

Accessibility and safety issues can result from blocked, narrow or lack of footpaths, lack of accessible crossing, lack of protection when crossing streets particularly for those moving at slower paces, lack of cycle facilities, poor intersection designs, and other surface hazards [19]. Increasing accessibility has a number of outcomes including improving the quality of life of all citizens, regardless of age, size and ability, by providing a safe and inclusive environment. Furthermore, it increases mobility thereby contributing to public health outcomes.

In addition to eliminating permanent obstructions, supporting measures exist for integrating audio and signal cues along the street. These may be designed in street furniture or involve a system of Bluetooth beacons that provide audio or text messages to smart phones, or local visual signals to alert those in need. For example, Southern Cross Station in Melbourne, Australia uses Bluetooth and a free GPS smartphone app, BlindSquare, to create a beacon navigation system [42]. Users can receive audio cues via their smartphones, providing directions or real time information about issues such as escalator outages [42]. Additionally, object detection systems can be used to identify unpermitted obstructions, water pooling or other seasonal or anomalous issues without first notification from the public. It is worth noting that accessibility is not just about removing obstruction. Research suggests that benches to rest on and designing pavements and footpaths with clear separation of pedestrians and cyclists are high priority concerns for older citizens [43]. Furthermore, as mentioned previously, micro-mobile AVs can be used as taxibots to transport those who qualify short distances, and smart technologies can be used to prioritise parking for those accessibility issues.

Security cameras managed by local authorities can help monitor speeding vehicles, prevent crime, support access management, enable payment transactions (e.g., parking), and either deter or identify unwanted activities, with reduced labour costs and human error [19]. Notwithstanding this, there is a tension between personal privacy rights and the public interest. Any such implementation requires compliance with the General Data Protection Regulation (GDPR) and a persistent and consistent enforcement of clear data management policies. While recognising public concerns about mass surveillance, cameras and software can be configured for semi-anonymous analysis, i.e., an individual can be tracked but their individual personal information is never stored, or that only objects are tracked e.g., license plates.

E. Smart Street Furniture

Street furniture is designed primarily for passive consumption. It typically includes benches, transit stops and other shelters, waste receptacles, and public toilets. Smart street furniture re-imagines street furniture as not only a passive object but an active part of the street experience supporting different activities and behaviours to meet social, economic and public health outcomes. For example, in the current COVID-19 pandemic, it is worth noting the smart kiosks that have been implemented as part of variety of health initiatives to facilitate dialogue with health professionals and public health announcements. Street furniture can be categorised in a variety of ways including production method, function, target cohort, and public space typology.

1) Smart Lamp Posts

As per DMURS, good quality lighting promotes safer and secure environments by making it easier for all stakeholders to see each other and potential obstructions. Furthermore, it encourages greater mobility. State-of-the-art smart lamp posts operate a master and slave system and are designed for street illumination and telecommunications. As such, they include LED-smart lights and built-in GPS, Wi-Fi, telecommunications antennas and switchboards. Furthermore, many feature programmable NEMA controllers that can also be used for traffic signal and pedestrian crossing. Additional functionality includes CCTV, telemetry, and EV charging units. In addition to those mentioned, smart lamp posts are typically designed for extensibility thus ideal for supporting a wide range of other cyber-physical interventions including environmental sensing, security, ALPR use cases (e.g., speed, access, payment and demand management), vehicular, cyclist and pedestrian signals. It should be noted that existing legacy lampposts can be enhanced through a network of sensors, such as University of Chicago's Array of Things (AOT). AOT can be mounted to existing lampposts and other infrastructure to collect environmental data about temperature, humidity, light, air quality, wind, precipitation, noise levels, vibrations, proximity detection of Bluetooth- and Wi-Fi-enabled devices including measuring vehicular and pedestrian traffic [45].

TABLE V. CATEGORIES OF STREET FURNITURE (ADAPTED AND EXTENDED FROM [44])

Production method	Standardised	Designed for mass production but can be adapted for a specific place.
	Atypical	Designed for a specific place and often artistic in nature.
	Digital	Designed for connectivity.
	Sustainable	Designed for environmental sustainability.
Function	Service	Shelters, sunshades, waste receptacles, public transit stops, etc.
	Safety	Public lighting, protective railings, bollards, etc.
	Information	Signage, Information panels, etc.
	Relaxation	Benches, tables, cycle racks, drinking fountains, play areas, etc.
	Aesthetic	Artistic and architectural elements.
Target group	Younger	Street furniture should be sited and designed to take in to account the needs, limitations, safety and security of vulnerable populations.
	Older	
	Disabled	
Public space type	Urban	Street furniture is exposed to greater strain e.g., greater use and greater likelihood of dirt and destruction.
	Village	Less strained street furniture.

