Citiverse Initiative

AI-enabled Citiverse Standardization Landscape – Release 1



Foreword

This publication was developed within the framework of the Discovering the Citiverse – Global Initiative on AI, Digital Twins and Virtual Worlds, a global multistakeholder platform bringing together the International Telecommunication Union (ITU), the United Nations International Computing Centre (UNICC), Digital Dubai, the European Commission, Open & Agile Smart Cities (OASC), and more than 70 international partners.

The Initiative aims to advance an AI-enabled, interoperable, inclusive and people-centred citiverse where artificial intelligence, spatial intelligence, digital twins and immersive technologies converge to address real-world challenges and unlock new opportunities for cities and communities. By fostering international collaboration, promoting common standards and facilitating knowledge exchange, it seeks to ensure that emerging technologies deliver tangible benefits for people, while strengthening trust, interoperability and digital inclusion.

Bringing together cities, governments, industry, academia and the United Nations system, the Initiative bridges the gap between technological innovation and practical implementation, empowering decision-makers to harness the potential of the AI-enabled citiverse to improve quality of life, strengthen urban resilience and accelerate sustainable and inclusive development.

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Disclaimers

The opinions expressed in this publication are those of the authors and do not necessarily represent the views of their respective organizations, Executive Committee members or Steering Committee members of the Initiative. The findings presented in this report are based on a comprehensive review of existing literature and voluntary written contributions submitted by a diverse range of stakeholders.

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AI-enabled Citiverse Standardization Landscape – Release 1

Table of contents

Foreword ii

Acknowledgements ii

Abbreviations and acronyms viii

Executive summary xii

1 Introduction 1

1.1 Background 1

1.2 Core terminology and definitions 2

1.2.1 AI-enabled citiverse 2

1.2.2 Related terminology 2

2 Standardization Landscape – Participating Organizations 4

2.1 International standards development organizations 4

2.2 Regional Standards Bodies, Industry Forums and Consortia 5

3 Citiverse Standards System Architecture and Core Standards Inventory 7

3.1 Overall architecture 7

3.2 Core capabilities and standard maturity by layer 8

3.3 Core standards inventory 10

3.3.1 Cross-cutting technical support standards 10

3.3.2 Governance system standards 24

3.3.3 Vertical technology stack layer standards 37

4 Standardization Gap Analysis 64

4.1 Priority assessment methodology 64

4.2 Cross-cutting standards gaps 65

4.2.1 Cross-cutting technical support standards gaps 65

4.2.2 Governance System Standards Gaps 66

4.3 Vertical technology stack layer gaps 69

4.3.1 Layer 1: Network & connectivity layer gaps 69

4.3.2 Layer 2: Digital infrastructure & platform layer gaps 69

4.3.3 Layer 3: Data & analytics layer gaps 71

4.3.4 Layer 4: Virtual world construction layer gaps 72

4.3.5 Layer 5: Application scenario layer gaps 74

4.4 Gap priority summary 75

5 Conclusions and Next Steps 76

6 About the Discovering the Citiverse – Global Initiative on AI, Digital Twins and Virtual Worlds 78

Appendix 1: Core Standards Inventory 81

Appendix 2: Standards Gap Summary 97
References 103

List of figures and tables

Figures

Figure 1: Executive summary xiii
Figure 2: AI-enabled Citiverse Standards System Architecture 7
Figure 3: Conclusions and next steps 77

Tables

Table 1: Standards Development Organizations and Industry Forums 4
Table 2: Core Element Requirements for Citiverse Standards 8
Table 3: Layer Capabilities, AI Enablement, Governance Alignment and Maturity 9
Table 4: Gap Priority Summary 75

Abbreviations and acronyms

3GPP	3rd Generation Partnership Project
5G/6G	Fifth / sixth generation mobile networks
5GS	5G System
AI	Artificial intelligence
AOUSD	Alliance for OpenUSD
API	Application programming interface
AR	Augmented reality
AWI	Approved work item
BIM	Building information modelling
C2PA	Coalition for Content Provenance and Authenticity
CD	Committee draft
CEN-CENELEC	European Committee for Standardization and European Committee for Electrotechnical Standardization
DetNet	Deterministic Networking
DID	Decentralized identifier
DLT	Distributed ledger technology
DPI	Digital public infrastructure
DTC	Digital Twin Consortium
eIDAS	Electronic identification, authentication and trust services (EU regulation)
ETSI	European Telecommunications Standards Institute
EU	European Union
EUDI	European Digital Identity (Wallet)
FG-MV	ITU-T Focus Group on Metaverse
GDPR	General Data Protection Regulation
GeoAI	Geospatial artificial intelligence
GIS	Geographic information system
glTF	Graphics Library Transmission Format
GPU	Graphics processing unit
GS	Group specification (ETSI)

(continued)

GSMA	Global System for Mobile Communications Association
IACS	Industrial automation and control systems
ICT	Information and communication technology
IDSA	International Data Spaces Association
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IFC	Industry Foundation Classes
IoT	Internet of Things
ISG	Industry specification group (ETSI)
ISMS	Information security management system
ISO	International Organization for Standardization
ITS	Intelligent transport system
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
JTC 1	Joint Technical Committee 1 (ISO/IEC)
JSON	JavaScript Object Notation
KPI	Key performance indicator
LoD	Level of detail
LPWAN	Low-power wide-area network
MAR	Mixed and augmented reality
MEC	Multi-access edge computing
MIM	Minimal Interoperability Mechanism
MIV	MPEG immersive video
ML	Machine learning
MPEG	Moving Picture Experts Group
MR	Mixed reality
MSF	Metaverse Standards Forum
NGSI-LD	Next Generation Service Interfaces, Linked Data
NIS2	Network and Information Security Directive (EU, 2022)
NIST	National Institute of Standards and Technology

(continued)

OASC	Open & Agile Smart Cities
ODRL	Open Digital Rights Language
OGC	Open Geospatial Consortium
OMG	Object Management Group
OT	Operational technology
PIMS	Privacy information management system
PTP	Precision Time Protocol
QoE	Quality of experience
QoS	Quality of service
RMF	Risk Management Framework (NIST AI RMF)
SA	Service and System Aspects (3GPP working group)
SASB	IEEE Standards Association Standards Board
SC	Subcommittee
SCG	Strategic Coordination Group
SDG	Sustainable Development Goal
SDO	Standards development organization
SEAL	Service Enabler Architecture Layer (3GPP)
SG	Study Group
SLA	Service level agreement
SSC&C	Smart sustainable cities and communities
TC	Technical committee
TR	Technical report
TS	Technical specification
TSN	Time-Sensitive Networking
U4SSC	United for Smart Sustainable Cities
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNICC	United Nations International Computing Centre
V-DMC	Video-based dynamic mesh coding
V-PCC	Video-based point cloud compression
VC	Verifiable credential

(continued)

VR	Virtual reality
W3C	World Wide Web Consortium
WCAG	Web Content Accessibility Guidelines
WeGO	World Smart Sustainable Cities Organization
WG	Working group
WoT	Web of Things
XML	Extensible Markup Language
XR	Extended reality

Executive summary

The AI-enabled citiverse brings together artificial intelligence, digital twins, spatial intelligence and immersive technologies to support urban planning, public services and more informed decision-making. As cities explore these capabilities through pilots and emerging deployments, international standards provide essential foundations for connecting systems, sharing data and supporting trusted, inclusive services. Relevant standards already exist across several technology domains; however, their application to integrated, city-scale environments remains uneven.

Developed under the Discovering the Citiverse – Global Initiative on AI, Digital Twins and Virtual Worlds, this report maps the AI-enabled citiverse standardization landscape and identifies priorities for further work. Building on earlier research by StandICT.eu, it brings together relevant standards and initiatives from international standards development organizations, regional bodies, industry forums and consortia. Its focus is on city-level architectures, cross-platform interoperability and applications that connect urban departments and services.

The report proposes a reference framework comprising five technology layers: network and connectivity; digital infrastructure and platforms; data and analytics; virtual world construction; and application scenarios. AI enablement and people-centred security and governance extend across all five layers. Cross-layer support standards provide common technical foundations and governance requirements, including terminology, reference architectures, interoperability, trust, digital identity, ethics and compliance. This structure helps readers understand how individual standards contribute to an integrated urban ecosystem.

Within this framework, the report catalogues 201 inventory entries, covering published standards, standard series, technical reports, specifications and formally initiated projects. It considers their maturity and readiness, citiverse relevance, interoperability and openness, and governance and trust alignment. A separate qualitative assessment identifies 36 standardization gaps: two highest-priority, 27 high-priority and seven medium-priority gaps, based on interoperability impact, deployment urgency, market fragmentation, and regulatory or safety implications. The two highest-priority gaps concern cross-domain semantic interoperability and multisystem interoperability for emergency response.

A central finding is that many gaps concern the adaptation and integration of existing standards. Progress will, therefore, depend on citiverse-specific profiles, interface mappings, evaluation methods and implementation guidance, alongside new normative requirements where these are needed. Technical interoperability must also be addressed, together with privacy, cybersecurity, accessibility, accountability and applicable regulatory requirements.

Who should read this report

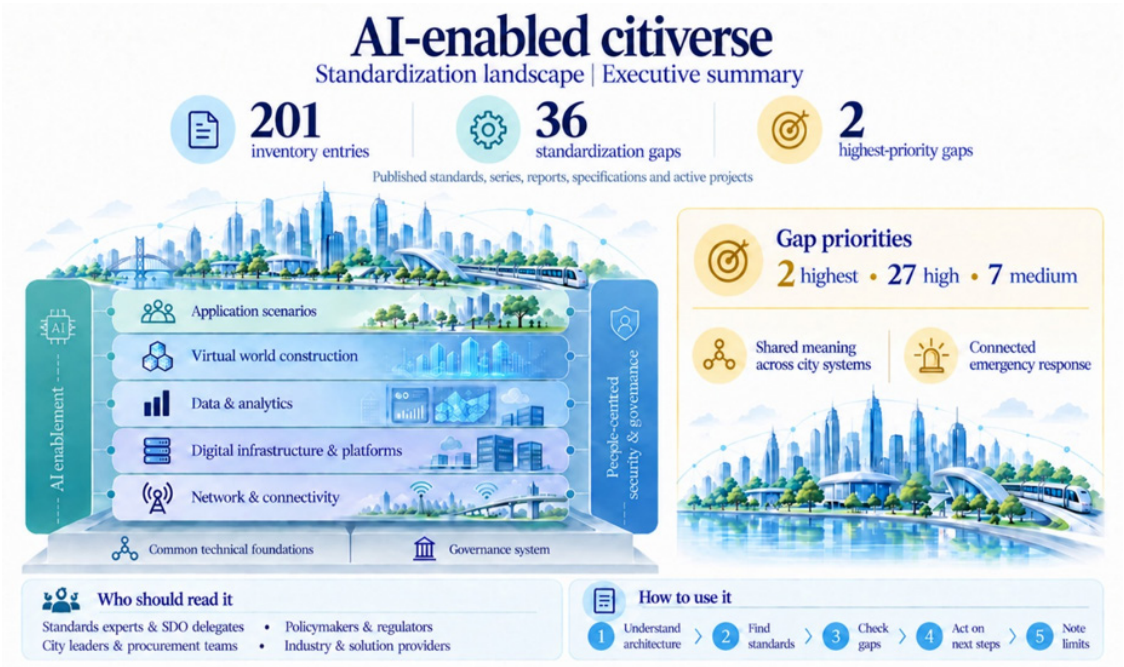
- **Standards experts and SDO delegates**: to see where work overlaps, what is in progress, and where new work items, profiles or revisions are most needed.
- **Policymakers and regulators**: to link standards to policies, and to see where regulatory expectations lack supporting standards.
- **City leaders and procurement teams**: to identify the standards to reference in strategies, pilots and procurement, and to understand where interoperability and trust risks remain.

- **Industry and solution providers**: to align product roadmaps with maturing standards and to find where to contribute.

How to use this report

- **Understand the architecture**. Start with Section 3.1 and Figure 2 to place your area of interest in the five-layer stack; then use Table 3 to see the maturity of each layer.
- **Find specific standards**. Section 3.3 describes each of the 201 entries with its status and source, and Appendix 1 gives an index by layer. Descriptions of each standard are kept separate from the report's own view of its potential citiverse application.
- **Check the gaps**. Section 4 gives the priority and type of each gap. Standards bodies can use it to plan work items, and cities can use it to shape pilot and procurement requirements.
- **Act on the next steps**. Section 5 sets out recommended actions for standards bodies, regulators and cities.
- **Note the limit**s. Gap priorities are qualitative and reflect the report's own assessment, not determinations by standards bodies. Status information reflects the date of writing, and the landscape will be updated annually.

Figure 1: Executive summary





1 Introduction

1.1 Background

The citiverse is at a critical juncture, transitioning from conceptual exploration toward pilot implementation and potential deployment across urban services. As the United Nations specialized agency for digital technologies, ITU is playing a leading role in advancing the global standardization of the AI-enabled citiverse through its ITU-T Study Group 20 (SG20), the lead study group for AI-enabled citiverse standardization.

Recognizing the need for greater international coordination, the Second Citiverse Assembly, held on 12 May 2026 in Geneva, was co-organized by ITU, the European Commission, the Open & Agile Smart Cities (OASC) network, and UNICC under the "Discovering the Citiverse – Global Initiative on AI, Digital Twins and Virtual Worlds". Bringing together governments, standards development organizations, industry, academia, cities, and United Nations entities, the Assembly called for the development of a dynamic "**Global Citiverse Standardization Landscape**", a living reference that systematically maps the standards, initiatives, and technical developments shaping the AI-enabled citiverse worldwide.

This document leverages the research carried out in the "Citiverse Standardization Landscape" developed by StandICT.eu, supported through the European Commission-funded StandICT.eu 2029 project. This report catalogued approximately 350 standards, technical reports, and specifications relevant to the emerging citiverse ecosystem. However, since the publication of that report, the field has evolved significantly beyond foundational technologies. In particular, there is now a growing need to examine application-specific standards, the transformative role of artificial intelligence, the latest developments across standards organizations, and the growing importance of governance, interoperability, and regional regulatory compliance.

Building on this earlier work, the present report provides an updated assessment that incorporates recent developments of the global citiverse standardization ecosystem. It incorporates the latest published standards, ongoing projects, and publicly announced work programmes, including the 2025 achievements and 2026 work plans of ITU-T Study Group 20 (IoT, Digital Twins and Smart Sustainable Cities and Communities) and other leading standards development organizations including ISO, IEEE, ETSI and W3C. Through systematic standards verification, classification, mapping, and gap analysis, the report establishes a robust baseline for international coordination of AI-enabled citiverse standardization.

National and regional smart city strategies, including the EU Smart Cities and Communities initiative, China's New Urban Construction agenda, and similar frameworks in other regions shape the adoption priorities and implementation pathways for citiverse standards. Effective standardization must align with these strategic frameworks to ensure relevance and uptake at the city level.

The report covers standards and technical initiatives developed by international standards development organizations, industry forums, and consortia, with particular emphasis on the convergence of five foundational technology domains:

- **smart sustainable cities and communities**
- **digital twins**
- **artificial intelligence**

- **geospatial information**
- **immersive technologies (including metaverse).**

In addition to technical standards, it also considers governance frameworks, trust and security requirements, interoperability mechanisms, and regional regulatory initiatives, providing a comprehensive reference for policymakers, standards experts, industry, and city leaders working to build an open, interoperable, secure, and people-centred AI-enabled citiverse. The citiverse has been defined by the UN as "*an emerging, human-centred digital ecosystem that combines digital twins, virtual reality and AI to create interconnected 3D models of real-world cities*".[1]

1.2 Core terminology and definitions

The definitions below are drawn from international standards, technical reports and recognized policy sources. Where no formal international definition was identified, a working definition is explicitly labelled as such.

1.2.1 AI-enabled citiverse

The AI-enabled citiverse aims to create shared pathways that enable interoperability for a city's departmental IT systems, along with data from sensors and digital twins, integrated with immersive visualization environments, creating a coherent and interoperable framework. This enables participatory co-design, testing of policy interventions in low-risk virtual environments before physical commitment, and the sharing of experiences and know-how between cities and citizens.

1.2.2 Related terminology

Metaverse: A collective virtual environment where physical and virtual worlds converge, that enables users to interact with shared digital spaces, objects and services. (NOTE – A metaverse can be virtual, augmented, representative of or associated with the physical world.)[2]

Interoperability: The ability of a client component in a device to communicate and share data with a variety of server components in an unambiguous and predictable manner, to exchange data accurately, effectively and consistently and to understand and use the information that is exchanged.[3]

Minimal interoperability: The minimal sufficient degree needed to meet a certain requirement for interoperability relating to smart cities and communities. (NOTE – This is an approach to build a set of modular mechanisms, across multiple domains, locations and events.)[4]

It should be noted that the concept of minimal interoperability deals with the fact that cities and communities need to bring together information from data that is being gathered for different use cases and applications and so may be in different formats, and use different data models, APIs etc., that are appropriate to those use cases and applications. Minimal interoperability describes how a minimal but sufficient alignment between these different data sources can be achieved without requiring them to comply with the same detailed sets of standards. The methodology for doing this is described in Recommendation ITU-T Y.4505 – Minimal Interoperability mechanisms for smart and sustainable cities and communities.

Regulatory compliance: The alignment requirements of citiverse systems with the regulatory frameworks of the deployment region, including AI governance, data security, and public data management rules. It is a prerequisite for large-scale deployment. [Working definition; aligned with EU AI Act (Regulation 2024/1689), GDPR, and NIST AI RMF 1.0 governance frameworks.]

Digital twin: A digital representation of an object of interest. (NOTE – A digital twin may require different capabilities (e.g., synchronization, real-time support) according to the specific domain of application).[5]

Urban/local digital twin: A digital twin applied to a city or urban district, integrating geospatial, infrastructural, environmental and social data to support urban planning, management and decision-making. [Working definition, adapted from Recommendations ITU-T Y.4600 and ITU-T Y.4605; no single international standard defines this compound term.]

Spatial intelligence: The capability to acquire, analyse, model and visualize geospatially referenced information to support understanding, prediction and decision-making in physical and virtual environments. [Working definition; no formal international standard definition identified as of 2026.]

Immersive technology: Tools that enable the integration of virtual content and the physical environment in a manner that supports user engagement with the resulting blended reality.[6]

Avatar/digital human: Avatar: graphical representation of a user or the user's alter ego or character; digital human: a digital representation of a human or human-like entity capable of visual, verbal and behavioural interaction, potentially AI-driven. [Digital human definition adapted from Recommendation ITU-T F.748.63 framework; ISO/IEC 24216-1:2026 provides avatar categorization.]

Artificial intelligence (AI): Engineered system that generates outputs such as content, forecasts, recommendations or decisions for a given set of human-defined objectives.[7]

Data space: Environment enabling trusted data sharing between participating parties, based on an agreed governance framework, along with an agreed set of policies, semantic models, standardized protocols, processes, and facilitating services.[8]

Digital public infrastructure (DPI): A set of shared digital systems that are secure and interoperable, built on open standards and specifications, to deliver and provide equitable access to public and/or private services at societal scale.[9]

Syntactic interoperability: The ability of systems to exchange data through compatible formats, protocols and application programming interfaces (APIs), ensuring structural consistency at the syntax level. [Working definition; syntactic interoperability ensures structural consistency through compatible formats and protocols, whereas semantic interoperability ensures exchanged data carry shared, formally defined domain meaning.]