2) Smart Kiosks

Modern smart kiosks are a form of multifunctional street furniture that features hardware and software components for sensing different environmental conditions, multi-modal interaction with users, and for capturing and transmitting data for analysis locally or in the cloud [46]. Media poles have similar functionality but with a conventional pole form which may restrict display and associated advertising. Smart kiosks often include much of the functionality of previous generations of related technology including digital signage, media poles and other wayfinding technologies.

Smart kiosks are increasingly adopted as part of smart city initiatives for a variety of use cases including as:

- Information points e.g., public services and related announcements, transit information, weather, route and wayfinding, town or city guide, and local events.
- Transaction points e.g., bicycle sharing, voter registration, seasonal transactions, parking, transit or other event tickets.
- Communication points e.g., emergency contact, public telephone access, and social interactions through

machine agents.

- Connectivity points e.g., relaying or providing access to Wi-Fi.
- Device charging points e.g., EV or USB charging
- Sensing points e.g., collecting passive environmental, traffic or security data through sensors and cameras.
- Research points e.g., collecting active survey data from citizens.
- Advertising points e.g., displaying advertising for sponsors, local retailers and events or other advertisers.

It is important to note that smart kiosks have the potential to be customisable, movable and more critically, a multi-modal experience in that they are interactive and can display visual information and broadcast sound, if required. They also typically include sensors to alert the authority to tampering. Security can be provided through secured WPA/WPA2 or an encrypted network thus requiring proprietary network keys. The CityBridge Link System has been rolled out in New York City and London, in conjunction with local authorities and utility providers providing free Wi-Fi access with speeds up to 1Gb per second, funded through advertising [47]. Each Link Kiosk provides coverage from 150-400ft. Some functionality was disabled due to misuses e.g., unlimited content browsing directly through the kiosk [48].

Smart kiosks can also become a destination in themselves thus attracting people to their location. Research suggests that smart kiosks incentivise local retail activity through proximity and assist people, especially visitors, to discover and navigate local businesses in different business categories [47]. Smart kiosks provide a vital bridge in crossing the digital divide by providing vulnerable communities with access to free Wi-Fi and public services and therefore support social inclusion [49].

3) Smart Benches

Modern smart street benches can include a wide range of functionality that encourage different street uses. For example, they can include additional functionality such as shelter, lighting, CCTV, USB and EV charging, bicycle parking and air pressure, as well as video displays that can be used for information, advertising, and entertainment e.g., games and other programming. Increasingly, smart benches can power themselves completely or partially using solar panels.

In addition to the functionality of the smart bench, three other factors warrant consideration by smart street designers. First, the location and orientation of smart benches can be a determining factor on successful outcomes, use and utility. In effect, local authorities make a decision about what a member of the public will look at and how close they will be to other elements of the street including retail outlets, waste receptacles, junctions, etc. For example, if a local authority wishes to use the smart benches for EV charging, then this determines location and proximity to car parking spaces and the associated impact that such activity has relative to the bench. Second, the design and placement of smart benches can include or exclude those with mobility limitations including participation by wheelchair users, or those with strollers, and accessibility on the footpath for other street users. Third, in addition to services for local stakeholders, smart street benches can provide additional functionality to support the connectivity corridor by housing multiple radio access units, backhaul equipment, power supplies and antennas [50]. Additionally, they can be located at convenient intervals between smart lampposts thereby boosting the coverage and strength of wireless signals.

4) Other Smart Furniture

Waste receptacles are a form of smart street furniture with a primary function. While necessary, they can adversely affect the visual identity of the street, and introduce accessibility issues. Smart waste solutions can be autonomous and robot-based or fixed. The former include making standardised waste containers (organised by organic, recyclable and landfill material) available and having robots that move these containers to centralised units for compaction and removal by type. The EU-funded projectm, FP6-Dustbot, and subsequent ROBOSWEEP projects, resulted in an autonomous street cleaning robot [51]. Similarly, the Lumebot is used to sweep and vacuum pavements, move snow, sweep and steam clean pavements, and dispense salt, sand and gravel [52]. Others have proposed more ‘fun’ designs. For example, Giant Food Stores has rolled out “Marty” to 172 stores, a robot that identifies spills and other dangerous obstructions [53].

There are a variety of fixed waste collection systems. Vacuum-based systems involve users throwing their waste bags into accessible waste inlets located indoors or outdoors and it is then stored in closed underground screw tanks which are linked together with docking points and a network of underground pipes. The docking points are positioned on the periphery so that the truck picking up the waste does not have to drive into gardens or narrow streets. More conventional smart bin designs are increasingly solar-powered waste receptacles with built-in compactors. Sensors signal the need for collection, as well as recording data on volume, fill rate and collection activity for analysis and chargeback.

Electronic storage units are another form of street furniture that can be used by public services, street vendors, and members of the public to store items. They can also be used by retailers and the public to deliver and collect goods and products out of hours. This may be particularly useful in the context of competing against online trading and limitations due to COVID19. Such units increasingly include advertising displays, reservation and payment, thereby facilitating income generation. Smart solutions also exist for (i) public toilets including access management, intelligent wash disinfection, and other related systems, and (ii) smart public drinking fountains that monitor usage, water quality and hygiene.

F. Climate Protection, Environmental Monitoring, and Weather Mitigation

As discussed, local climate conditions can discourage mobility and outdoor activities. Two achievable interventions include (i) weather monitoring and prediction capabilities, and (ii) support for a variety of weather mitigation strategies that can be triggered based on data, that (i) block wind, and (ii) provide shelter from precipitation, and (iii) shade from the sun. As previously mentioned, AOT is an experimental urban measurement system that provides programmable, modular “nodes” with sensors and computing capability for measuring climate, air quality, noise levels, flood and water levels, as

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well as counting the number of vehicles at an intersection (and then deleting the image data rather than sending it to a data center) [45]. Use cases today include consumer recommender systems for healthiest and unhealthiest walking times and routes, real-time detection of urban flooding, and micro-climate measurement and analysis [45].

In addition to monitoring the natural environment, sensor technology can be used to monitor the built environment including use and building decay. Smart street development provides the opportunity to embed sensors and other infrastructure systems for monitoring purposes. This includes footpaths, roadbeds, water pipes and electricity systems, providing operators with proactive and predictive maintenance and management systems to ensure usage and costs are within expected ranges, potential and actual anomalies, for example leaks, are detected and resolved, and that service levels are met through cleaning, repair, augmentation and other interventions.

Weather and traffic data can be used to actuate zonal public realm management including weather mitigation strategies. Such strategies may include fixed retractable umbrellas, retractable smart awnings or umbrellas managed and maintained by property owners (retailers), or even street use prioritisation during different weather conditions, in combination with increased tree canopy coverage. However, such technologies can represent a significant investment in themselves. The ultimate outcome of weather mitigation strategies will be to catalyse new uses for a street year-round including markets, events and other activities. As well as the socio-economic impact, it benefits public health by increasing mobility and street use by pedestrians and cyclists.

G. Environmental Sustainability

It is widely accepted that private motor vehicles are the most significant challenge to sustainable travel [54]. In rural communities, it may be infeasible to restrict conventional vehicles from shopping streets for parking or transit, particularly where local public transit alternatives are limited. As discussed, an alternative is to invest in the public realm digital fabric to enable a programmable flexible and adaptive system that prioritises roadbed use and parking space for pedestrians, cyclists, EVs, ride sharing and other sustainable practices. Similarly, reducing barriers to mobility including accessibility, security and safety measures will result in reduced carbon emissions. Implementation of a sensor network for collecting environmental data, for example via the AOT [45], will provide enhanced climate and environmental measurement capabilities and inform local decision making.

A number of the proposed interventions can make use of alternative energy sources e.g. solar power street furniture. To reinforce the sustainability of the street and proposed innovations, dedicated space on streets can be reserved for installing and demonstrating pavement interventions that encourage physical activity and convert alternative energy into off grid electrical energy to power lighting, kiosks, digital signage and other smart furniture. For example, even a relatively small strip of Pavegen tiles can generate 6 to 8 joules of off-grid electrical energy [55]. Bluetooth beacons in the system connect to smartphones, rewarding users for their steps and generating permission-based analytics. Furthermore, it can be integrated with other platforms using APIs. Technologies like Pavegen can be used in different scenarios including powering kiosks and lighting walls. A variety of alternative energy harvesting technologies can be used to store and power innovative street furniture and systems. These include specially- designed light-tiles at pedestrian crossings that only appear when pedestrians or cyclists approach and photovoltaic road cells that convert sunlight into energy. Dutch company, Energy Floors, has designed a number kinetic and solar-powered floors that serve dual purposes as both lighting and interactive street art, interactive games for kids, and dancing [56]. The Korea Advanced Institute of Science and Technology (KAIST) has run trials using induction coils embedded in roads to charge public transit vehicles [57]. Similarly, a UK project is developing smart roads that generate power using piezoelectricity and hydro-mechanical dynamics from passing cars, trucks and buses [58]. The electricity harvested is stored by roadside batteries to power street lamps, road signs, air pollution monitors, plus sensors that detect when potholes are forming, and generate data on vehicle speeds, the types of vehicle travelling along the roads, as well as other information on traffic flows [58]. Israeli company, Innowattech, has experimented with piezoelectric sensors to capture energy created by the weight, motion and vibration of passing trains [59]. While some of these technologies may not be feasible for long-term use, particularly on busy roads, dedicated plug and play areas can be made available to companies wishing to test their technologies in a live environment, and space for power storage supporting hardware as part of redevelopment plans.