Semantic interoperability: Ability for data shared by systems to be understood at the level of formally defined domain concepts. [Working definition.]

2 Standardization Landscape – Participating Organizations

The global citiverse standardization landscape is characterized by coordinated, multistakeholder efforts across standards development organizations, regional standards bodies, industry forums and consortia. Relevant standards are distributed across their respective work programmes and areas of expertise. As the United Nations specialized agency for digital technologies, ITU provides the multilateral platform for international coordination of citiverse standardization activities, with ITU-T Study Group 20 serving as the lead ITU study group for citiverse standardization, including digital twins, AI-enabled urban systems, and smart sustainable cities and communities. Other organizations including ISO/IEC, IEEE, 3GPP, OGC, W3C, and additional standards bodies continue to develop complementary standards within their respective areas of expertise, contributing to an interoperable and globally aligned citiverse ecosystem. Core participants fall into two main categories:

2.1 International standards development organizations

Table 1: Standards Development Organizations and Industry Forums

Organization	Scope	Key Activities	2026 Progress	Key Committee(s)/ Working Groups
ITU-T SG20	Smart cities, IoT, digital twins, citiverse	City platforms, interoperability, digital twin and citiverse requirements	Multiple new international standards approved (called ITU-T Recommendations); digital twin visualization and data assetization work progressing	SG20 (IoT & smart cities); Q1/20 (digital twin & citiverse)
ISO/IEC JTC 1	Digital twins, IoT, AI, XR	Reference architectures, data models, security frameworks	30151/30152/30153 digital twin series in development; 23090-29 (V-DMC) published	SC 41 (IoT & digital twin); SC 42 (AI); SC 24 (computer graphics & metaverse); SC 27 (security); SC 29 (MPEG/JPEG); SC 32 (data management); SC 38 (cloud); WG 11 (smart cities); SCG 2/ CG 2 (metaverse coordination); JSEG 15
IEEE	Metaverse security, digital humans, synchronization	Blockchain security, digital human standards, cyber-physical synchronization	P2048 security series in draft; 2888.3 published; P2048.121 digital human standard progressing	802.1 (TSN); 802.11 (Wi-Fi); 802.3 (Ethernet); P2048 (metaverse security); 2888 WG (cyber-physical interface); 3079 WG (immersive content); 7000-series (ethics); SASB

Table 1: Standards Development Organizations and Industry Forums (continued)

Organization	Scope	Key Activities	2026 Progress	Key Committee(s)/ Working Groups
3GPP	Mobile networks, metaverse services	5G/6G support for spatial comput-ing, mobile metaverse	Release 19 mobile metaverse standards published; Release 20 spatial services in development	SA1 (services); SA2 (architecture); SA4 (codecs); SA6 (edge/ MEC); RAN1/RAN2 (radio access)
OGC	Geospatial standards, 3D city models	CityGML, SensorThings, API standards	3D Tiles 1.1 stable; digital twin geospatial alignment ongoing	3D Tiles SWG; SensorThings SWG; GeoAI DWG
W3C	Web stan-dards, immersive web	WebXR, DID, Verifiable Credentials	WebXR Candidate Recommendation Draft; DID stan-dard stable; VC 2.0 published	WebXR WG; DID WG; Verifiable Credentials WG; Immersive Web CG
ETSI	network functions, edge comput-ing, data interopera-bility, local digital twins	MEC, NFV, network slicing, NGSI-LD, MIMs, LDT reference architecture	MEC standards supporting XR deployment; network slicing for metaverse use cases defined; EN 304 181 (LDT refer-ence architecture) and EN 304 182 (MIM profiles) under devel-opment	ISG MEC; ISG NFV; TC TISPAN; TC SEC (security); ISG CIM; TC DATA

2.2 Regional Standards Bodies, Industry Forums and Consortia

Open & Agile Smart Cities and Communities (OASC): A global network of nearly 200 subnational governments headquartered in Brussels, focusing on interoperability. OASC drives the development of the Minimal Interoperability Mechanisms (MIMs).

StandICT.eu: An EU-supported ICT standardization observatory operating under the StandICT.eu 2029 project.

Web3D Consortium: An industry alliance for 3D Web technologies, maintaining the ISO/IEC 19775 (X3D) standard, advancing updates to Web-based 3D city model interaction specifications.

Khronos Group: Industry consortium developing open standards for 3D graphics, XR, and parallel computing, including glTF, OpenXR, Vulkan, and related technologies critical for citiverse rendering and interaction.

Metaverse Standards Forum (MSF): An industry consortium coordinating interoperability standards across metaverse and virtual worlds technologies, liaising with ITU, ISO/IEC, IEEE, W3C and OGC to reduce fragmentation.

Digital Twin Consortium (DTC)/OMG: A consortium developing open source code, reference architectures and terminology for digital twin systems, in liaison with ISO/IEC JTC 1/SC41 and ITU-T Study Group 20.

Alliance for OpenUSD (AOUSD): An industry alliance promoting the Open Universal Scene Description (OpenUSD) specification as a standard for 3D content interoperability, relevant for citiverse virtual world construction.

FIWARE Foundation: An open-source community developing Smart Data Models and the FIWARE platform, widely deployed by European cities as the data-model layer for smart city and citiverse applications.

LDT CitiVERSE EDIC: A consortium of European countries that develops and operates shared infrastructure for networked local digital twins, including the LDT Toolbox.

CEN-CENELEC JTC 21 / JTC 13 / JTC 25 / TC 465: European standardization committees addressing artificial intelligence (CEN-CLC/JTC 21), cybersecurity and data protection (CEN-CLC/JTC 13), data and data spaces (CEN-CLC/JTC 25) and sustainable cities and communities (CEN/TC 465), producing European standards and pre-standards that inform international work.

NIST (National Institute of Standards and Technology): U.S. federal agency under the Department of Commerce, producing the AI Risk Management Framework (AI RMF), cybersecurity frameworks, and digital twin guidance relevant to citiverse governance.

TM Forum: An industry association developing open digital architecture and APIs for telecom and smart city service management, relevant to citiverse service layer interoperability.

GSMA: The global mobile industry association, developing specifications for mobile networks, IoT and digital identity that underpin citiverse connectivity infrastructure.

U4SSC (United for Smart Sustainable Cities): A UN initiative coordinated by ITU, UNECE and UN-Habitat, supported by 22 UN entities developing technical specifications and policy frameworks on AI, digital twins and other emerging digital technologies, in order to help cities accelerate their digital transformation.

Discovering the Citiverse – Global Initiative on AI, Digital Twins and Virtual Worlds: A global multistakeholder platform launched by ITU, UNICC and Digital Dubai, supported by more than 70 partners, to advance the AI-enabled citiverse, where AI, spatial intelligence and digital twins converge to deliver real-world impact.

oneM2M: Global partnership developing common service layer standards for M2M and IoT systems, providing horizontal architecture for city-scale IoT deployments.

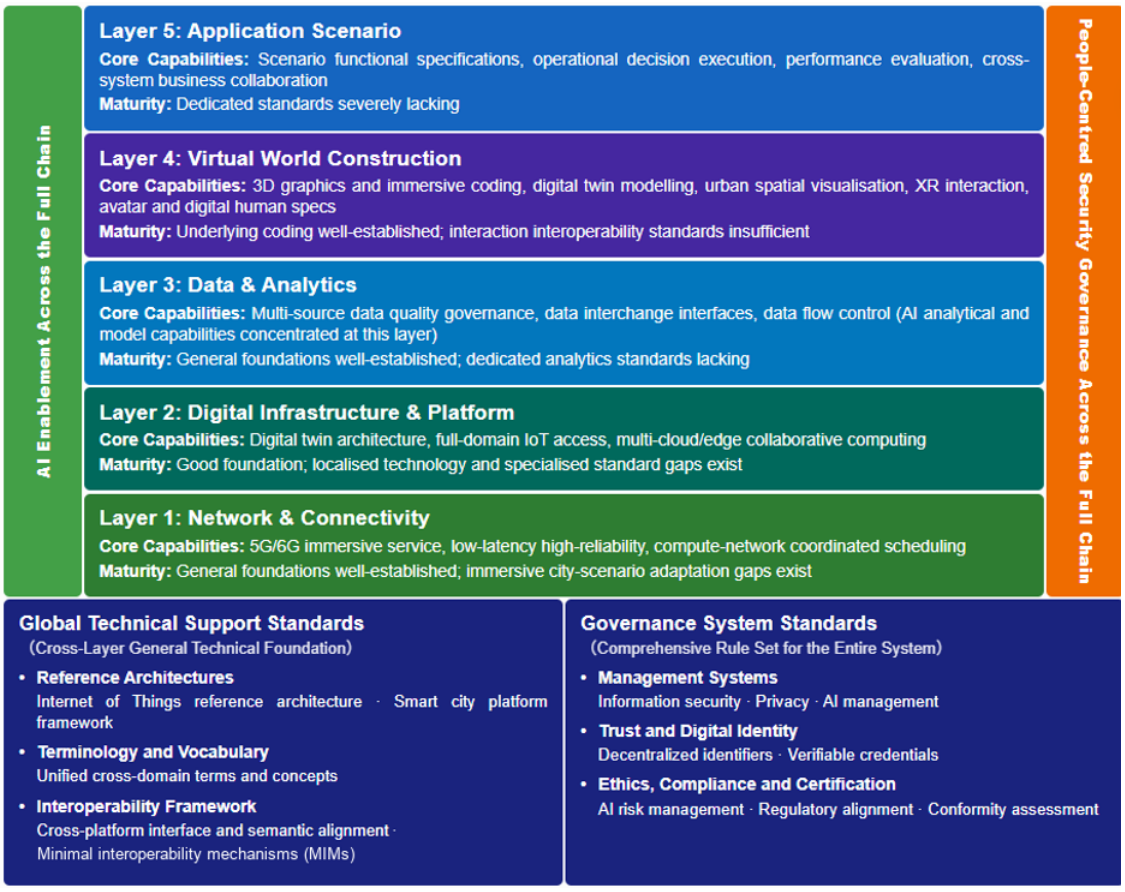
C2PA (Coalition for Content Provenance and Authenticity): Industry consortium developing technical standards for digital content provenance, including AI-generated content attribution.

3 Citiverse Standards System Architecture and Core Standards Inventory

3.1 Overall architecture

This report uses the definition of citiverse endorsed by 20 UN entities and developed under the coordination of ITU, integrating the StandICT.eu classification framework, the ISO/IEC JTC 1 SCG 2 Metaverse reference architecture, and the ITU-T Study Group 20 smart city digital twin architecture, to form an optimized standards system framework comprising "a five-layer vertical technology stack, two cross-cutting horizontal dimensions, and cross-layer support standards split into a general technical foundation and a governance system".

Figure 2: AI-enabled Citiverse Standards System Architecture



The middle 5 layers are technology layers, with lower layers supporting upper layers; all layer-specific standards are categorized accordingly.

The left and right sides represent cross-cutting attribute dimensions, not independent layers, only reflecting the cross-cutting attributes of AI enablement (permeating all five layers as a cross-cutting enablement dimension, not a standalone layer), and people-centred security governance (combining inclusivity, privacy and cybersecurity).

The bottom two modules comprise cross-layer general rule sets: a general technical foundation and a governance system, avoiding duplicate standard categorization.

Architectural design logic

(i) AI-enabled citiverse workflow analysis and element identification

The operation of a complete AI-enabled citiverse system can be abstracted as a five-stage workflow chain, with AI capabilities permeating every node from sensing to decision-making.

Table 2: Core Element Requirements for Citiverse Standards

Workflow Stage	Core Element Requirements
Physical city sensing with AI edge processing	Sensing device access protocols, data collection formats, device identification and authentication, AI edge preprocessing.
Data transmission and aggregation with AI scheduling	Low-latency reliable communications, wide-area coverage access, AI-driven dynamic network resource scheduling.
Data fusion and intelligent processing driven by AI	Multisource data quality governance, data interchange interfaces, AI model training and inference, spatial semantic analysis.
Virtual world construction with AI content generation	3D model formats and coding, scene description languages, XR interaction interfaces, AI-generated content validation.
Scenario application and AI-assisted decision execution	Scenario functional specifications, AI decision-making process standards, performance evaluation metrics, business collaboration interfaces.

(ii) Design considerations for the citiverse standards system

- The five-stage workflow identified above is the functional basis for the design of the standards system. The architecture is constructed to fully match the technical characteristics and governance requirements of each stage.
- Five-layer vertical technology stack: Matches the workflow business division, aligned with the professional division of major global standards development organizations.
- Bottom cross-layer support: a general technical foundation covering reference architectures, unified terminology and vocabulary, and interoperability baselines including minimal interoperability mechanisms; and a governance system covering management systems, trust and digital identity, ethics, compliance and certification; avoiding cross-layer duplication.
- Two cross-cutting horizontal dimensions: AI enablement and people-centred security and governance run across the entire technology stack. At the bottom of the stack, cross-layer support standards are organized into a general technical foundation and a governance system.

3.2 Core capabilities and standard maturity by layer

The core inventory includes standards that meet at least one of the following criteria: (1) directly relevant to citiverse architecture layers or cross-cutting dimensions; (2) published or formally under development by recognized SDOs with clear citiverse applicability; (3) identified by external experts as high-priority for citiverse interoperability or governance. Standards are

excluded when: (1) they are purely domain-specific with no citiverse relevance; (2) they are superseded or withdrawn; (3) they duplicate another included standard without added scope.

The inventory focuses on standards with direct relevance to city-level citiverse architecture, cross-platform interoperability and cross-department applications. Very vertical industry-specific projects (e.g., power equipment hoisting, renewable energy plant training, personal well-being measurement) are not individually listed, as they target single industrial or personal-use scenarios rather than urban-scale citiverse deployment. Vertical industry standards are included only when they address city-scale public service delivery or cross-domain urban integration (e.g., intelligent transport, public health emergency, tourism, education, power-grid digital twins), not intra-plant or intra-enterprise engineering use cases.

Table 3: Layer Capabilities, AI Enablement, Governance Alignment and Maturity

Layer	Core Capabilities	AI enablement	People-Centred & Governance	Maturity
Layer 1: Network & Connectivity	5G/6G immersive service, low-latency high-reliability, compute-network coordinated scheduling	AI-driven intelligent scheduling, dynamic bandwidth allocation	Transmission encryption, cross-border data compliance, low-bandwidth universal access	General foundations well-established; immersive city-scenario adaptation gaps exist
Layer 2: Digital Infrastructure & Platform	Digital twin architecture, full-domain IoT access, multi-cloud/edge collaborative computing	AI-driven intelligent operations, fault self-healing, elastic resource scheduling	Platform security, cloud service compliance, privacy-preserving computing, accessible service infrastructure	Good foundation; localized technology and specialized standard gaps exist
Layer 3: Data & Analytics	Multisource data quality governance, data interchange interfaces, data flow control	AI model training and inference, model interoperability, spatiotemporal data analysis, automated geospatial annotation (AI analytical and model capabilities concentrated at this layer, while AI-driven optimization and support extend across all layers.)	Data classification and grading, algorithm compliance, algorithmic fairness control, special needs group data adaptation, data sovereignty	General foundations well-established; dedicated analytics standards lacking

Table 3: Layer Capabilities, AI Enablement, Governance Alignment and Maturity (continued)

Layer	Core Capabilities	AI enablement	People-Centred & Governance	Maturity
Layer 4: Virtual World Construction	3D graphics and immersive coding, digital twin modelling, urban spatial visualization, XR interaction, avatar and digital human specs	AI-driven scene generation, digital human animation, intelligent content validation, rendering resource optimization	Content compliance review, digital identity trustworthiness, intellectual property protection, accessible interaction, age-friendly adaptation	Underlying coding well-established; interaction interoperability standards insufficient
Layer 5: Application Scenario	Scenario functional specifications, operational decision execution, performance evaluation, cross-system business collaboration	AI-driven solution generation, decision support, simulation optimization, risk prediction	Decision accountability, operational safety, scenario compliance, equal access to public services, citizen participation channels	Dedicated standards severely lacking

3.3 Core standards inventory

3.3.1 Cross-cutting technical support standards

These are cross-layer general technical standards that provide unified baselines for reference architectures, terminology and vocabulary, interoperability, and common technical enablers supporting all layers of the citiverse technology stack.

[1.1] ITU-T Y.4200 – Requirements for the interoperability of smart city platforms

This Recommendation defines interoperability requirements for smart city platforms across technical, semantic, and organizational dimensions. It addresses the critical industry problem of siloed city systems that cannot exchange data or coordinate services. As a foundational interoperability standard for the smart city domain, it can serve as an important reference for citiverse deployments, establishing baseline interface requirements that enable cross-platform data sharing and service orchestration between different city systems and domains. It works in conjunction with Recommendation ITU-T Y.4201 to provide a complete platform interoperability framework.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2018-02) | URL: https://www.itu.int/rec/T-REC-Y.4200/en

[1.2] ITU-T Y.4113 – Requirements of the network for the Internet of things

This Recommendation describes network requirements for IoT deployments, focusing on connectivity needs for smart meters, sensors, and devices in urban environments. It addresses the challenge of network heterogeneity where different IoT devices (e.g., NB-IoT, LTE-M, LoRaWAN)

require different network capabilities. This standard can serve as a network requirement baseline for citiverse implementations, ensuring that the underlying communication infrastructure can support the diverse IoT data flows essential for digital twin synchronization and real-time city sensing. It complements Recommendation ITU-T Y.4200 by providing network-layer requirements that underpin platform-level interoperability.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2016-09) | URL: https://www.itu.int/rec/T-REC-Y.4113/en

[1.3] ITU-T Y.4201 – High-level requirements and reference framework of smart city platforms

This Recommendation defines high-level requirements and the reference framework for smart city platforms, establishing the core platform capabilities and structural model that have been widely adopted for city platform deployments globally. It addresses the lack of a standardized blueprint for city platform architecture. This standard can serve as a foundational platform framework for citiverse implementations, defining core platform functions including data management, service orchestration, and capability exposure that can support digital twin and AI capabilities. It works in conjunction with Recommendation ITU-T Y.4200 to provide a complete platform interoperability framework.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2018-02) | URL: https://www.itu.int/rec/T-REC-Y.4201-201802-I

[1.4] ITU-T Y.4464 – Framework of data sharing in IoT-based smart city platforms

This Recommendation defines a framework for data sharing in IoT-based smart city platforms, including data sharing models, trust mechanisms, and technical requirements for enabling cross-organization data exchange. It addresses the challenge of enabling data sharing between government agencies, private operators, and citizens while maintaining security, privacy, and data sovereignty. This framework can be applied to citiverse scenarios to enable controlled data sharing across the virtual city environment, supporting multistakeholder collaboration, while preserving data ownership and usage rights. It complements Recommendation ITU-T Y.4560 by providing the data sharing governance framework for blockchain-enabled data exchange.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2020-03) | URL: https://www.itu.int/rec/T-REC-Y.4464/en

[1.5] ITU-T Y.4505 – Minimal Interoperability Mechanisms for smart and sustainable cities and communities

This Recommendation defines minimal interoperability mechanisms (MIMs) as a method of specifying sets of requirements that will enable minimal but sufficient interoperability for smart and sustainable cities and communities, along with describing one or more mechanisms that address those requirements, and providing guidance on achieving relevant interoperability between those mechanisms and on conformance and compliance testing. This Recommendation can provide the common ground for interoperability between city platforms, data spaces and digital twins in the citiverse, without requiring all systems to adopt the same detailed standards.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2024-08) | URL: https://www.itu.int/rec/T-REC-Y.4505/en

[1.6] ITU-T Y.4560 – Blockchain-based data exchange and sharing for supporting Internet of things and smart cities and communities

This Recommendation specifies requirements, functional models and deployment modes for blockchain-based urban data exchange and sharing. It addresses the need for trusted, tamper-proof data exchange across multiple city stakeholders where traditional centralized approaches cannot provide sufficient trust. This standard can serve as a technical baseline for blockchain-enabled cross-domain twin data interconnection in citiverse, supporting immutable audit trails for digital twin data exchanges, smart contract-based data access control, and transparent data lineage tracking for AI training datasets.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2023-03) | URL: https://www.itu.int/rec/T-REC-Y.4560-202303-P/en

[1.7] ITU-T Y.4561 – Blockchain-based Data Management for supporting Internet of things and smart cities and communities

Along with the development of the Internet of Things (IoT) and smart sustainable cities and communities (SSC&C), various applications have different kinds of requirements for data management, and there are many challenges, especially in data representing, data processing, data service provisioning, and other aspects in a secure and effective manner. Meanwhile, blockchain as an emerging technology possesses the characteristics of trust, transparency, traceability and accountability. It has the potential capabilities to solve the existing issues in data management. This Recommendation specifies the requirements, generic reference model, common capabilities and procedures of blockchain-based data management.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved 2020-08-29 | Question: Q4/20 | URL: https://www.itu.int/rec/T-REC-Y.4561/en

[1.8] ITU-T Y.4812 – Interoperability of the identity of Internet of things devices across metaverse platforms

This Recommendation specifies technical requirements and reference framework for IoT device identity interoperability across metaverse platforms. It addresses the challenge of establishing trusted identity relationships between physical IoT devices and their virtual representations in the metaverse. This standard can serve as an identity foundation for citiverse, enabling physical-virtual identity alignment, ensuring that IoT devices in the physical city can be reliably identified and authenticated within the virtual city environment, supporting digital twin integrity and secure IoT-to-virtual world interactions.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2025-03) | URL: https://www.itu.int/rec/T-REC-Y.4812/en

[1.9] ITU-T Y.4240 – Interoperability for integrating virtual and physical worlds through digital twins in the metaverse

This Recommendation defines three foundational interfaces and their specific reference points that enable the interoperability required to integrate virtual and physical worlds through digital twins in the metaverse. It provides an overview of interoperability for integrating virtual and physical worlds through digital twins in the metaverse, outlines the interfaces and their related reference points, and describes operational procedures through these reference points.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved 2025-11-13 | Question: Q1/20 | URL: https://www.itu.int/rec/T-REC-Y.4240/en

[1.10] ITU-T Y.4246 – Accessibility requirements for metaverse services supporting Internet of things

This Recommendation specifies accessibility requirements for metaverse services supporting IoT, complementing Recommendation ITU-T Y.4204 by addressing issues specific to immersive and digital twin environments. It identifies three key areas: sensory perception, spatial navigation, and communication/action. The text requires alternative representations of visual and audio information, support for assistive technologies, personalization of virtual objects and audio characteristics, and clear notification when adaptations such as size scaling, contrast adjustment, colour change, or sound modification may distort real-world information. Its aim is to ensure that persons with disabilities and users with specific needs can access, understand, navigate, communicate, and interact effectively in IoT-supported metaverse services.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved 2026-06-29 | Question: Q8/20 | URL: https://www.itu.int/rec/T-REC-Y.4246/en

[1.11] ITU-T Y.4489 – Reference architecture of digital twin federation in smart cities and communities

A digital twin is a digital representation of an object of interest, with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization. Digital twin federation is operations among one or more digital twins initiated to solve the problem crossing the boundaries of multiple domains. Recommendation ITU-T Y.4224 defines the requirements for digital twin federation. Based on the requirements, this Recommendation addresses the reference architecture of digital twin federation. This Recommendation defines the functionalities of each entity and the interfaces among the entities. In addition, this Recommendation also addresses operational flows of digital twin federation in different scenarios.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved 2023-11-29 | Question: Q1/20 | URL: https://www.itu.int/rec/T-REC-Y.4489/en

[1.12] ITU-T Y.4605 – Information exchange model for digital twin federation in smart cities and communities

A digital twin is the digital representation of an object of interest with data connection that enables convergence between the physical state and digital state at an appropriate rate of synchronization. The digital twin has been applied in various industry domains including manufacturing, transportation, energy, firefighting, medical and safety. Digital twin federation

is the act of sharing data and functions among two or more digital twins to solve the problems related to multiple domains. The Recommendation ITU-T Y.4489 defines the reference architecture of digital twin federation. The information exchange model among the components, which are the digital twins, the registry and the communication adaptor, is required to define for digital twin federation based on the reference architecture. The exchangeable information is the data and functions used for digital twin federation. The information exchange model provides the overview and defines the message structure with actions and objects.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved 2023-11-29 | Question: Q1/20 | URL: https://www.itu.int/rec/T-REC-Y.4605/en

[1.13] ITU-T Y.4805 – Identifier service requirements for the interoperability of Smart City applications

This Recommendation specifies a set of requirements for identifier services in smart city applications with a view to ensure that such systems are interoperable and secure. This set of requirements may additionally serve as guidelines for developing new identifier services for smart city. It will include security features for service integrity, data confidentiality. The Recommendation will define a full list of identifier service requirement, including security requirements, for the identifier service.

▸ Standard Organization: ITU-T SG20 (Q6/20) | STATUS: Published (2017-08) | URL: https://www.itu.int/rec/T-REC-Y.4805/en

[1.14] ITU-T Y.metaID – Framework and requirements for identity visualization in and across metaverse

The metaverse offers an immersive experience that blends virtual and augmented realities, creating environments where digital representations feel genuine. However, as these representations become increasingly lifelike, distinguishing between genuine identities and AI-generated or fake ones becomes challenging. This lack of clarity raises concerns, as users may unknowingly interact with inauthentic entities, eroding trust in the metaverse. Identity visualization can foster trust in the metaverse and improve confidence and interaction in the metaverse, which usually includes identity representation, visual indication of verified identities, consistency across multiple metaverse and identity visibility control. This draft new Recommendation studies the identity visualization in and across metaverse, and provides its concept, framework and requirements.

▸ Standard Organization: ITU-T SG20 (Q4/20) | STATUS: Under study | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22081

[1.15] ITU-T Y.Interop-DPM – Integrated Interoperability framework for Data Processing and Management

A key challenge for data processing and management is that often interoperability needs to be addressed across a number of layers to process and manage the data successfully. It is often not sufficient to address technical interoperability without also ensuring semantic interoperability between the data being shared, processed and managed and addressing any barriers to data processing and management related to the different processes and organizational constraints of the organizations sharing and processing the data. This draft Recommendation covers: How

the development of Recommendations related to technical and semantic interoperability should take these wider considerations into account; and what requirements and recommendations smart cities and communities need to follow to allow them to gain maximum value from Recommendations related to technical and semantic aspects of data interoperability by addressing the organizational and other barriers to interoperability of data.

▸ Standard Organization: ITU-T SG20 (Q4/20) | STATUS: Under study | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22028

[1.16] ITU-T Y.citiverse-ai-reqts – Requirements for AI-enabled interoperability in citiverse

This draft Recommendation specifies cross-city and cross-platform interoperability technical requirements for AI-enabled citiverse systems. It addresses the emerging challenge of AI models and services needing to operate across different city platforms that use different data semantics and interface patterns. In citiverse, this standard will define interoperability requirements for AI model deployment, data exchange between AI systems, and cross-domain AI service orchestration, ensuring that AI capabilities can be shared and composed across the citiverse ecosystem.

▸ Standard Organization: ITU-T SG20 (Q4/20) | STATUS: Under study (new work item approved) | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23498

[1.17] ISO/IEC 30141:2024 – Internet of Things (IoT) – Reference Architecture

This international standard provides a standardized IoT reference architecture, defining the core characteristics, system elements, and conceptual model for IoT systems. It establishes a common vocabulary and architectural blueprint for IoT deployments across different domains. This reference architecture can serve as a top-level structural blueprint for city-scale IoT deployments in citiverse, ensuring architectural consistency across different city sectors and providing the foundation upon which domain-specific IoT standards build. It works in conjunction with the oneM2M functional architecture to provide complete IoT system coverage.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2024) | URL: https://www.iso.org/standard/88800.html

[1.18] ISO/IEC 21823-1:2019 – Internet of things (IoT) – Interoperability for IoT systems – Part 1: Framework

This standard provides a general framework for IoT system interoperability, defining interoperability models, categories, and approaches across different IoT domains. It addresses the fragmentation of IoT ecosystems where vertically integrated solutions cannot communicate across domains. This framework can serve as the basis for unified data ingestion into the city digital twin, achieving interoperability across heterogeneous IoT systems deployed in different city sectors (transport, energy, buildings, public safety). It serves as the ISO/IEC counterpart to Recommendation ITU-T Y.4113, providing complementary interoperability models.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2019) | URL: https://www.iso.org/standard/71885.html

[1.19] ISO/IEC 21823-2:2020 – Internet of things (IoT) – Interoperability for IoT systems – Part 2: Transport interoperability

This standard specifies transport interoperability solutions for IoT systems, defining protocols and mechanisms for reliable data exchange across different network transports. It solves the problem of transport layer fragmentation across heterogeneous IoT networks (5G, LPWAN, Wi-Fi, Ethernet). This standard can ensure reliable data transport across the mix of networks that connect city sensors and devices in citiverse, providing consistent transport quality for different types of digital twin data (real-time telemetry, bulk model updates, event streams).

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2020) | URL: https://www.iso.org/standard/80986.html

[1.20] ISO/IEC 21823-3:2021 – Internet of things (IoT) – Interoperability for IoT systems – Part 3: Semantic interoperability

This standard addresses semantic interoperability for IoT systems, defining approaches for achieving common understanding of data meaning across different systems and domains. It solves the critical problem of data having different meanings across different city departments and systems. In citiverse, semantic interoperability ensures that data from different city domains (transport, energy, public safety) can be meaningfully combined in the digital twin, enabling cross-domain AI analytics and simulation without semantic mismatches. This is essential for creating a unified, coherent virtual city model where data from disparate sources can be integrated seamlessly.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2021) | URL: https://www.iso.org/standard/83752.html

[1.21] ISO/IEC 21823-4:2022 – Internet of things (IoT) – Interoperability for IoT systems – Part 4: Syntactic interoperability

This standard addresses syntactic interoperability for IoT systems, specifying approaches for ensuring consistent data syntax across different systems and platforms. It addresses the challenge of data format mismatches that prevent data exchange even when semantic understanding exists. This standard can ensure consistent data encoding and structure across different city IoT systems in citiverse, enabling data from different platforms to be processed uniformly within the digital twin. It complements 21823-3 (semantic interoperability) by addressing the syntax layer of interoperability.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2022-03) | URL: https://www.iso.org/standard/84773.html

[1.22] ISO/IEC 21823-5 – Internet of things (IoT) – Interoperability for IoT systems – Part 5: Behavioural and policy interoperability

This standard addresses behavioural and policy interoperability for IoT systems, ensuring that the actual result achieves the expected outcome across different system interactions. It addresses the challenge of ensuring that systems with different internal behaviour can still interoperate correctly. This standard can ensure consistent behaviour across different city systems interacting through the digital twin in citiverse, defining how expectations, policies,

and behaviour constraints are expressed and enforced during cross-system interactions. It completes the 21823 series, providing full coverage of IoT interoperability dimensions.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Committee Draft (CD, 2025-07) | URL: https://www.iso.org/standard/83852.html

[1.23] oneM2M TS-0001 – Functional Architecture

This specification defines the common service layer architecture for M2M/IoT systems, providing standardized service functions for device management, data management, and security. It addresses the lack of a horizontal service layer across different IoT technology verticals. This architecture can provide the common IoT service layer that abstracts underlying network heterogeneity in citiverse, enabling consistent device and data management across the city's diverse IoT deployments. It complements ISO/IEC 30141 by providing a detailed functional architecture that can be implemented across different city IoT deployments.

▸ Standard Organization: oneM2M | STATUS: Published (ongoing updates, v4.24.0) | URL: https://www.onem2m.org/technical/published-specifications

[1.24] ETSI GS MEC 003 – Multi-access Edge Computing (MEC); Framework and Reference Architecture

This standard defines the reference architecture for multi-access edge computing, enabling cloud computing capabilities at the edge of mobile networks. It solves the latency and bandwidth challenges of processing massive IoT and XR data in centralized clouds. In citiverse, MEC architecture enables low-latency processing for real-time digital twin synchronization, immersive XR rendering, and AI inference at the network edge, supporting low-latency requirements that vary by application and deployment context for interactive city-scale virtual experiences. It works with ETSI GS MEC 012 to provide the overall MEC framework and specific APIs for network-aware applications.

▸ Standard Organization: ETSI ISG MEC | STATUS: Published (ongoing updates) | URL: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/

[1.25] ETSI GS MEC 012 – MEC; Radio Network Information API

This standard defines the API for exposing radio network information to MEC applications, enabling applications to access real-time network and user location information. It solves the problem of applications being unaware of underlying network conditions and user context. This API can enable XR and digital twin applications in citiverse to adapt to network conditions in real-time, optimize rendering based on user location and radio conditions, and support seamless handover for mobile users moving through the city while maintaining immersive experience continuity.

▸ Standard Organization: ETSI ISG MEC | STATUS: Published (V2.1.1/V2.2.1) | URL: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/012/

[1.26] OGC SensorThings API – Part 1: Sensing

This standard provides an open, geospatially enabled API for IoT sensor data, following the OGC Sensor Web Enablement framework and RESTful principles. It solves the problem of inconsistent sensor data access across different geospatial IoT deployments. This standard can provide a standardized API layer for accessing real-time geospatial sensor data from city IoT deployments in citiverse, enabling location-aware digital twin updates and spatial analytics. It is widely implemented in city IoT platforms and integrates with CityGML for 3D spatial context, making it a practical interoperability solution for city sensor data.

▸ Standard Organization: OGC | STATUS: Published (2016) | URL: https://www.ogc.org/standard/sensorthings/

[1.27] OGC API – Features

This standard defines a modern RESTful API for querying geospatial feature data, replacing legacy OGC Web Feature Service interfaces with a more flexible, developer-friendly API. It provides standardized access to vector geospatial data over the web using modern API patterns. This API can provide the standard interface for accessing geospatial feature data (buildings, roads, infrastructure) that forms the base layer of the 3D city model in citiverse, enabling consistent access to city geospatial data across different applications and platforms.

▸ Standard Organization: OGC | STATUS: Published (2019, ongoing updates) | URL: https://ogcapi.ogc.org/features/

[1.28] OGC API – Processes

This standard defines an API for executing geospatial processing processes over the web, enabling distributed processing of geospatial data. It addresses the challenge of executing complex spatial analytics across distributed computing resources. This API can enable distributed execution of digital twin simulation and AI inference processes across edge and cloud resources in citiverse, supporting large-scale city simulations (traffic, flooding, energy) without requiring all processing to occur on a single centralized platform.

▸ Standard Organization: OGC | STATUS: Published (2021) | URL: https://ogcapi.ogc.org/processes/

[1.29] ISO 19177-1:2026 – Geographic information – Geospatial application programming interface (API) for tiles – Part 1: Core

This standard specifies the behaviour of web APIs for geospatial tile data access, providing a modern, lightweight interface for accessing tiled geospatial data. It addresses the need for efficient, web-friendly access to map tile data. This API can serve as the core interface basis for cross-platform spatial base map data interoperability in citiverse, enabling efficient delivery of 2D map tiles that provide the geographic context for 3D city models. It works in conjunction with OGC 3D Tiles to provide a complete tiled geospatial data access solution.

▸ Standard Organization: ISO/TC 211 | STATUS: Published (2026-03) | URL: https://www.iso.org/standard/88296.html

[1.30] ISO/TR 23262:2021 – GIS (geospatial) / BIM interoperability

This technical report investigates barriers and proposes measures to improve interoperability between geospatial and BIM domains, aligning GIS standards (ISO/TC 211) and BIM standards (ISO/TC 59/SC 13). It addresses the historical divide between GIS and BIM communities that has prevented seamless integration of city-scale and building-scale models. This report can provide a methodological framework for integrating building-level BIM data (IFC) with city-level GIS data (CityGML) in citiverse, supporting multiscale spatial data integration from individual buildings to entire city districts.

▸ Standard Organization: ISO/TC 211, ISO/TC 59 | STATUS: Published (Technical Report) | URL: https://www.iso.org/standard/78821.html

[1.31] ETSI TS 104 175 – Data Solutions (DATA); NGSI-LD Core API

This standard specifies the core functionality of the NGSI-LD API. It builds on the NGSI-LD Information Model, which is conceptually a Property Graph model. The API is for the exchange of information (about entities, their properties and relationships to other entities, including metadata) with the intent that the associated protocol becomes the "glue" between different kinds of applications and smart services. The API allows users to provide, consume and subscribe to information in multiple scenarios and involving multiple stakeholders. It provides advanced geo-temporal queries, and it includes notification mechanisms. It uses JSON-LD for serialization. It replaces the former NGSI-LD API specification from ETSI ISG CIM. It is completed by ETSI TS 104 243 ("NGSI-LD MQTT Notification Binding") and ETSI TS 104 176 ("NGSI-LD HTTP Binding").

▸ Standard Organization: ETSI TC DATA | STATUS: Published | URL: https://www.etsi.org/deliver/etsi_ts/104100_104199/104175/01.01.01_60/ts_104175v010101p.pdf

[1.32] ETSI TS 104 178 – Data Solutions (DATA); NGSI-LD Information Model

This standard specifies the NGSI-LD Information Model, to be used together with the NGSI-LD API. The NGSI-LD Information Model is conceptually a Property Graph model about entities, their properties and relationships to other entities, including metadata. It is based on the Linked Data principles. Additional properties and relationships extend the base model for supporting cross-domain interoperability.

▸ Standard Organization: ETSI TC DATA | STATUS: Published | URL: https://www.etsi.org/deliver/etsi_ts/104100_104199/104178/01.01.01_60/ts_104178v010101p.pdf

[1.33] ETSI EN 304 181 – Data Solutions (DATA); AI-based EU Local Digital Twin reference architecture

This standard specifies a reference architecture for the execution of Local Digital Twins (LDTs) in European cities and communities. The architecture defines the essential components, interfaces, and data flows required to enable interoperable, AI-enabled digital twin solutions, supporting real-time integration of heterogeneous data sources, advanced analytics, and simulation capabilities.

The standard covers the logical and technical layers necessary for the deployment, operation, and federation of digital twins, including context management (e.g. using NGSI-LD), data models (e.g. using SAREF), AI/ML integration (with ethical considerations aligned to the EU

AI Act), secure data exchange, and IoT device integration (e.g. via oneM2M standards). It ensures alignment with ongoing European initiatives such as CitiVerse EDIC, and Minimal Interoperability Mechanisms (MIMs/ITU-T Y.4505), while supporting compliance with relevant EU regulations and standards including the Interoperable Europe Act.