H. Street Activity

Research suggests that while street-improvement projects can increase the level of pedestrian satisfaction, they may fail to increase pedestrian volume without specific interventions to invite greater street activity [60]. Inviting street activity is key to the sustainability of shopping streets. As discussed in Section I, thriving shopping streets are both social spaces and commercial spaces, with not only clusters of similar retail outlets but also other diverse retail and social activities [12]. The redevelopment of rural shopping streets should not only serve the needs of existing stakeholders but attract new businesses, customers, visitors and users. The public realm, and in this case one infused with cyber-physical infrastructure should be a destination in itself.

Local retail activity can generate greater economic activity through higher traffic (due to free Wi-Fi and other services) and proximity to smart street furniture (e.g., kiosks, benches and cycle parking and sharing). It can also assist people, especially visitors, to discover and navigate local businesses [47] and thus add value to existing businesses. The siting of such furniture should consider the types of audience a community wishes to attract, move through, and/or stay at different parts of the street, and where they wish to encourage more use at different hours of the day. Geo-fencing can be used in conjunction with smart street furniture to create a sense of digital enclosure and create dialogue with users of street, as well as promote social and commercial activities and retailers on the street. In addition, it can provide income generation through data trading and advertising.

In addition to inherent functionality, street furniture can be augmented with software-enabled solutions to make them interactive using machine learning, if connected, or QR and AR codes, when offline. Advances in intelligent chat technology and even simple conversational technologies can transform street furniture in to a social experience. For example, the Hello Lamp Post project demonstrated how the public could interact with everyday street objects through text messaging providing a fun and novel way for street interaction. More advanced conversational technologies may be used for stimulating interaction with at risk communities. Research also suggests that AI-based conversational technologies provides "valuable practice" and coaching to help older adults navigate challenging conversations and improve both their health and quality of life [61]. Such initiatives can be low cost and attract visitors for this interaction alone.

In conjunction with a more flexible programmable public realm, public projection and sound systems can transform the public space for outdoor events and extend after hours activity including in evenings. In addition to retractable awnings, this may represent another opportunity for the existing retail community on a street to contribute to a smart street through sharing off-peak use of their physical infrastructure. Retailers could be encouraged or incentivised to integrate smart glass and related initiatives. Smart glass takes many forms, often based on liquid crystal technology, to transform storefronts by allowing window glass for projection e.g. it can switch to opaque, transparent, for projecting media including advertising, or even using it as a mirror. Smart glass and motion sensor natural user interfaces can transform how the public engages with retail frontage, even out of hours. Such innovations provide 100% glass window utilisation out of hours including monetisation through advertising. When multiple units are linked together with a street sound system, they can be used for creating multimedia experiences and shows to attract visitors. In effect, they provide the opportunity to turn passive retail units in to information kiosks, entertainment systems, and digital out of home advertising.

Encouraging new uses, particularly transient uses, requires changes to the geometry of a street. Smart technologies can use digital technologies to experiment with using specific zones on the street as reservable outdoor spaces for short-term uses for regular or seasonal retail, performances, community and personal events (e.g., markets, school activities or hackathons), and food trucks. As well as systems to delineate these areas (e.g., automated retractable bollards and digital signage), utilities (power and water), and storage for pop-up stall units and street vendors and performers. New pop-up configuration and designs are emerging that can be used for multiple purposes such as street seating, movable and collapsible units. Similarly, historically unused or redundant space can be can be used for smart delivery and distribution centres (storage lockers) where citizens can have goods delivered or retail outlets can leave goods for customers to collect out of hours. Parklets, planters and dedicated units could also be used for Urban Farm projects with local schools.

V. CONCLUSION

Forecasts suggest that by 2050, over 68% of the world's population will live in cities [1]. Rural towns, communities, and their citizens are in danger of being left behind. The sustainable management of urban growth involves investments in smart city technologies and improving the lives of urban dwellers, however an alternative is improving the quality of life and attractiveness of rural living to reduce migration to urban centers, and ideally changing the flow. Digital technologies can play a significant role in sustaining and revitalising rural towns, and building economic and social linkages between urban and rural areas. We suggest the first step in the digital transformation of rural towns is sustaining rural shopping streets, often the economic core of rural communities. Smart streets are a manageable and feasible investment for rural towns that can sustain rural shopping streets while enhancing the lives of those who live in and around rural towns.

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