The architecture is designed to be extensible, supporting cross-domain use cases (such as mobility, energy and urban planning) and future technological advancements, exploring on-going standards developments for digital twins (e.g. in ISO/IEC, ITU-T, CEN/CENELEC). Implementation guidance will be provided to facilitate adoption by cities and ensure vendor-neutral solutions.

▸ Standard Organization: ETSI TC DATA | STATUS: Under development | URL: https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=74885

[1.34] ETSI EN 304 182 – MIM key specifications Smart City platforms and Local Digital Twins

This European Standard specifies profiles for Minimal Interoperability Mechanisms 0, 1, 2 and 7, following the structure of Recommendation ITU-T Y.4505; an extension to MIMs 3, 6 and 8 is planned. These profiles can give citiverse platforms a testable baseline of minimal interoperability requirements that cities can reference in procurement.

▸ Standard Organization: ETSI TC DATA | STATUS: Under development | URL: https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=74886

[1.35] IDS-RAM 4.0 – International Data Spaces Reference Architecture Model

This reference architecture provides a standardized framework for sovereign, secure data exchange across organizational domains, defining functional components, roles, and interfaces for trusted data sharing ecosystems. This architecture can serve as a reference for citiverse data spaces, enabling cross-city, cross-sector data interoperability while preserving data sovereignty and governance requirements.

▸ Standard Organization: International Data Spaces Association (IDSA) | STATUS: Published (v4.0, 2023) | URL: https://internationaldataspaces.org/ram/

[1.36] IEEE 2874-2025 – Standard for Spatial Web Protocol, Architecture and Governance

This standard describes the services, hypergraphs, protocols and languages that enable interoperable, semantically compatible connections between network-connected hardware (sensors, IoT devices, robots) and software (user agents, services, platforms, AI systems). It establishes a functional layer stack, information models and governance framework for the Spatial Web, providing foundational protocol and semantic interoperability infrastructure for citiverse systems. Approved by IEEE SASB on 28 May 2025.

▸ Standard Organization: IEEE Computer Society / AISC | STATUS: Published (2025-05) | URL: https://standards.ieee.org/ieee/2874/10375/

[1.37] ISO/IEC 5087 series — Information technology — City data model

This multipart standard defines a foundational ontology and city-level concepts for urban data modelling, providing a common semantic framework for city data exchange. Part 1 (Foundation level concepts, 2023) defines core entities, properties and relationships; Part 2 (City level concepts, 2024) defines city-level concepts; Part 3 (Transportation service level, 2026) extends to the transport domain. It provides the semantic data model foundation for citiverse data interoperability.

▸ Standard Organization: ISO/IEC JTC 1/WG11 | STATUS: Published (5087-1:2023, 5087-2:2024, ISO/TS 5087-3:2026); Parts 4-5 under development | URL: https://www.iso.org/standard/80718.html

[1.38] ISO 19111 / 19115 / 19157 — Geographic information foundations

ISO 19111 defines spatial referencing by coordinates (geodetic reference frames); ISO 19115 defines geographic information metadata; ISO 19157 defines geographic data quality principles and measures. Together they provide the geospatial foundation upon which citiverse 3D city models and spatial data interoperability are built.

▸ Standard Organization: ISO/TC 211 | STATUS: Published | URL: https://www.iso.org/committee/54914.html

[1.39] IEC 62443 series — Industrial automation and control systems security

This series defines cybersecurity requirements for industrial automation and control systems (IACS), covering security for industrial automation and control systems across all industry sectors including critical city infrastructure (energy, water, transport). It provides the OT/ICS security baseline for citiverse systems that interface with physical city infrastructure.

▸ Standard Organization: IEC TC 65 / ISA | STATUS: Published (multipart) | URL: https://webstore.iec.ch/en/publication/7033

[1.40] IEEE 2888.1-2023 / 2888.2-2023 / 2888.4-2023 — Sensor/actuator interfaces and VR disaster response

IEEE 2888.1 defines vocabulary, data formats and APIs for acquiring sensor information for cyber-physical synchronization. IEEE 2888.2 defines actuator interfaces. IEEE 2888.4 defines the architecture for a VR disaster response training system with six degrees of freedom. These standards support the sensing-actuation loop and emergency response training capabilities in citiverse systems.

▸ Standard Organization: IEEE | STATUS: Published (2023) | URL: https://standards.ieee.org/standard/2888_1-2023.html

[1.41] IEEE 3079.3-2023 — Framework for Evaluating the Quality of Digital Humans

This standard provides a framework for evaluating the visual quality of digital humans, including appearance and motion fidelity metrics. It serves as a reference assessment baseline for AI-driven digital humans deployed in citiverse public service scenarios.

▸ Standard Organization: IEEE | STATUS: Published (2023) | URL: https://standards.ieee.org/ieee/3079.3/10893/

[1.42] NIST AI Risk Management Framework (AI RMF 1.0)

This framework provides a flexible, risk-based approach to managing AI risks, structured around four functions: Govern, Map, Measure, and Manage. It serves as a reference governance framework for trustworthy AI deployment in citiverse systems, complementing ISO/IEC AI standards and ITU-T AI governance Recommendations.

▸ Standard Organization: NIST (U.S.) | STATUS: Published (2023) | URL: https://www.nist.gov/itl/ai-risk-management-framework

[1.43] W3C Web of Things (WoT) Architecture

This standard defines the Web of Things architecture that uses web technologies (HTTP, REST, JSON-LD) to enable interoperability across IoT platforms and application domains. It addresses IoT fragmentation by providing a common metadata model (Thing Description) and interaction patterns based on web standards. This architecture can enable web-based access to city IoT devices and digital twin entities in citiverse, simplifying integration with web-based XR and visualization applications and enabling browser-based access to citiverse services without proprietary plugins.

▸ Standard Organization: W3C | STATUS: Recommendation (2023) | URL: https://www.w3.org/TR/wot-architecture/

[1.44] OGC GeoPose 1.0 – Geographic information – GeoPose – Part 1: A geospatial pose standard for XR

This standard defines a geospatial pose representation for describing the position and orientation of real or virtual objects in 3D space, enabling consistent spatial anchoring across different platforms and devices. It addresses the fragmentation of pose representation across XR and geospatial systems. In citiverse, GeoPose can provide the standardized spatial pose framework that ensures consistent positioning of virtual objects relative to physical city geography, supporting AR content alignment, multi-user spatial coordination, and seamless physical-virtual integration.

▸ Standard Organization: OGC | STATUS: Published | URL: https://www.ogc.org/standards/geopose/

[1.45] OGC API – Moving Features 1.0

This standard defines a RESTful API for accessing and querying moving features, geospatial entities whose position changes over time, such as vehicles, pedestrians, and mobile assets. It addresses the lack of standardized interfaces for dynamic geospatial data. In citiverse, this API can provide the standard interface for accessing real-time trajectories of moving entities within the city, supporting traffic monitoring, crowd management, and dynamic digital twin updates.

▸ Standard Organization: OGC | STATUS: Published | URL: https://www.ogc.org/standards/ogc-api-moving-features/

[1.46] OGC API – Environmental Data Retrieval

This standard defines a Web API for accessing and retrieving environmental data, including observations, forecasts, and reanalysis data across various environmental domains. It addresses the fragmentation of environmental data access interfaces. In the citiverse, this API can enable standardized access to environmental data (air quality, weather, flood risk, heatwave predictions) for integration into city digital twin simulations and resilience planning scenarios.

- Standard Organization: OGC | STATUS: Published | URL: https://ogcapi.ogc.org/edr/

Beyond the ITU smart-city recommendations, the cross-cutting technical layer also draws on the ISO/IEC JTC 1/SC 41, ISO/TC 211 and ISO/TC59/SC 13 foundation standards: the ISO/IEC 30145 series (smart city ICT reference framework: business process, knowledge management and engineering frameworks, 2020–2021), ISO/IEC 30146 (smart city ICT indicators, 2019) and ISO/IEC 30182 (smart city concept model, 2017) provide the overarching framework, indicators and shared ontology for city-scale data integration; ISO 19650-1/-2 (organization and digitization of information about buildings and civil engineering works, BIM information management, 2018) governs the digitized asset data that feeds the urban digital twin.

[1.47] ISO 19650-1:2018 / 19650-2:2018 – Organization and digitization of information about buildings and civil engineering works – BIM information management

ISO 19650 defines organization and digitization of information for the full lifecycle of built assets using building information modelling. For citiverse, it provides a structured framework for managing 3D city model data from design through operation, ensuring consistent information delivery across city departments.

- Standard Organization: ISO/TC 59 (buildings/civil engineering) | URL: https://www.iso.org/standard/68078.html

[1.48] ISO/IEC 30182:2017 – Smart city concept model – Guidance for establishing a model for data interoperability

ISO/IEC 30182 defines a smart city concept model that establishes a common data model and shared vocabulary for urban information systems. For citiverse, it provides a foundational semantic framework for cross-domain data integration, enabling consistent representation of city entities and relationships across platforms.

- Standard Organization: ISO/IEC JTC 1/WG11 | STATUS: Published (2017-05) | URL: https://www.iso.org/standard/53302.html

[1.49] ISO/IEC 30146:2019 – Smart city ICT indicators

ISO/IEC 30146 provides a measurement framework for assessing smart city ICT performance across infrastructure, services and governance dimensions. For citiverse, it offers baseline metrics for evaluating the maturity and effectiveness of city digital infrastructure platforms.

- Standard Organization: ISO/IEC JTC 1 | URL: https://www.iso.org/standard/70302.html

[1.50] ISO/IEC 30145-1:2021 / 30145-2:2020 / 30145-3:2020 – Smart city ICT reference framework

Three-part reference view for smart city ICT infrastructure covering business processes (Part 1), knowledge management (Part 2), and engineering (Part 3).

- Standard Organization: ISO/IEC JTC 1 | URL: https://www.iso.org/standard/76371.html

[1.51] W3C PROV-O – PROV Ontology: Provenance Data Model and Ontology

W3C PROV-O is an OWL2 ontology for representing provenance information in a machine-readable format, enabling tracing of data origin, derivation and usage. For citiverse, it supports transparent tracking of AI-generated 3D city model provenance and simulation result lineage.

- Standard Organization: W3C | URL: https://www.w3.org/TR/prov-o/

[1.52] IEEE 2413-2019 – Standard for an Architecture Framework for the Internet of Things

IEEE 2413 defines a conceptual architecture framework for IoT systems, addressing cross-domain interoperability, security and data management across heterogeneous deployments. For citiverse, it provides a reference architecture for integrating diverse city IoT devices and data sources into a unified digital twin platform.

- Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/2413-2019.html

3.3.2 Governance system standards

This section covers foundational governance standards spanning performance indicators, information security, data privacy, AI ethics, digital identity, and metaverse governance, forming the compliance and trust baseline for AI-enabled citiverse deployment.

[2.1] ITU-T Y.4900 – Overview of key performance indicators in smart sustainable cities

This Recommendation provides a unified indicator framework covering urban services, governance, and sustainable development. It addresses the lack of standardized city performance measurement across different city deployments. This framework can serve as a KPI baseline for citiverse performance monitoring and simulation, enabling consistent measurement of city performance, comparison across districts, and prediction of how policy changes will impact quality of life metrics. It works with ISO 37120 to provide a comprehensive city indicator framework.

- Standard Organization: ITU-T SG20 | STATUS: Published (2016-08) | URL: https://www.itu.int/rec/T-REC-Y.4900-201608-I/en

[2.2] ITU-T X.2012 – Security measures for digital twin system of smart cities

This Recommendation specifies security requirements, risk boundaries, and protection measures for smart city digital twin systems. It addresses the unique security challenges of digital twin

systems, which expose city infrastructure to cyber-physical risks. This standard can provide a dedicated security governance baseline for the full lifecycle of city digital twin deployment in citiverse, covering data security, access control, vulnerability management, and incident response.

▸ Standard Organization: ITU-T SG17 | STATUS: Published (2024-10) | URL: https://www.itu.int/rec/T-REC-X.2012-202410-I/en

[2.3] ITU-T Y.4806 – Security capabilities supporting safety of the Internet of things

This Recommendation specifies security capabilities supporting IoT safety, addressing the unique safety risks introduced by connected IoT devices in critical infrastructure. It bridges the gap between traditional IT security and physical safety in IoT deployments. In citiverse, where digital twins monitor and potentially control critical city infrastructure (traffic, energy, public safety), this standard can provide the security capabilities necessary to ensure that IoT security breaches cannot translate into physical harm to citizens or damage to city infrastructure. It complements X.2012 by addressing IoT-specific safety requirements.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2017-06) | URL: https://www.itu.int/rec/T-REC-Y.4806/en

[2.4] ITU-T Y.SSC-AISE-sec – Security capabilities and guidelines for artificial intelligence service exposure for smart sustainable cities

This draft Recommendation specifies security capabilities and guidelines for exposing AI services in smart sustainable city environments, addressing the unique security risks introduced by AI model inference and automated decision-making across city platforms. For citiverse, it supports secure deployment of AI-driven digital twin analytics, automated urban governance decisions, and AI service exposure across cross-platform virtual city environments, complementing Recommendation ITU-T Y.4806 (IoT safety) and Recommendation ITU-T X.2012 (digital twin security) with AI-specific service exposure protections.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q6/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23994

[2.5] ITU-T Y.diwi-reqts – Requirements of digital identity wallet interoperability for smart city services

This draft Recommendation defines interoperability requirements for digital identity wallets supporting smart city services, enabling cross-wallet and cross-jurisdiction acceptance of digital credentials. It addresses the current fragmentation where different city services and regions deploy incompatible identity wallet solutions. This standard can enable citizens to use a single digital identity wallet across all city services and virtual environments in citiverse, supporting seamless access to physical and virtual city services while maintaining user control over credential presentation. It works in conjunction with W3C DID and VC standards to provide a complete digital identity framework.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study (2026) | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23496

[2.6] ITU-T FG-MV-034 – Metaverse terminology and definitions

This document is an informative ITU Technical Report developed by the ITU-T Focus Group on Metaverse (FG-MV), approved at the 7th meeting of FG-MV held on 12–13 June 2024. It contains proposed terminology and definitions for metaverse and related concepts (including citiverse) for further consideration at ITU-T study groups. As a Focus Group technical report, it is not a normative ITU-T Recommendation but provides valuable terminological foundations that inform ongoing standardization work. The report establishes a common language for city administrators, technologists, and standards developers working on citiverse projects, noting that the definitions remain subject to formal approval through the ITU-T study group process.

▸ Standard Organization: ITU-T FG-MV | STATUS: Published (Technical Report, 2024) | URL: https://www.itu.int/en/ITU-T/focusgroups/mv/Pages/default.aspx

[2.7] ETSI TS 104 179 – Data Solutions (DATA); NGSI-LD Provenance and Integrity

This Work item specifies a solution to verify integrity, and to precisely evaluate provenance and authenticity of NGSI-LD information, throughout its lifecycle.

▸ Standard Organization: ETSI TC DATA | STATUS: Published | URL: https://www.etsi.org/deliver/etsi_ts/104100_104199/104179/01.01.01_60/ts_104179v010101p.pdf

[2.8] ETSI TS 104 312 – Data Solutions (DATA); Data Quality Metrics: Measurement Methodologies and Assessment Procedures

This standard develops and identifies quality metrics for data. It focuses on identifying key properties of data quality including trustworthiness (e.g., completeness, accuracy, bias, reliability, redundancy, source reliability, and integrity) and formulating standardized methods to assess these properties.

▸ Standard Organization: ETSI TC DATA | STATUS: Planned | URL: https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=78853

[2.9] ETSI EN 304 311 – Data Solutions (DATA); Data Quality Metrics: Framework and Definitions

This standard establishes a normative framework for defining and categorizing data quality metrics to ensure security, privacy, and trustworthiness in AI and data ecosystems. Building upon the foundational analysis in the published ETSI TR 104 180, it provides standardized terminology and conceptual definitions for an extensible set of quality attributes. The scope includes defining core principles for data quality and providing a structured mechanism for the continuous identification and update of metrics to reflect evolving technological requirements and diverse data domains.

▸ Standard Organization: ETSI TC DATA | STATUS: Planned | URL: https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=78851

[2.10] ISO/IEC 27001:2022 – Information security, cybersecurity and privacy protection – Information security management systems – Requirements

This is the international standard for information security management systems (ISMS), specifying requirements for establishing, implementing, maintaining, and continually improving an ISMS. It provides a systematic, risk-based approach to managing sensitive company and customer information. As a globally recognized information security management standard, ISO/IEC 27001 can serve as the foundational security management framework for citiverse deployments, ensuring that city data, citizen information, and critical infrastructure controls are managed according to global best practices.

▸ Standard Organization: ISO/IEC JTC 1 SC 27 | STATUS: Published (2022) | URL: https://www.iso.org/standard/27001

[2.11] ISO/IEC 27701:2025 – Information security, cybersecurity and privacy protection – Privacy information management systems – Requirements and guidance

This standard specifies requirements and guidance for establishing, implementing, maintaining, and continually improving a Privacy Information Management System (PIMS). This second edition cancels and replaces the first edition (ISO/IEC 27701:2019), and now operates as a standalone standard with enhanced privacy controls that can be implemented independently or integrated with ISO/IEC 27001. For citiverse deployments processing vast amounts of citizen data through digital twins and AI analytics, this PIMS standard can serve as the framework for managing personal data privacy, ensuring compliance with global privacy regulations and maintaining citizen trust.

▸ Standard Organization: ISO/IEC JTC 1 SC 27 | STATUS: Published (Edition 2, October 2025) | URL: https://www.iso.org/standard/27701

[2.12] ISO/IEC 38505-1:2017 – Information technology – Governance of IT – Governance of data – Part 1: Application of ISO/IEC 38500 to the governance of data

This standard provides guidance on the governance of data, applying ISO/IEC 38500 IT governance principles to data management. It addresses the need for executive-level oversight and accountability for organizational data assets. This data governance standard can serve as a reference framework for citiverse data management, ensuring that city data are managed as a strategic asset with clear accountability, decision rights, and oversight mechanisms appropriate for the sensitive, high-value data contained in city-scale digital twins.

▸ Standard Organization: ISO/IEC JTC 1 | STATUS: Published (2017) | URL: https://www.iso.org/standard/56639.html

[2.13] ISO/IEC 42001:2023 – Information technology – Artificial intelligence – Management system

This standard specifies requirements for an AI management system (AIMS), providing a systematic framework for managing AI responsibilities, risks, and opportunities throughout the AI lifecycle. It addresses the need for systematic governance of AI deployments. This standard can provide the management system framework for governing all AI systems operating within the virtual city in citiverse, establishing processes for AI risk management, transparency, accountability, and continual improvement across all city AI applications.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2023-12) | URL: https://www.iso.org/standard/81230.html

[2.14] ISO/IEC 23894:2023 – Information technology – Artificial intelligence – Guidance on risk management

This standard provides guidance on managing AI-specific risks, extending generic risk management approaches to the unique characteristics of AI systems. It addresses the novel risks introduced by AI systems including opacity, bias, robustness, and emergent behaviour. This standard can provide a framework for systematically identifying, assessing, and treating AI risks in citiverse deployments, ensuring that AI systems operating in the virtual city environment are reliable, fair and safe.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2023) | URL: https://www.iso.org/standard/77304.html

[2.15] IEEE 7000-2021 – Standard Model Process for Addressing Ethical Concerns during System Design

This standard provides a process model for addressing ethical concerns throughout the system design lifecycle, incorporating ethical value considerations into engineering processes. It addresses the challenge of identifying and mitigating ethical risks in complex systems like AI and autonomous systems. This ethical design standard can serve as a process reference for identifying and mitigating ethical risks in citiverse AI systems, providing structured approaches for addressing bias, fairness, transparency, and accountability from the earliest design stages. It works in conjunction with IEEE P7016 to provide comprehensive ethical guidance for metaverse and AI systems.

▸ Standard Organization: IEEE | STATUS: Published (2021) | URL: https://standards.ieee.org/standard/7000-2021.html

[2.16] IEEE P7016 – Standard for Ethically Aligned Design and Operation of Metaverse Systems

This draft standard defines a methodology for creating Metaverse systems, providing a description of the techno-socio aspects of Metaverse systems together with a high-level ethical assessment methodology for the design and operation of Metaverse systems. It addresses the ethical challenges unique to persistent virtual worlds, including user well-being, digital rights, and governance. This standard can provide the ethical design and operation framework specific to metaverse environments in citiverse, complementing IEEE 7000 by addressing citiverse-specific concerns such as digital identity sovereignty, virtual property rights, and algorithmic governance of virtual spaces.

▸ Standard Organization: IEEE SSIT/SC | STATUS: Under study | URL: https://standards.ieee.org/ieee/7016/

[2.17] IEEE 3812.1-2023 – IEEE Standard for General Requirements for Identity Framework for Metaverse

This standard defines the requirements of an identity framework for metaverse, providing an identity framework for use across different metaverse systems. It helps to recognize the relevance between real world and virtual world entities, utilizing distributed ledger technology as the trust anchor. It covers business logic, operational procedures, authentication programmes, and key indicators. This standard can provide the identity framework baseline that ensures citizens and city entities can maintain consistent identity across different virtual city services and environments in citiverse, enabling seamless cross-platform interactions while maintaining trust and security.

▸ Standard Organization: IEEE CTS/MSC | STATUS: Published (2023-12) | URL: https://standards.ieee.org/ieee/3812.1/

[2.18] IEEE P2048 – Standard for Metaverse: Terminology, Definitions, and Taxonomy

This draft standard specifies the terminology, definitions, and taxonomy for metaverse and related terms. It defines categories and levels of metaverse to provide clarification for metaverse users and a roadmap for metaverse developers. It addresses the confusion caused by inconsistent metaverse terminology across different implementations and standards. This standard can provide the metaverse terminological foundation that ensures consistent understanding across the broader metaverse ecosystem, clarifying where citiverse fits within the metaverse taxonomy and providing a shared vocabulary for cross-domain collaboration.

▸ Standard Organization: IEEE CTS/MSC | STATUS: Active PAR (Approved 2023-02-15) | URL: https://standards.ieee.org/ieee/2048/11169/

[2.19] IEEE P2048.201 – Security Specification of Blockchain-based Metaverse Accounts

This draft standard specifies security requirements for blockchain-based metaverse accounts, covering personal and public/enterprise accounts, including key management, authentication, and account recovery mechanisms. It addresses the unique security risks of blockchain-based accounts in metaverse environments where account compromise leads to permanent asset loss. This standard can provide a security baseline for user and organizational accounts that manage virtual land, digital twin assets, and other digital property within the city metaverse economy in citiverse, protecting against account theft and unauthorized access.

▸ Standard Organization: IEEE CTS/MSC | STATUS: Draft (D5, Nov 2025) | URL: https://standards.ieee.org/ieee/2048.201/

[2.20] IEEE P2048.202 – Security Specifications of Blockchain-Based Metaverse Data

This draft standard specifies consumer data security requirements in the blockchain-based metaverse, including data transmission, storage, migration, sharing, backup and recovery, and destruction. It addresses the security challenges of immutable blockchain storage including data privacy, right to be forgotten, and data integrity. This standard can ensure that blockchain-stored city data, digital twin records, and transaction history in citiverse maintain appropriate

security and privacy controls, balancing blockchain immutability with regulatory requirements for data protection and deletion rights.

▸ Standard Organization: IEEE CTS/MSC | STATUS: Draft (D5, Apr 2026) | URL: https://standards.ieee.org/ieee/2048.202/

[2.21] W3C Decentralized Identifiers (DIDs) v1.0

This W3C Recommendation defines decentralized identifiers: verifiable, decentralized digital identifiers that enable verifiable, decentralized digital identity. It addresses the limitations of centralized identity systems, including single points of failure and vendor lock-in. DIDs can enable self-sovereign identity for citizens, devices, and digital assets within the virtual city in citiverse, supporting portable, user-controlled identity that works across different city services and virtual environments without relying on centralized identity providers. It works with W3C Verifiable Credentials to provide a complete decentralized identity ecosystem.

▸ Standard Organization: W3C | STATUS: Recommendation (2022) | URL: https://www.w3.org/TR/did-core/

[2.22] W3C Verifiable Credentials Data Model v2.0

This standard defines a data model for verifiable credentials: digital credentials that are cryptographically secure, privacy-respecting, and machine-verifiable. It enables digital credentials that can be shared and verified without contacting the issuing authority. Version 2.0 became a W3C Recommendation in 2025 and replaces v1.1. Verifiable credentials can enable citizens to present digitally signed proofs of qualifications, access rights, and attributes within the virtual city environment in citiverse, supporting privacy-preserving age verification, access control, and service eligibility without disclosing unnecessary personal data.

▸ Standard Organization: W3C | STATUS: Recommendation (2025) | URL: https://www.w3.org/TR/vc-data-model-2.0/

[2.23] ISO/IEC 5259-1:2024 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 1: Overview, terminology and examples

This part of the ISO/IEC 5259 series provides an overview of AI data quality, establishing common terminology and illustrative examples for data quality in AI systems. It addresses the foundational need for a shared vocabulary and conceptual framework for data quality in AI, where inconsistent terminology has hindered effective communication and governance. For citiverse, this standard can provide the baseline terminology and conceptual understanding for all data quality discussions, ensuring that city administrators, AI developers, and data stewards share a common language when managing the vast data assets that feed into city digital twins and AI models.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2024) | URL: https://www.iso.org/standard/81088.html

[2.24] ISO/IEC 5259-2:2024 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 2: Data quality measures

This standard specifies data quality measures for AI systems, defining quantitative and qualitative metrics for assessing data quality characteristics such as accuracy, completeness, consistency, and timeliness. It addresses the challenge of measuring data quality in a standardized, comparable way across different AI deployments. In citiverse, these data quality measures can provide the quantitative framework for assessing the fitness of urban data for AI applications, enabling cities to establish data quality baselines, monitor data quality over time, and compare data quality across different city departments and data sources feeding into the digital twin.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2024) | URL: https://www.iso.org/standard/81860.html

[2.25] ISO/IEC 5259-3:2024 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 3: Data quality management requirements and guidance

This standard specifies requirements and provides guidance for managing data quality in AI systems throughout the data lifecycle, from collection to deployment. It addresses the need for systematic data quality management processes. For citiverse, this standard can provide the requirements and guidance for establishing data quality management processes across the city's AI data pipeline, ensuring that data used for training and inference meets defined quality criteria and that quality issues are identified and addressed systematically before they affect AI system performance and governance decisions.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2024) | URL: https://www.iso.org/standard/81861.html

[2.26] ISO/IEC 5259-4:2024 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 4: Data quality process framework

This standard defines a process framework for data quality in AI systems, specifying the processes, activities, and tasks necessary for achieving and maintaining data quality throughout the AI lifecycle. It addresses the gap between high-level data quality requirements and implementable processes. In citiverse, this process framework can provide the operational blueprint for city AI teams to implement data quality management, defining who does what, when, and how to ensure that data quality is systematically addressed from data acquisition through AI model deployment and monitoring.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2024) | URL: https://www.iso.org/standard/81862.html

[2.27] ISO/IEC 5259-5:2025 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 5: Data quality governance framework

This standard specifies a governance framework for AI data quality, defining roles, responsibilities, decision rights, and accountability structures for data quality management in AI systems. It addresses the organizational and governance dimensions of data quality that are often overlooked in purely technical approaches. For citiverse, this standard can provide the governance framework that ensures accountability for data quality across city AI systems,

defining who is responsible for data quality decisions, how data quality issues are escalated, and how data quality performance is reported to city leadership and oversight bodies.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2025) | URL: https://www.iso.org/standard/81863.html

[2.28] ISO/IEC 5338:2023 – Information technology – Artificial intelligence – AI system lifecycle processes

This standard defines processes for the AI system lifecycle, covering system design, development, deployment, operation, and retirement. It addresses the lack of standardized lifecycle management for AI systems. For citiverse, this standard can provide the process framework for managing AI systems across their entire lifecycle, from initial conception through deployment and decommissioning, ensuring systematic governance of city AI applications.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2023) | URL: https://www.iso.org/standard/81118.html

[2.29] ISO/IEC 42005:2025 – Information technology – Artificial intelligence – AI system impact assessment

This standard provides guidance on conducting impact assessments for AI systems, including societal, ethical, and organizational impact considerations. It addresses the need for systematic AI impact evaluation before deployment. For citiverse, this standard can provide the baseline methodology for assessing the impacts of AI systems deployed in urban governance, supporting public sector accountability and responsible AI adoption in city services.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2025) | URL: https://www.iso.org/standard/42005

[2.30] ISO/IEC 42006:2025 – Information technology – Artificial intelligence – Requirements for bodies providing audit and certification of AI management systems

This standard provides requirements for bodies auditing and certifying an organization's AI management system. Such certification should not be interpreted as certification of an individual AI model or product. For citiverse, it supports consistent, credible third-party auditing of the AI management systems underpinning virtual city operations against ISO/IEC 42001.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2025) | URL: https://www.iso.org/standard/42006

[2.31] ISO/IEC 12792:2025 – Information technology – Artificial intelligence – Transparency taxonomy

This standard defines a taxonomy for AI system transparency, establishing categories and levels of transparency appropriate for different AI applications and contexts. It addresses the challenge of inconsistent transparency expectations across AI deployments. For citiverse, this taxonomy can support model disclosure, algorithmic registration, explanation requirements, and audit readiness for AI systems used in urban governance, enabling appropriate transparency for different risk levels of city AI applications.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2025) | URL: https://www.iso.org/standard/84111.html

[2.32] ISO/IEC 38507:2022 – Information technology – Governance of IT – Governance implications of the use of artificial intelligence by organizations

This standard provides guidance on the governance implications of AI use by organizations, covering organizational responsibilities, decision rights, and accountability frameworks. It addresses the need for organizational-level governance of AI beyond technical management systems. For citiverse, this standard can provide the organizational governance framework for city governments and platform operators using AI, defining accountability structures, oversight mechanisms, and stakeholder engagement approaches for AI-enabled city services.

▸ Standard Organization: ISO/IEC JTC 1 SC 40 | STATUS: Published (2022) | URL: https://www.iso.org/standard/80007.html

[2.33] ISO/IEC 40500:2025 – Information technology – W3C Web Content Accessibility Guidelines (WCAG) 2.2

This standard specifies the Web Content Accessibility Guidelines (WCAG) 2.2, providing accessibility requirements for web content to ensure digital services are accessible to people with disabilities. The standard was published as ISO/IEC 40500:2025 (Edition 2) in September 2025. It is an adoption of the W3C WCAG 2.2 Recommendation as an ISO/IEC International Standard. A subsequent revision (WCAG 3.0) is already under development. For citiverse, WCAG 2.2 can serve as the accessibility baseline for public-facing web-based citiverse portals and citizen engagement platforms. However, it should be noted that WCAG 2.2 success criteria are designed for web content and browsers; their direct applicability to fully immersive XR interactions requires further evaluation and may necessitate additional accessibility standards tailored for immersive environments.

▸ Standard Organization: ISO/IEC JTC 1 (adopting W3C) | STATUS: Published (Edition 2, September 2025) | URL: https://www.iso.org/standard/91029.html | W3C: https://www.w3.org/TR/WCAG22/

[2.34] ISO/IEC TR 5469:2024 – Artificial intelligence – Functional safety and AI systems

ISO/IEC TR 5469 examines functional safety considerations for AI systems, including hazard analysis, risk assessment and safety assurance approaches. For citiverse, it informs safety requirements for AI-assisted urban governance and emergency response systems where incorrect decisions can have safety-critical consequences.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | URL: https://www.iso.org/standard/81283.html

[2.35] ISO/IEC TS 12791:2024 – AI – Treatment of unwanted bias in classification and regression machine learning tasks

ISO/IEC TS 12791 provides technical guidance for detecting, measuring and mitigating unwanted bias in AI classification systems. For citiverse, it supports fairness assessment of urban

governance AI algorithms used in resource allocation, service prioritization and public safety decisions.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | URL: https://www.iso.org/standard/81229.html

[2.36] ISO 37101:2016 (Amd 1:2024) – Sustainable development in communities – Management system – Requirements with guidance for use

ISO 37101 specifies a management system for sustainable development in communities, covering strategic planning, implementation and continuous improvement. For citiverse, it provides a governance framework for aligning digital twin deployment with city sustainability objectives and environmental impact targets.

▸ Standard Organization: ISO/TC 268 | STATUS: Published (2016; Amd 1:2024-02) | URL: https://www.iso.org/standard/61885.html

[2.37] ISO/IEC 27400:2022 – Cybersecurity – IoT security and privacy – Guidelines

ISO/IEC 27400 provides guidelines for security and privacy risk management in IoT systems, covering threat identification, risk assessment and mitigation controls. For citiverse, it informs security requirements for the large-scale IoT sensor networks and edge devices that feed city digital twins.

▸ Standard Organization: ISO/IEC JTC 1/SC 27 | URL: https://www.iso.org/standard/44373.html

[2.38] IEEE 7014-2024 – Standard for Ethical Considerations in Emulated Empathy in Autonomous and Intelligent Systems

IEEE 7014 addresses ethical considerations in AI systems that emulate empathy, including transparency, boundary-setting and user autonomy. For citiverse, it guides design of AI-driven digital humans deployed in citizen-facing public service roles.

▸ Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/7014-2024.html

[2.39] IEEE 7010-2020 – Standard for Well-Being Metrics for Artificial Intelligence and Autonomous Systems

IEEE 7010 defines metrics for evaluating the impact of AI systems on human well-being, covering physical, psychological and social dimensions. For citiverse, it supports assessment of how AI-assisted urban services affect citizen quality of life and inclusive access.

▸ Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/7010-2020.html

[2.40] IEEE 7009-2024 – Standard for Fail-Safe Design of Autonomous and Semi-Autonomous Systems

IEEE 7009 specifies requirements for fail-safe design in autonomous and semi-autonomous systems, ensuring safe degradation and recovery when components fail. For citiverse, it is relevant to AI-assisted emergency response and autonomous urban infrastructure management where system failure must not cause harm.

- Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/7009-2024.html

[2.41] IEEE 7003-2022 – Standard for Algorithmic Bias Considerations

IEEE 7003 provides a process framework for identifying, measuring and mitigating algorithmic bias throughout the AI system lifecycle. For citiverse, it directly supports the urban AI fairness assessment gap by offering methodology for bias testing in city governance algorithms.

- Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/7003-2022.html

[2.42] IEEE 7002-2022 – Standard for Data Privacy Process

IEEE 7002 specifies a systematic process for data privacy management in systems and organizations, covering data collection, use, retention and disclosure. For citiverse, it informs privacy requirements for cross-departmental data sharing and citizen-facing immersive services.

- Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/7002-2022.html

[2.43] W3C ODRL – ODRL Information Model and Vocabulary

W3C ODRL is a policy expression language for representing digital rights, permissions, prohibitions and obligations in a machine-readable format. For citiverse, it supports automated rights management for virtual assets, AI-generated content and digital twin data products.

- Standard Organization: W3C | URL: https://www.w3.org/TR/odrl-model/

[2.44] ISO/IEC 25059:2023 – Software engineering – Systems and software Quality Requirements and Evaluation (SQuaRE) – Quality model for AI systems

ISO/IEC 25059 extends the ISO 25010 quality model with AI-specific characteristics including functional suitability, performance efficiency and robustness for AI systems. For citiverse, it provides quality criteria for evaluating AI models deployed in city digital twin platforms.

- Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2023-06) | URL: https://www.iso.org/standard/80655.html

[2.45] ISO/IEC TR 24028:2020 – Information technology – Artificial intelligence – Overview of trustworthiness

ISO/IEC TR 24028 examines trustworthiness characteristics of AI systems, including transparency, robustness, explainability and accountability. For citiverse, it provides a conceptual foundation for trustworthiness evaluation of urban AI systems.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | URL: https://www.iso.org/standard/73528.html

[2.46] ISO/IEC TR 24027:2021 – Information technology – Artificial intelligence – Bias in AI systems and AI aided decision making

ISO/IEC TR 24027 surveys bias in AI systems, covering sources of bias, measurement methods and mitigation techniques across the AI lifecycle. For citiverse, it informs methodology for assessing fairness in urban governance AI decision-making.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | URL: https://www.iso.org/standard/73527.html

[2.47] IEEE 2089-2021 – Standard for Age Appropriate Design Process for AI Systems

IEEE 2089 provides an age-appropriate design process framework for AI systems, specifying requirements for assessing and mitigating risks to children and vulnerable user groups. For citiverse, it informs the design of AI-driven city services that are accessible and safe across all age groups, ensuring that immersive and automated public services do not expose minors or elderly citizens to inappropriate content or undue privacy risks.

▸ Standard Organization: IEEE | STATUS: Published (2021) | URL: https://standards.ieee.org/standard/2089-2021.html

[2.48] IEEE 7001-2021 – IEEE Standard for Transparency of Autonomous Systems

IEEE 7001 specifies transparency requirements for autonomous systems, including disclosure of capabilities, limitations and decision-making processes. For citiverse, it supports transparency in AI-assisted urban governance and automated service delivery, ensuring that citizens and city administrators can understand how AI-driven decisions are made in public service contexts.

▸ Standard Organization: IEEE | STATUS: Published (2021) | URL: https://standards.ieee.org/standard/7001-2021.html

[2.49] ETSI TS 104 309 – Data Solutions (DATA); MIM-Q; Qualification and Conformance Scheme

A Technical Specification defining qualification levels, MIM-Q profiles, evidence rules, the European Registry for Qualified Implementations, and scheme governance provisions.

▸ Standard Organization: ETSI | STATUS: Planned | URL: https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=78847

3.3.3 Vertical technology stack layer standards

Standards are categorized into five sequential technology layers, matching the end-to-end workflow of the AI-enabled citiverse system. ITU-led standards are listed first in each layer.

Layer 1: Network & Connectivity Layer

[3.1.1] ITU-T Y.2501 – Computing power network – Framework and architecture

This Recommendation defines the overall framework, functional entities and architecture of computing power networks. It addresses the challenge of coordinating distributed computing resources across the network to meet the diverse requirements of different applications. This standard can provide foundational network architecture specifications for AI computing resource scheduling in citiverse, enabling dynamic allocation of computing resources (edge, cloud, end devices) to meet the varying demands of digital twin synchronization, XR rendering, and AI inference across the city.

▸ Standard Organization: ITU-T SG13 | STATUS: Published (2021-09) | URL: https://www.itu.int/rec/T-REC-Y.2501-202109-I/en

[3.1.2] ITU-T Y.4700 – Smart sustainable cities – Deployment guidelines for ubiquitous sensor network applications and services

This Recommendation provides deployment guidelines for ubiquitous sensor network applications and services in the context of smart sustainable cities. It addresses the need for systematic deployment of urban sensing infrastructure. This standard can provide a foundational framework for urban sensing infrastructure in citiverse, defining the IoT capabilities that feed data into the digital twin and establishing the baseline understanding of IoT's role in city digitalization.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2016, renumbered) | URL: https://www.itu.int/rec/T-REC-Y.4700/en

[3.1.3] ITU-T Y.4247 – Requirements of smart city communication network system

This Recommendation specifies requirements for smart city communication network systems, defining the network capabilities needed to support diverse city services including IoT, video surveillance, and real-time data exchange. It addresses the challenge of designing communication networks that can meet the diverse QoS requirements of different city applications. This standard can provide the top-level requirements for city communication networks in citiverse, defining the bandwidth, latency, reliability, and security capabilities needed to support the full range of citiverse services from IoT data collection to immersive XR experiences.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved and in force, prepublished version (2026-06-29) | URL: https://www.itu.int/rec/T-REC-Y.4247-202606-P

[3.1.4] ITU-T Y.4509 – Functional architecture of AI-enabled device-edge-cloud collaborative services for IoT and smart city

The maturity of Internet of Things technology and the widespread deployment of network provide good infrastructure conditions to the application of AI at the device, edge and cloud for IoT and smart city. The requirements of AI models in IoT and smart city are dynamic; consequently, how to make the AI system continuously and dynamically update, as well as how to infer and predict in real-time, is essential to the application of AI in IoT and smart city. The device-edge-cloud collaborative service enables collaborative inference, and dynamic learning and updating of AI models on the device-edge-cloud architecture, so as to meet the needs of various current and future application scenarios. This recommendation specifies the functional architecture of AI-enabled device-edge-cloud collaborative services for IoT and smart city.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved 2025-03-01 | Question: Q3/20 | URL: https://www.itu.int/rec/T-REC-Y.4509/en

[3.1.5] 3GPP TS 22.156 – Mobile Metaverse Services; Stage 1 (Release 19)

This specification defines Stage 1 service requirements for mobile metaverse services over 5G networks, including use cases, requirements, and service capabilities for immersive experiences on mobile devices. It addresses the lack of standardized network requirements for metaverse services over mobile networks. This specification can define the service-level requirements that mobile networks must meet to support city-scale mobile metaverse experiences in citiverse, including avatar communication, spatial interaction, and multi-user immersive experiences on mobile devices throughout the city.

▸ Standard Organization: 3GPP SA1 | STATUS: Published (V19.1.0, 2024-03) | URL: https://www.3gpp.org/DynaReport/22156.htm

[3.1.6] 3GPP TS 23.434 – Service Enabler Architecture Layer for Verticals (SEAL); Functional architecture and information flows

This specification defines the architecture for common services within the 3GPP Service Enabler Architecture Layer (SEAL), providing generic services (e.g., group management, configuration management, location reporting) that can be reused across different vertical applications. It addresses the need for a common services layer to avoid duplication of functionality across different vertical applications. This standard can provide the SEAL common services foundation that supports the mobile metaverse applications defined in TS 23.437 and TS 23.438 in citiverse, enabling consistent service capabilities across different citiverse applications on mobile networks.

▸ Standard Organization: 3GPP SA6 | STATUS: Under change control

| URL: https://www.3gpp.org/DynaReport/23434.htm

[3.1.7] 3GPP TS 23.437 – SEAL; Spatial map and Spatial anchors (Release 19)

This specification defines the architecture for spatial map and spatial anchor services within the 3GPP SEAL framework, enabling network-based spatial computing services. It addresses the challenge of consistent spatial reference across devices and networks for AR/VR experiences. This standard can provide the network-layer spatial computing capabilities that enable consistent

spatial anchoring across the entire city in citiverse, allowing AR content and virtual objects to be precisely positioned in physical space across different devices and users, which is essential for city-scale augmented reality experiences.

▸ Standard Organization: 3GPP SA6 | STATUS: Published (V19.4.0, 2026-02; under change control) | URL: https://www.3gpp.org/DynaReport/23437.htm

[3.1.8] 3GPP TS 23.438 – SEAL; Digital assets (Release 19/20)

This specification defines the architecture for digital asset services within the SEAL framework, supporting management, discovery, and delivery of digital assets for metaverse services over mobile networks. It addresses the need for standardized network support for digital asset distribution in mobile metaverse environments. This standard can enable efficient, secure delivery and management of digital assets (3D models, textures, AI models, virtual items) over mobile networks in citiverse, supporting asset caching, synchronization, and rights management across mobile users accessing the virtual city environment. The specification is currently under change control within 3GPP, with its initial release for Release 19 and ongoing enhancements for Release 20.

▸ Standard Organization: 3GPP SA6 | STATUS: Published (Release 19; under change control) | URL: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=4372

[3.1.9] 3GPP TS 23.501 – System architecture for the 5G System (5GS)

This is the core 5G system architecture specification, defining the overall architecture, network functions, and interfaces for 5G networks including network slicing, edge computing, and QoS framework. It provides the foundational network architecture upon which all advanced services build. This standard can provide the underlying 5G network architecture that supports network slicing for different citiverse service types (massive IoT, low-latency XR, high-bandwidth digital twin synchronization) in citiverse, enabling differentiated QoS for different citiverse traffic types on the same physical network.

▸ Standard Organization: 3GPP SA2 | STATUS: Published (ongoing updates) | URL: https://www.3gpp.org/DynaReport/23501.htm

[3.1.10] 3GPP TS 29.437 – SEAL; Metaverse Enablement Services; Stage 3 (Release 19)

This specification specifies the stage 3 protocol and data model for the Spatial Anchor (SAn) and Spatial Map (SM) services, for enabling the support of Spatial Anchor and Spatial Map management services for vertical applications. It provides stage 3 protocol definitions and message flows, and specifies the API for each service offered by the SAn and SM servers. This standard can provide the protocol-level implementation details that complement the stage 2 architecture defined in TS 23.437 in citiverse, enabling interoperable deployment of spatial anchor and spatial map services across different network implementations. It is the essential implementation counterpart to TS 23.437, ensuring consistent API behaviour across vendors.

▸ Standard Organization: 3GPP CT3 | STATUS: Published (V19.0.0, 2026-02) | URL: https://www.3gpp.org/DynaReport/29437.htm

[3.1.11] 3GPP TS 26.118 – Virtual Reality (VR) profiles for streaming applications

This specification defines media profiles and codecs for VR streaming over 3GPP networks, specifying quality parameters, latency targets, and media formats for immersive video. It addresses the challenge of delivering high-quality VR content within mobile network bandwidth constraints. This standard can provide the media streaming foundation for delivering immersive 360° video and VR content from the virtual city environment to mobile users in citiverse, defining the quality and latency parameters necessary for comfortable immersive experiences while optimizing network bandwidth usage.

▸ Standard Organization: 3GPP SA4 | STATUS: Published (ongoing updates) | URL: https://www.3gpp.org/DynaReport/26118.htm

[3.1.12] 3GPP TS 26.119 – Media Capabilities for Augmented Reality

This specification defines media capabilities for augmented reality services, including media formats, codec requirements, timing and synchronization, and adaptive streaming behaviour for AR/XR content delivery across 3GPP networks. It addresses the need for a common media framework supporting immersive and augmented-reality use cases on mobile devices.

▸ Standard Organization: 3GPP SA4 | STATUS: Published (2024) | URL: https://www.3gpp.org/DynaReport/26119.htm

[3.1.13] IEEE 802.11bf – Wi-Fi Sensing

This IEEE 802.11 amendment standardizes Wi-Fi sensing technology that enables Wi-Fi devices to detect presence, motion, and characteristics of objects in the environment without dedicated sensors. It addresses the need for environment sensing using existing Wi-Fi infrastructure. Wi-Fi sensing can augment dedicated IoT sensors in citiverse by providing environment awareness through existing city Wi-Fi networks, supporting digital twin updates for presence detection, crowd monitoring, and physical environment changes without additional sensor hardware deployment.

▸ Standard Organization: IEEE 802.11 | STATUS: Published (2025-09-26) | URL: https://standards.ieee.org/ieee/802.11bf/11574/

[3.1.14] IETF RFC 8655 – Deterministic Networking (DetNet) Architecture

This RFC defines the overall architecture for Deterministic Networking (DetNet), which provides bounded latency, extremely low data loss and jitter control for critical real-time flows within a network domain. It addresses the inability of traditional IP networks to support determinism for industrial, transport and immersive-city traffic.

▸ Standard Organization: IETF | STATUS: Published (2019-10) | URL: https://www.rfc-editor.org/rfc/rfc8655.html

[3.1.15] IEEE 1918.1-2024 – Tactile Internet: Application Scenarios, Definitions and Terminology, Architecture, Functions, and Technical Assumptions

IEEE 1918.1 defines an architectural framework for the tactile internet, enabling ultra-low-latency haptic and tactile interactions over networks. For citiverse, it supports immersive interaction scenarios requiring real-time haptic feedback in virtual city environments.

▸ Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/1918_1-2024.html

[3.1.16] IEEE 802.11be-2024 – Wireless LAN Enhancements for Extremely High Throughput (EHT)

IEEE 802.11be (Wi-Fi 7) introduces extremely high throughput, multilink operation and enhanced QoS for wireless LANs. For citiverse, it provides the wireless access capacity needed for city-scale mobile AR/XR and high-density immersive public spaces.

▸ Standard Organization: IEEE 802 LAN/MAN | URL: https://standards.ieee.org/standard/802_11be-2024.html

[3.1.17] IEEE 802.1 TSN Series – Time-Sensitive Networking

The IEEE 802.1 Time-Sensitive Networking (TSN) series provides deterministic Ethernet with bounded latency, time synchronization and resource reservation. For citiverse, it supports real-time synchronization of digital twin simulation, sensor networks and emergency response systems.

▸ Standard Organization: IEEE 802 LAN/MAN | URL: https://1.ieee802.org/tsn/

[3.1.18] IEEE 1588-2019 – Precision Clock Synchronization Protocol for Networked Measurement and Control Systems

IEEE 1588 (PTP) enables sub-microsecond clock synchronization across packet-switched networks through master-slave timing distribution. For citiverse, it is essential for time-aligned data fusion across heterogeneous city sensor networks and coordinated multisystem emergency response.

▸ Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/1588-2019.html

[3.1.19] IEEE 1451.0-2017 – Standard for a Smart Transducer Interface for Sensors and Actuators

IEEE 1451.0 defines a standard interface for smart transducers, enabling interoperability of sensors and actuators across heterogeneous networks. For citiverse, it supports plug-and-play integration of diverse city sensors into the digital twin data acquisition layer.

▸ Standard Organization: IEEE | STATUS: Published (2017) | URL: https://standards.ieee.org/standard/1451_0-2017.html

Layer 2: Digital Infrastructure & Platform

[3.2.1] ITU-T Y.4201-Rev – High-level requirements and reference framework of smart city platforms (Revision)

This major revision updates the 2018 smart city platform framework to incorporate AI, digital twins, and metaverse capabilities that have emerged in smart city deployments. It addresses the gap between the original platform framework and modern AI-enabled city environments. This revised standard can provide the updated platform reference architecture that natively supports digital twin synchronization, AI model management, and immersive service orchestration in citiverse, serving as the updated foundational platform standard for next-generation AI-enabled city platforms including citiverse implementations.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study

| URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22088

[3.2.2] ITU-T Y.4239 – Reference model for integrating virtual and physical worlds through digital twins in the metaverse

This Recommendation defines the reference model for integrating physical and virtual worlds through digital twins in metaverse environments, specifying functional entities and interfaces for bidirectional physical-virtual synchronization. It addresses the lack of standardized architecture for metaverse digital twin integration. This standard can provide the core reference model for digital twin integration within the city metaverse in citiverse, defining how physical city entities synchronize with their virtual representations and how virtual interactions affect physical city operations, forming the central architectural blueprint for citiverse platform capabilities.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2025-11) | URL: https://www.itu.int/rec/T-REC-Y.4239/en

[3.2.3] ITU-T Y.4241 – Common requirements and capability framework of digital twin for smart complex and campus

This Recommendation defines common requirements and capability framework for digital twins in smart complexes and campuses, providing a scalable digital twin framework that can be aggregated to city scale. It addresses the need for standardized digital twin capabilities at smaller scales that can federate into city-scale deployments. This standard can provide the building-block digital twin capabilities for districts, campuses, and complexes within the larger city in citiverse, enabling hierarchical digital twin deployment where smaller-scale twins federate into the unified city-scale digital twin, supporting consistent capabilities across different granularities of virtual city representation.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved and in force, prepublished version (2026-05-12) | URL: https://www.itu.int/rec/T-REC-Y.4241-202605-P

[3.2.4] ITU-T Y.4237 – Requirements and capability framework of digital twin for intelligent water conservancy system

Recommendation ITU-T Y.4237 specifies the requirements and capability framework of the digital twin for intelligent water conservancy system (DT-IWCS). Water conservancy is always an

important factor in water resource scheduling. An intelligent water conservancy system driven by digital twin can support intelligent monitoring, and control and management of the usage of water conservancy via the digital twin interaction between digital objects and physical objects of the intelligent water conservancy system.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved 2025-09-23 | Question: Q2/20 | URL: https://www.itu.int/rec/T-REC-Y.4237/en

[3.2.5] ITU-T Y.4513 – Requirements and functional architecture for blockchain-based sustainable and cooperative digital twin creation system

To encourage digital twins creation, maintenance and usage among many entities including municipalities, companies, other organizations, and individuals, this Recommendation defines the concept of cooperative digital twin creation system (CDTCS). CDTCS promotes cooperation through an incentive mechanism where incentive is managed by using blockchain technology. The Recommendation also specifies the requirements and functional architecture for CDTCS.

▸ Standard Organization: ITU-T SG20 | STATUS: Approved 2025-11-13 | Question: Q9/20 | URL: https://www.itu.int/rec/T-REC-Y.4513/en

[3.2.6] ITU-T Y.4515 – Functional framework of an IoT platform for metaverse applications

This Recommendation specifies the functional framework of an IoT platform designed to support metaverse applications, defining how IoT capabilities are exposed to and consumed by metaverse environments. It addresses the critical gap between IoT data collection and metaverse consumption, enabling seamless integration of physical world data into virtual experiences. This standard can provide the IoT platform framework that bridges physical IoT infrastructure and the virtual city environment in citiverse, enabling standardized IoT data access and control from within the metaverse platform. It is a key enabler for bidirectional physical-virtual integration, complementing Recommendation ITU-T Y.4239 by adding IoT-specific platform functions.

▸ Standard Organization: ITU-T SG20 | STATUS: In force (prepublished) | URL: https://www.itu.int/rec/T-REC-Y.4515/en

[3.2.7] ITU-T Y.4600 – Requirements and capabilities of a digital twin system for smart cities

This core Recommendation defines requirements and capabilities for smart city digital twin systems, establishing the baseline functional requirements that city digital twins must meet. It was one of the first international standards specifically for city digital twins. This standard can provide the foundational digital twin requirements that all citiverse platforms build upon, defining core capabilities including data ingestion, modelling, simulation, and visualization that form the digital twin core of the virtual city.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2022) | URL: https://www.itu.int/rec/T-REC-Y.4600/en

[3.2.8] ITU-T Y.4224 – Requirements for digital twin federation in smart cities and communities

This Recommendation defines requirements for digital twin federation, enabling multiple independent digital twins to interoperate and form larger, composite digital twin systems. It addresses the challenge of connecting twins developed by different organizations for different domains. This standard can enable federation of district, departmental, and domain-specific digital twins into the unified city-scale citiverse, supporting incremental development where different stakeholders can build twins that connect into the overall city virtual environment.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2023-11) | URL: https://www.itu.int/rec/T-REC-Y.4224-202311-I

[3.2.9] ITU-T Y.aidt-reqts – Requirements of AI integrated digital twin for cities and communities

This draft Recommendation specifies core capabilities and technical requirements for AI and digital twin integration in urban scenarios. It addresses the gap between digital twin platforms and AI capabilities, defining how AI models should be integrated into digital twin workflows. This standard can define the AI-native twin architecture in citiverse, specifying how AI models are deployed, managed and orchestrated within the digital twin platform. It is a key enabler for intelligent citiverse capabilities including predictive simulation and automated decision support.

▸ Standard Organization: ITU-T SG20 | STATUS: New project initiated | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23966

[3.2.10] ISO/IEC 30173:2023 – Digital twin – Concepts and terminology

This international standard defines concepts and terminology for digital twins, establishing a common vocabulary across different digital twin implementations and domains. It addresses the terminology confusion that has accompanied rapid digital twin adoption across industries. This standard can provide the standardized digital twin terminology that ensures consistent understanding across all digital twin standards and implementations in citiverse, providing the conceptual foundation for all digital twin-related standards in the citiverse architecture.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2023-11) | URL: https://www.iso.org/standard/81442.html

[3.2.11] ISO/IEC 30186:2025 – Digital twin – Maturity model and guidance for a maturity assessment

This standard defines digital twin system capability maturity levels and assessment indicators, providing a framework for evaluating digital twin implementations. It addresses the lack of standardized assessment criteria for comparing digital twin capabilities across different implementations. This standard can support graded evaluation of citiverse platform construction, enabling cities to assess their digital twin capabilities against a standardized maturity model and plan capability improvements.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2025-07) | URL: https://www.iso.org/standard/53306.html

[3.2.12] ISO/IEC 30187:2026 – Internet of Things (IoT) – Evaluation indicators for IoT systems

This document specifies the evaluation indicators for IoT systems, applicable to the compilation of the evaluation indicators for IoT systems in specific industries. This standard can provide the evaluation indicator framework for city-scale IoT systems that underpin the digital twin platform in citiverse, enabling consistent assessment of IoT infrastructure performance across different city deployments.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2026-05) | URL: https://www.iso.org/standard/53307.html

[3.2.13] ISO/IEC 30188:2026 – Digital twin – Reference architecture

This International Standard specifies a general reference architecture for a digital twin system in terms of defining system fundamentals through the use of architecture views. This reference architecture can provide the ISO/IEC-aligned digital twin platform structure that complements Recommendation ITU-T Y.4239 in citiverse, defining the internal platform components for digital twin modelling, synchronization, simulation, and visualization that underpin the city-scale virtual environment.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2026-07) | URL: https://www.iso.org/standard/53308.html

[3.2.14] ISO/IEC 30151 – Digital twin – Extraction and transactions of data components

This draft standard specifies approaches for extracting data components from digital twins and enabling transactions of digital twin data products. It addresses the challenge of enabling data component reuse and exchange across different digital twin implementations. This standard can enable standardized extraction and exchange of digital twin data components in citiverse, supporting data assetization within the city platform, enabling cross-domain data transactions, and supporting the development of a data marketplace for city digital twin components.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Committee Draft (CD, 2026) | URL: https://www.iso.org/standard/89834.html

[3.2.15] ISO/IEC 30152 ED1 – IoT and digital twins – Guidance on the connection to data spaces

This draft standard provides guidance on connecting IoT systems and digital twins to data spaces, enabling sovereign, cross-organization data sharing. It addresses the challenge of integrating digital twins into emerging data space ecosystems. This standard can provide guidance for connecting the city digital twin platform to European and international data spaces in citiverse, enabling secure, sovereign cross-city and cross-organization data sharing while preserving data sovereignty, supporting federated digital twin deployments across jurisdictions.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Approved Work Item (AWI, 2025) | URL: https://www.iso.org/standard/89835.html

[3.2.16] ISO/IEC 30153 ED1 – Digital Twin – Guidelines for digital entity modelling

This draft standard provides guidelines for modelling digital entities within digital twin systems, defining modelling approaches, entity relationships, and model evolution practices. It addresses inconsistent digital entity modelling across different digital twin tools and platforms. These guidelines can ensure consistent modelling of city entities (buildings, infrastructure, people, vehicles) within the digital twin in citiverse, enabling model reuse, interoperability between different modelling tools, and consistent representation across different city domains.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Approved Work Item (AWI, 2025) | URL: https://www.iso.org/standard/89836.html

[3.2.17] ISO/IEC 30194:2024 – Internet of things (IoT) and digital twin – Best practices for use case projects

This standard provides best practices for implementing IoT and digital twin use case projects, compiling lessons learned from global digital twin deployments. It addresses implementation challenges and interoperability risks in digital twin projects that arise from lack of implementation guidance. This standard can provide practical implementation guidance drawn from global best practices for citiverse deployments, supporting successful city-scale digital twin deployment by providing proven approaches to project planning, data integration, stakeholder engagement, and capability rollout.

▸ Standard Organization: ISO/IEC JTC 1 SC 41 | STATUS: Published (2024-12) | URL: https://www.iso.org/standard/53314.html

[3.2.18] ISO/IEC CD TR 30138 – Digital Twin – Fidelity metric of digital twin system (under development)

This technical report defines fidelity metrics for digital twin systems, establishing quantitative measures of how accurately a digital twin represents its physical counterpart across multiple dimensions. It addresses the lack of standardized metrics for assessing digital twin accuracy and trustworthiness. This technical report can provide the metrics framework for assessing and certifying the fidelity of city digital twins in citiverse, establishing quantitative measures of geometric accuracy, temporal synchronization, and behavioural correctness that determine how much trust can be placed in digital twin simulations and predictions for governance decision-making.

▸ Standard Organization: ISO/IEC (JTC 1 SC 41) | STATUS: In development (CD) | URL: https://www.iso.org/standard/53258.html

[3.2.19] IEEE 2888.3-2024 – IEEE Standard for Orchestration of Digital Synchronization Between Cyber and Physical Worlds

This standard specifies orchestration mechanisms for digital synchronization between cyber and physical worlds, defining interfaces and protocols for maintaining real-time alignment between physical entities and their digital representations. It addresses the lack of standardized synchronization mechanisms for cyber-physical systems. This standard can provide the synchronization orchestration layer that maintains real-time alignment between the physical city and its virtual representation in citiverse, defining synchronization frequency, conflict resolution,

and state convergence mechanisms that ensure the virtual city remains an accurate reflection of physical reality.

▸ Standard Organization: IEEE | STATUS: Published (2024) | URL: https://standards.ieee.org/standard/2888.3-2024.html

[3.2.20] IEEE 2302-2021 – Standard for Intercloud Interoperability and Federation

IEEE 2302 specifies interoperability and federation between cloud computing systems, enabling resource exchange across cloud providers. For citiverse, it supports the federation of city digital twin platforms across departments and jurisdictions.

▸ Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/2302-2021.html

[3.2.21] IEEE 1934-2018 – Standard for Adoption of OpenFog Reference Architecture for Fog Computing

IEEE 1934 adopts the OpenFog reference architecture for fog computing, defining a scalable hierarchy for edge-to-cloud processing. For citiverse, it informs the end-edge-cloud collaborative computing architecture needed for low-latency immersive services.

▸ Standard Organization: IEEE SA | URL: https://standards.ieee.org/standard/1934-2018.html

Layer 3: Data & Analytics Layer

[3.3.1] ITU-T Y.4614 – Energy data model for city-level energy management platform

This Recommendation specifies a standardized energy data model for the city-level energy management platform (CL-EMP), defining data structures for sharing energy data across city platforms to support integrated city energy services. It addresses the fragmentation of energy data across different building, grid and transportation systems that prevents city-scale energy optimization. This standard can provide the common data model that enables unified representation of energy data across the city digital twin in citiverse, supporting cross-sector energy simulation, optimization, and carbon footprint analysis within the virtual city environment.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2026-05) | URL: https://www.itu.int/rec/T-REC-Y.4614-202605-P

[3.3.2] ITU-T Y.C&D-SCP-req – Requirements for centralized and decentralized data flow control on smart city platforms

A key challenge for data flows in cities is their control on smart city platforms (SCP). Smart and Sustainable Cities and Communities (SSC&C) can have centralized or decentralized control of data flows and give easy access to data consumers (who want to gain access to the available information and services of an SSC&C) and to data providers (who want to offer information and services within an SSC&C). This draft Recommendation specifies the requirements for the centralized and the decentralized data flow control on SCP. It introduces the concept of the "smart city as a hub/smart city hub" (SCHub), which can enable cities to perform a centralized control on data flows, with the use of standardized APIs. It also introduces the concept of "DCITY"

that enables decentralized data flow control and applies rules on data sovereignty. It introduces the high-level architecture for the SCHub and the DCITY, and the requirements for centralized and for decentralized data flow control on SCP.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q4/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23984

[3.3.3] ITU-T Y.DPM-DT – Requirements of data processing and management for digital twin-based smart cities and communities

This draft Recommendation focuses on the Requirements of data processing and management (DPM) for digital twin-based smart cities and communities. The proposed standard addresses the limitations of conventional DPM frameworks, which are insufficient for handling the real-time, dynamic, and spatiotemporally correlated data flows essential for digital twin operations. The core of this draft Recommendation is to specify the enhanced capabilities required for DPM to facilitate the closed-loop interaction between physical entities and virtual entities. This document structures these requirements into three key areas: P2V Synchronization Support, Data-Driven Model and Simulation Support, and V2P Control Support, which boost operational efficiency for smart cities while advancing global collaboration in the digital transformation of cities.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q4/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23558

[3.3.4] ITU-T Y.FML-AISF – Federated machine learning-based artificial intelligence software framework with blockchain-driven edge data sharing

In order to enable distributed training and deployment of AI models while preserving privacy, enhancing trust, and promoting interoperability across diverse edge devices, this Recommendation employs federated machine learning to keep raw data on local devices, thereby reducing privacy leakage and network overhead. It also uses blockchain technologies to provide immutable records, smart-contract-based governance, and secure edge-to-edge data sharing. In traditional FML-based services, FML coordinators and participants exchange information directly, as specified in Recommendation ITU-T F.748.35. However, traditional FML-based services face several challenges in distributed or decentralized environments due to the lack of trust among multiple participants, regardless of whether such environments are considered trusted or untrusted. In such cases, distributed ledger technologies (DLT) provide inherent advantages for data management and sharing, including peer-to-peer communication, decentralization, immutability, openness, crowd consensus, and support for smart-contract automation. The convergence of FML and DLT can, therefore, provide significant benefits for FML-based services.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q9/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23546

[3.3.5] ITU-T Y.Sup.DAM-SCC – Supplement to ITU-T Y.4223 - Use cases of data asset management in smart cities and communities

This draft Supplement to Recommendation ITU-T Y.4223 provides overview, use cases, and challenges and opportunities for Data Asset Management (DAM) in Smart Cities and Communities

(SC&C). It emphasizes the strategic shift from managing raw datasets to governing data as critical urban resources characterized by intrinsic operational value, clear ownership, actionable utility, and the potential for secure exchange. Data assets, sourced from heterogeneous urban infrastructure (e.g., IoT devices, mobility networks, geospatial systems), are managed across the sensing and infrastructure, smart city platform, and service and application layers. The document explains how DAM practices such as metadata harmonization, privacy-preserving mechanisms, and federated data sharing enable city operators to transform isolated data into tradable assets and actionable intelligence. Furthermore, the Supplement identifies key challenges and opportunities in data governance, valuation, and secure sharing, providing informative guidance to support a collaborative, data-driven urban economy.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q4/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23985

[3.3.6] ISO/IEC 25012:2008 – Software engineering – Software product Quality Requirements and Evaluation (SQuaRE) – Data quality model

This standard defines a data quality model for software products, establishing characteristics for measuring data quality including accuracy, completeness, consistency and timeliness. It provides a generic data quality framework applicable across domains. This data quality model can provide the baseline quality framework for all data flowing into the digital twin in citiverse, defining quality dimensions and metrics that ensure city data are fit for use in AI models and simulations.

▸ Standard Organization: ISO/IEC JTC 1 SC 7 | STATUS: Published (2008) | URL: https://www.iso.org/standard/35736.html

[3.3.7] ISO/IEC 22989:2022 – Information technology – Artificial intelligence – Artificial intelligence concepts and terminology

This standard establishes concepts and terminology for artificial intelligence, defining common vocabulary across the AI ecosystem and establishing a shared understanding of AI capabilities and characteristics. It addresses the terminology confusion that has accompanied rapid AI development. This standard can provide the standardized AI terminology that ensures consistent understanding across different AI standards and implementations in citiverse, providing the conceptual foundation for all AI-related standards and capabilities within the citiverse architecture.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2022) | URL: https://www.iso.org/standard/74296.html

[3.3.8] C2PA 2.1 – Content Provenance and Authenticity Specification

This open technical standard provides a mechanism to attest to the origin and history of digital content, including AI-generated content. It supports verification of content provenance and tamper-evident assertions; it does not, by itself, establish the factual accuracy of the content. For citiverse, it provides the technical foundation for tracking the provenance of AI-generated 3D models, simulation results, and city data, supporting compliance with AI content disclosure requirements.

▸ Standard Organization: C2PA (Coalition for Content Provenance and Authenticity) | STATUS: Published (v2.1, 2024) | URL: https://spec.c2pa.org/specifications/specifications/2.1/specs/_attachments/C2PA_Specification.pdf

[3.3.9] ISO/IEC 23053:2022 – Information technology – Artificial intelligence – Framework for AI systems using machine learning

This standard provides a framework for artificial intelligence systems using machine learning, defining reference architecture and common terms for AI systems. It addresses the fragmentation of AI system architectures across different implementations. This standard can provide the reference architecture for AI systems deployed within the digital twin platform in citiverse, ensuring consistent implementation of machine learning models, training pipelines, and inference services across different city AI applications.

▸ Standard Organization: ISO/IEC JTC 1/SC 42 | STATUS: Published (2022) | URL: https://www.iso.org/standard/74437.html

Layer 4: Virtual World Construction Layer

[3.4.1] ITU-T Y.4519 – Functional architecture of visualization system in digital twin for smart sustainable cities and communities

This Recommendation defines the functional architecture for digital twin visualization systems in smart sustainable cities and communities, specifying functional components, interfaces, and capabilities for city-scale digital twin visualization. It addresses the lack of standardized architecture for digital twin visualization platforms across different city deployments. This standard can provide the reference architecture for the virtual world rendering and visualization layer in citiverse, defining how digital twin data are processed, rendered, and presented to users across different devices and visualization modalities. It works in conjunction with Y.DT-SSC-CVP to provide a complete visualization standardization framework.

▸ Standard Organization: ITU-T SG20 | STATUS: Determined, pending publication (2026-05) | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22090

[3.4.2] ITU-T Y.DT-SSC-CVP – Classification of visualization precision levels for digital twin systems in smart sustainable cities

This draft Recommendation establishes a unified classification of visualization precision levels for digital twin systems in smart sustainable cities, defining standardized levels of detail, accuracy, and realism for different digital twin use cases. It addresses the current situation where different vendors use inconsistent precision definitions leading to mismatched expectations. This classification can enable appropriate precision levels for different use cases in citiverse from high-precision engineering views for infrastructure management to lighter-weight visualizations for citizen-facing services, optimising performance while ensuring appropriate visual fidelity for each application scenario. It is the companion standard to Recommendation ITU-T Y.4519, defining the precision levels that the visualization architecture must support.

▸ Standard Organization: ITU-T SG20 | STATUS: Under development | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22057

[3.4.3] ITU-T YSTR.Acc-Tools – Tools for accessible interactions in IoT-enabled immersive environments and virtual worlds for smart sustainable cities and communities

The draft Technical Report introduces an interaction framework for accessible virtual environments in the citiverse, describing key interaction components that enable inclusive user experiences. It maps out key technologies, from hand tracking and haptics to brain-computer interfaces, and their relevance for designing user-centric, accessible environments. It explains how users perceive, navigate, and interact with virtual environments through mechanisms such as proprioception, object manipulation, communication, consent management, environmental customization, contextual guidance, and session persistence. The draft Technical Report emphasizes that these interaction elements must be designed with accessibility, usability, and interoperability in mind, allowing users with diverse abilities to participate effectively. It also highlights the importance of user-centric design, assistive technology compatibility, and adherence to international standards (e.g., ISO, W3C, WCAG) to ensure reliable, secure, and inclusive interactions. Overall, the Technical Report provides a structured model for designing accessible human system interactions in AI-powered virtual worlds.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q8/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=24007

[3.4.4] ITU-T YSTR.BP-DTw – Best Practices for Graphical Digital Twins of Smart Cities

This example-based report focuses on how emerging technology solutions can best address environmental issues within cities. The data used is based on information gained from the United Nations' United for Smart Sustainable Cities (U4SSC) initiative. Industrial Internet of Things (IoT) and smart cities gather a lot of data in data lakes and present the insights generated by machine learning or artificial intelligence in custom proprietary dashboards or in open APIs. It is a tedious task for stakeholders with low data literacy to apprehend so much information and in so many data formats in a way that helps them bend their decisions and adapt their behaviours towards a more sustainable future.

▸ Standard Organization: ITU-T SG20 | STATUS: Agreed 2023-02-10 | Question: Q1/20 | URL: https://www.itu.int/epublications/ru/publication/itu-t-ystr-bp-dtw-2023-02-best-practices-for-graphical-digital-twins-of-smart-cities

[3.4.5] ISO/IEC 5927:2024 – Augmented and virtual reality safety – Guidance on safe immersion, set up and usage

This standard provides guidance on safe immersion, setup, and usage of augmented and virtual reality systems, addressing physical safety risks including collisions, discomfort, and adverse health effects. It addresses the safety concerns that have accompanied widespread XR adoption. This standard can provide safety guidelines for public immersive experiences in the city in citiverse, ensuring that AR/VR experiences deployed in public spaces are designed to prevent physical injury, minimize motion sickness, and provide appropriate safety warnings for citizens using immersive services in the city environment.

▸ Standard Organization: ISO/IEC JTC 1 SC 24 | STATUS: Published (2024-02) | URL: https://www.iso.org/standard/81847.html

[3.4.6] ISO 9241-820:2024 – Ergonomics of human-system interaction – Part 820: Ergonomic guidance on interactions in immersive environments

This standard provides ergonomic guidance for human-system interaction in immersive environments, defining comfortable, usable interaction patterns for VR/AR systems. It addresses usability challenges including interaction fatigue, disorientation, and poor accessibility in immersive systems. This standard can guide the design of user interfaces and interaction patterns within the virtual city in citiverse, ensuring that immersive interactions with city services are ergonomic, comfortable, and accessible for diverse citizens including elderly users and people with disabilities.

▸ Standard Organization: ISO/TC 159/SC 4 | STATUS: Published (2024-04) | URL: https://www.iso.org/standard/83673.html

[3.4.7] ISO/IEC 23090-5:2026 – Coded representation of immersive media – Part 5: Visual volumetric video-based coding (V3C) and video-based point cloud compression (V-PCC)

This MPEG standard defines video-based point cloud compression, providing efficient coding for dynamic point clouds used in volumetric video and immersive telepresence. It addresses the large bandwidth requirements of uncompressed point cloud video. V-PCC can enable efficient streaming of dynamic point cloud content including volumetric video of people and dynamic objects within the virtual city in citiverse, supporting immersive telepresence and realistic dynamic content in citiverse experiences.

▸ Standard Organization: ISO/IEC JTC 1 SC 29 | STATUS: Published (2026-06, Ed. 4) | URL: https://www.iso.org/standard/91546.html

[3.4.8] ISO/IEC 23090-6:2021 – Coded representation of immersive media – Part 6: Immersive media metrics

This standard specifies immersive media metrics and the measurement framework for assessing the quality of immersive experiences. It addresses the need for standardized quality measurement in immersive media, where traditional video quality metrics are insufficient. This standard can provide the metrics framework for measuring and ensuring the quality of immersive experiences within the virtual city in citiverse, supporting QoE optimization for citizens accessing citiverse services across different devices and network conditions.

▸ Standard Organization: ISO/IEC JTC 1 SC 29 | STATUS: Published (2021) | URL: https://www.iso.org/standard/79417.html

[3.4.9] ISO/IEC 23090-12:2025 – Coded representation of immersive media – Part 12: MPEG immersive video (MIV)

This standard specifies the syntax, semantics and decoding processes for MPEG immersive video (MIV), providing support for playback of a 3D scene with 6 Degrees of Freedom (6DoF). It addresses the growing demand for immersive video that allows viewers to move within the scene. MIV can provide the video coding standard for immersive video experiences within the virtual city in citiverse, enabling citizens to view and interact with city environments from any angle and position, supporting high-quality 6DoF video for remote tourism, virtual events, and city exploration.

▸ Standard Organization: ISO/IEC JTC 1 SC 29 | STATUS: Published (2025-09, Ed. 2) | URL: https://www.iso.org/standard/83558.html

[3.4.10] ISO/IEC 23090-14:2025 – Coded representation of immersive media – Part 14: Scene description

This standard defines structured description syntax, semantics and rendering processing model for immersive media scenes, providing the scene description foundation for rich interactive 3D experiences. It addresses the lack of standardized scene description for complex immersive scenes. This standard can provide the scene description framework for the virtual city in citiverse, defining how objects, lighting, animations and interactions are structured and described within the virtual environment, enabling consistent rendering and interaction across different platforms.

▸ Standard Organization: ISO/IEC JTC 1 SC 29 | STATUS: Published (2025-11, Ed. 2) | URL: https://www.iso.org/standard/90191.html

[3.4.11] ISO/IEC 23090-29:2026 – Coded representation of immersive media – Part 29: Video-based dynamic mesh coding (V-DMC)

This standard specifies syntax, semantics, and decoding for video-based dynamic mesh coding (V-DMC), basemesh coding, MPEG edgebreaker static mesh coding, and arithmetic coded displacement. It supports efficient compression and streaming of dynamic mesh data for immersive media applications, enabling realistic representation of dynamic 3D objects and scenes within the virtual city environment.

▸ Standard Organization: ISO/IEC JTC 1 SC 29 | STATUS: Published (2026-07-17) | URL: https://www.iso.org/standard/85254.html

[3.4.12] ISO/IEC 19774:2019 – Information technology – Computer graphics and image processing – Humanoid animation (H-Anim)

This standard defines a specification for humanoid animation, defining a standard skeleton and animation system for virtual human characters that enables interoperable avatar representation across different platforms. It addresses avatar fragmentation where avatars created for one platform cannot be used in another. H-Anim can provide the standardized humanoid avatar model that enables citizen avatars to be portable across different virtual city environments and services in citiverse, supporting consistent avatar representation and animation across different XR platforms and devices.

▸ Standard Organization: ISO/IEC JTC 1 SC 24 | STATUS: Published (2019) | URL: https://www.iso.org/standard/74298.html

[3.4.13] ISO/IEC 37200:2022 – Information technology – Computer graphics and image processing – Mixed and augmented reality – Content model for virtual human

This standard defines a content model for virtual humans in mixed and augmented reality, specifying the structure and representation of virtual human characters including geometry, materials, rigging, and animation. It addresses interoperability issues for virtual human content across different platforms. This standard can provide the standardized virtual human content model that ensures digital human citizens, service agents, and NPCs are represented consistently

across different platforms and applications within the virtual city in citiverse. It complements H-Anim by defining the content structure in addition to the animation specification.

▸ Standard Organization: ISO/IEC JTC 1 SC 24 | STATUS: Published (2022) | URL: https://www.iso.org/standard/80917.html

[3.4.14] ISO/IEC 18039:2019 – Information technology – Computer graphics, image processing and environmental data representation – Mixed and augmented reality (MAR) reference model

This standard defines a reference model for mixed and augmented reality systems, establishing a common framework for understanding and comparing MAR systems. It addresses the lack of consistent architectural reference for AR/MR systems. This reference model can provide the architectural foundation for augmented reality experiences that overlay virtual city information onto the physical environment in citiverse, defining the components and interfaces that enable consistent AR experiences across different applications and devices in the city.

▸ Standard Organization: ISO/IEC JTC 1 SC 24 | STATUS: Published (2019) | URL: https://www.iso.org/standard/74297.html

[3.4.15] ISO/IEC 12113:2022 – Information technology – Runtime 3D asset delivery format – Khronos glTF™ 2.0

This standard defines the glTF file format, an API-neutral runtime asset delivery format that bridges the gap between 3D content creation tools and modern graphics applications. It addresses the proliferation of proprietary 3D formats that require inefficient conversion. glTF can serve as the standard runtime 3D asset format for all 3D content in the virtual city in citiverse (buildings, props, avatars, vehicles), enabling efficient delivery and rendering across all web and mobile platforms without proprietary plugins or format conversion.

▸ Standard Organization: ISO/IEC JTC 1 SC 24 | STATUS: Published (2022-07) | URL: https://www.iso.org/standard/83990.html

[3.4.16] ISO/IEC 19775-1:2023 (X3D) – Information technology – Computer graphics and image processing – Extensible 3D (X3D) – Part 1: Architecture and base components

This standard defines general architecture, core components and interaction specifications for X3D, providing the 3D graphics foundation for citiverse virtual world construction. It addresses the need for a standardized, extensible 3D graphics framework that works across different platforms. X3D can provide the foundational 3D graphics framework for building and interacting with the virtual city in citiverse, defining how 3D scenes are structured, rendered, and interacted with across different devices and applications.

▸ Standard Organization: ISO/IEC JTC 1 SC 24 | STATUS: Published (Edition 4, 2023-12) | URL: https://www.iso.org/standard/82562.html

[3.4.17] ISO/IEC 19775-2:2015 — Information technology — Computer graphics, image processing and environmental data representation — Extensible 3D (X3D) — Part 2: Scene Access Interface

This standard specifies a standard set of services that are made available by a browser so that an author can access the scene graph while it is running, supporting inspection and modification of the scene graph. It addresses the need for programmatic access to X3D scenes. This standard can provide the programmatic interface for accessing and manipulating the virtual city scene graph in citiverse, enabling dynamic updates, user interactions, and real-time modifications to the virtual environment.

▸ Standard Organization: ISO/IEC JTC 1 SC 24 | STATUS: Published (2015) | URL: https://www.iso.org/standard/60500.html

[3.4.18] ISO/IEC 3721:2023 — Information model for Mixed and Augmented Reality contents

This International Standard specifies the information model, data structures and semantic definitions for mixed and augmented reality contents, supporting standardized AR content representation. It addresses the need for a common information model for MAR content across different platforms. This standard can provide the information model for representing AR content within the virtual city in citiverse, supporting consistent AR content creation, storage, and rendering across different applications and devices.

▸ Standard Organization: ISO/IEC JTC 1 SC 24 | STATUS: Published (2023-09) | URL: https://www.iso.org/standard/81207.html

[3.4.19] OGC CityGML 3.0 — City Geography Markup Language 3.0

This international standard defines an open data model and XML-based format for the representation and exchange of 3D city models, supporting multiple levels of detail for different city objects. It addresses the lack of standardized 3D city model representation across different GIS and BIM tools. CityGML can provide the standardized 3D geospatial data model that forms the geometric foundation of the virtual city in citiverse, enabling consistent representation of buildings, roads, water bodies, vegetation, and other city objects across different platforms and applications.

▸ Standard Organization: OGC | STATUS: Published (2021) | URL: https://www.ogc.org/standard/citygml/

[3.4.20] OGC 3D Tiles 1.1

This standard defines a spatial data structure and tile format for streaming massive heterogeneous 3D geospatial datasets, enabling efficient streaming and rendering of large-scale 3D content. It addresses the challenge of rendering city-scale 3D models on client devices with limited memory and bandwidth. 3D Tiles 1.1 is the current approved standard (published January 2023). As of 30 July 2026, OGC 3D Tiles 2.0 remained a proposed Community Standard Work Item following a public comment period that closed on 23 July 2026. It was not yet an approved OGC standard. Cities with existing 3D Tiles 1.x deployments should monitor the 2.0 development and ensure citiverse requirements are fed into the standardization process.

▸ Standard Organization: OGC | STATUS: Published (2023) | URL: https://www.ogc.org/standard/3dtiles/

[3.4.21] OGC IndoorGML – Indoor Geography Markup Language

This OGC standard defines an open data model and XML schema for indoor spatial information, representing indoor spaces including connectivity between spaces for navigation and routing. It addresses the lack of standardized indoor spatial models. IndoorGML can enable modelling of indoor spaces within the virtual city in citiverse, supporting indoor navigation, indoor positioning, and indoor simulations that complement outdoor city models, enabling seamless indoor-outdoor experiences in the virtual city.

▸ Standard Organization: OGC | STATUS: Published | URL: https://www.ogc.org/standard/indoorgml/

[3.4.22] OGC InfraGML 1.0 – Infrastructure Geography Markup Language

This standard provides a semantic modelling framework for land and infrastructure, supporting digital modelling of transportation networks, utilities and other physical infrastructure assets within 3D city models. It addresses the lack of standardized representation for urban infrastructure in 3D city models. InfraGML enables infrastructure modelling within the virtual city in citiverse, supporting infrastructure simulation and planning; its coverage is defined by the OGC standard scope and should not be read as extending to every utility network.

▸ Standard Organization: OGC | STATUS: Published | URL: https://www.ogc.org/standard/infragml/

[3.4.23] ISO 16739-1:2024 – Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries

This standard defines the Industry Foundation Classes (IFC) data model for building information modelling, enabling rich data exchange between different BIM software tools. It is the dominant standard for BIM data exchange. IFC can enable integration of detailed BIM models of individual buildings into the city-scale virtual environment in citiverse, supporting detailed building-level simulations (energy, evacuation, facilities management) within the broader city context.

▸ Standard Organization: ISO/TC 59/SC 13 | STATUS: Published (2024) | URL: https://www.iso.org/standard/84123.html

[3.4.24] W3C WebXR Device API

This standard defines a JavaScript API for accessing virtual reality (VR) and augmented reality (AR) devices, including sensors and head-mounted displays, from web browsers. It addresses the historical fragmentation of XR device access requiring proprietary SDKs. WebXR can enable browser-based access to the virtual city environment in citiverse without requiring installation of proprietary applications, supporting accessible, cross-device immersive experiences that work across different XR hardware and operating systems through standard web browsers.

▸ Standard Organization: W3C | STATUS: Candidate Recommendation Draft (June 2026) | URL: https://www.w3.org/TR/webxr/

[3.4.25] OpenXR 1.0

This royalty-free open standard provides a high-performance, cross-platform API for VR/AR applications and engines, enabling applications to run on diverse XR hardware without porting. It addresses XR hardware and software fragmentation where applications required separate support for each headset vendor. OpenXR can enable immersive city applications to run across all major VR/AR hardware devices (e.g., Meta, HTC, Microsoft) in citiverse without separate development, supporting hardware-agnostic access to the virtual city environment across different citizen devices.

▸ Standard Organization: Khronos Group | STATUS: Published (2019, ongoing updates) | URL: https://www.khronos.org/openxr/

[3.4.26] W3C WebGPU – Web Graphics Processing Unit API

This standard defines a modern web API for high-performance 3D graphics and GPU computation, providing low-level access to GPU capabilities from web browsers. It addresses the performance limitations of WebGL for large-scale 3D rendering. WebGPU can enable high-performance rendering of city-scale 3D models directly in web browsers in citiverse, supporting smooth immersive experiences without requiring native applications, and enabling GPU-accelerated AI inference for client-side digital twin processing.

▸ Standard Organization: W3C | STATUS: Candidate Recommendation Draft (March 2026) | URL: https://www.w3.org/TR/webgpu/

[3.4.27] OGC CityJSON 2.0 – CityJSON encoding for 3D city models

This standard defines a JSON-based encoding for 3D city models, providing a web-friendly alternative to CityGML's XML encoding. It addresses the complexity of XML-based 3D city model exchange for web applications. CityJSON can enable efficient, web-native delivery of 3D city models to browsers and mobile devices in citiverse, supporting lightweight visualization and easy integration with web-based citiverse applications without complex XML parsing.

▸ Standard Organization: OGC | STATUS: Published (2023) | URL: https://www.ogc.org/standard/cityjson/

[3.4.28] IEEE 2048.101-2023 – IEEE Standard for Augmented Reality on Mobile Devices – General Requirements for Software Framework, Components, and Integration

This standard specifies the general technical framework, components, integration, and main business processes of augmented reality systems applied to mobile devices, defining technical requirements for AR-enabled mobile applications. It addresses the fragmentation of AR mobile implementations across different platforms and vendors. This standard can provide the framework for deploying augmented reality experiences on mobile devices within the city in citiverse, supporting mobile AR citizen services, wayfinding, and location-based information overlay in the physical city environment.

▸ Standard Organization: IEEE CTS/MSC | STATUS: Published (2023) | URL: https://standards.ieee.org/ieee/2048.101/

[3.4.29] ETSI GS ARF 003 – Augmented Reality Framework (ARF); AR framework architecture

This specification defines a functional reference architecture for AR components, systems and services, specifying the structure of the AR architecture and the functionalities of its components derived from AR use cases and standards landscape analysis. It addresses the lack of a standardized AR system architecture across different implementations. This architecture can provide the ETSI-aligned AR framework that supports augmented reality applications within the virtual city in citiverse, defining how AR components integrate with city data and services to provide consistent AR experiences across different AR devices and platforms.

▸ Standard Organization: ETSI ISG ARF | STATUS: Published | URL: https://www.etsi.org/deliver/etsi_gs/ARF/001_099/003/

[3.4.30] ISO/IEC TS 5147:2023 – Information technology – Computer graphics, image processing and environmental data representation – Guidelines for representation and visualization of smart cities

This Technical Specification provides guidance on the representation and visualization of smart cities, smart city objects and associated smart city data. It describes relevant concepts and data categories, offers guidance for selecting appropriate representation and visualization techniques, and provides use cases illustrating the application of related standards. It does not define smart city indicators, KPI calculation methods or a mandatory visualization format. In an AI-enabled citiverse, the guidance can inform the visualization of urban objects, sensor-derived information, city indicators and analytical outputs across different user and decision-making contexts.

▸ Standard Organization: ISO/IEC JTC 1 SC 24 | STATUS: Published (2023) | URL: https://www.iso.org/standard/80918.html

[3.4.31] IEEE P2048.121 – Standard for Service-oriented AI-based Digital Human

This draft standard specifies reference architecture and requirements for service-oriented AI-based digital humans, defining functional components, interfaces, and performance requirements for digital humans in service roles. It addresses the fragmentation of digital human implementations across different vendors and use cases. This standard can provide the framework for deploying AI digital humans as city service agents within the virtual city environment in citiverse, supporting intelligent customer service, virtual guides, and government digital assistants that provide consistent, interoperable services across different city platforms and applications.

▸ Standard Organization: IEEE CTS/MSC | STATUS: Under development (draft) | URL: https://standards.ieee.org/ieee/2048.121/

[3.4.32] IEEE 3079-2020 – Recommended Practice for Reducing the Effects of Motion Sickness in Virtual Reality Environments

IEEE 3079 provides recommended practices for reducing stimulus-to-motion sickness in virtual reality environments, including latency, field-of-view and rendering guidance. For citiverse, it supports accessible and comfortable immersive citizen services.

▸ Standard Organization: IEEE SA | URL: https://standards.ieee.org/ieee/3079/7156/

[3.4.33] IEEE P2888.6 – Standard for Holographic Visualization for Interfacing Cyber and Physical Worlds

IEEE P2888.6 defines standards for holographic visualization for interfacing cyber-physical systems. For citiverse, it supports next-generation immersive display technologies for city planning and emergency command centres.

▸ Standard Organization: IEEE SA | URL: https://standards.ieee.org/project/2888.6.html

[3.4.34] IEEE 2888.5-2024 – Standard for Virtual Training System Evaluation Methods

IEEE 2888.5 specifies evaluation methods for virtual training systems, including effectiveness, usability and learning outcome assessment. For citiverse, it supports evaluation of immersive emergency drill and urban planning simulation scenarios.

▸ Standard Organization: IEEE | STATUS: Published (2024) | URL: https://standards.ieee.org/standard/2888_5-2024.html

[3.4.35] IEEE 3333.1.4-2022 – Recommended Practice for Quality Assessment of Light Field and Holographic Display Systems

IEEE 3333.1.4 provides recommended practices for quality assessment of light field and holographic display systems. For citiverse, it informs quality metrics for 3D city model rendering and immersive visualization.

▸ Standard Organization: IEEE | STATUS: Published (2022) | URL: https://standards.ieee.org/standard/3333_1_4-2022.html

[3.4.36] IEEE P3079.1 – Standard for Motion-to-Photon Latency Measurement in Virtual Reality Environments

IEEE P3079.1 defines methods for measuring motion-to-photon latency in virtual environments, a key factor in user comfort and immersion. For citiverse, it supports SLA definition for immersive media services across city deployments.

▸ Standard Organization: IEEE | STATUS: Under development | URL: https://standards.ieee.org/project/3079.1.html

[3.4.37] IEEE P2048.2 – Standard for Metaverse: Framework

IEEE P2048.2 provides a framework standard for virtual reality systems, covering architecture, terminology and reference models. For citiverse, it offers a cross-cutting reference for virtual world construction layer standards, defining the structural baseline upon which city-scale immersive environments can be built.

▸ Standard Organization: IEEE | STATUS: Under development | URL: https://standards.ieee.org/ieee/2048.2/

Layer 5: Application Scenario Layer

[3.5.1] ITU-T Y.4205 – Requirements and reference framework for smart city operation centres

This Recommendation defines requirements and reference framework for smart city operation centres, the physical and virtual facilities where city operators monitor and manage city services. It addresses the need for standardized approaches to integrated city operations management. This standard can provide the framework for the city operations command centre within the virtual city environment in citiverse, defining how city managers monitor, analyse, and respond to city conditions through the digital twin interface.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2019-09) | URL: https://www.itu.int/rec/T-REC-Y.4205/en

[3.5.2] ITU-T Y.4215 – Requirements and common framework for crowdsourcing in smart sustainable cities

This Recommendation defines requirements and common framework for crowdsourcing in smart cities, enabling citizen participation and data contribution through digital platforms. It addresses the challenge of incorporating citizen input and distributed sensing into city management. This framework can enable citizen participation within the virtual city environment in citiverse, supporting crowdsourced issue reporting, citizen feedback, and participatory planning through the immersive platform, creating a two-way interaction channel between citizens and city government.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2020-03) | URL: https://www.itu.int/rec/T-REC-Y.4215/en

[3.5.3] ITU-T Y.4225 (formerly Y.dt-ITS) – Requirements and capability framework of digital twin for intelligent transport system

This Recommendation defines requirements and capabilities for intelligent transport system (ITS) digital twins, specifying digital twin capabilities for traffic management and transportation optimization. It addresses the need for standardized transport digital twins. This standard can provide the transport domain digital twin requirements that enable traffic simulation, prediction, and optimization within the virtual city in citiverse, supporting intelligent transport management as a core citiverse application scenario.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2024-07) | URL: https://www.itu.int/rec/T-REC-Y.4225/en

[3.5.4] ITU-T Y.4236 – Requirements for real-time event monitoring and integrated management on smart city platforms

This Recommendation specifies requirements for real-time event monitoring and integrated management on smart city platforms, enabling cross-domain event detection, correlation and response. It addresses the challenge of managing events across siloed city systems. This standard can enable real-time event monitoring within the virtual city in citiverse, supporting detection of incidents (traffic accidents, infrastructure failures, public safety events) across

multiple data sources, correlating events across domains, and enabling coordinated response through the digital twin interface.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2025-09) | URL: https://www.itu.int/rec/T-REC-Y.4236/en

[3.5.5] ITU-T Y.citiverse-reqts – Requirements of citiverse platform for smart sustainable cities and communities

This draft Recommendation specifies general functional, performance, architectural and security core requirements for citiverse platforms, serving as the top-level application framework standard for citiverse implementations. It addresses the need for a comprehensive, unified set of requirements specific to citiverse platforms. This standard can provide the top-level requirements framework that all citiverse implementations should satisfy, defining the essential capabilities that distinguish a citiverse platform from a general digital twin or metaverse platform.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study (draft May 2026) | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22087

[3.5.6] ITU-T Y.4496 – Requirements and reference architecture for a smart public health emergency information system

This Recommendation provides the requirements and reference architecture for a smart public health emergency information system that can be implemented to address current and future potential public health risks. This standard can provide the requirements and reference architecture for smart public health emergency information systems in citiverse, enabling the integration of public health data into the city digital twin for epidemic monitoring, emergency response coordination, and public health resource optimization within the virtual city environment.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2025-09) | URL: https://www.itu.int/rec/T-REC-Y.4496

[3.5.7] ITU-T Y.4233 – Information and communication technology implementation framework for smart public health emergency management in smart and sustainable cities

This Recommendation introduces an ICT implementation framework for public health emergency management within the smart city ecosystem. It explores the context of public health and associates it with the city environment. The result is a generic public health framework, which can be supported in terms of information and communication technology (ICT) implementation by smart sustainable city (SSC) technologies (e.g., Internet of Things (IoT), artificial intelligence (AI), data, apps and platforms), to deal with public health emergencies and to provide early responses to epidemics and pandemics. It then concludes with a smart public health framework, which is applied in the SSC, defining a pandemic's lifecycle and specifying when epidemic surveillance tools should be applied for dealing with the outbreaks.

▸ Standard Organization: ITU-T SG20 | STATUS: Published (2025-01) | URL: https://www.itu.int/rec/T-REC-Y.4233

[3.5.8] ITU-T Y.IECC – Framework and requirements of interactive emergency communication within citiverse

During an emergency, city governments can use AR (or various xR technologies) to provide real-time guidance to citizens through mobile apps (e.g., identifying safe evacuation routes, locating shelters, avoiding crowded spaces during outbreaks). The citiverse can host virtual town halls or press conferences or other virtual rooms where the city officials can provide updates and guidance, discuss strategies, and engage citizens in disaster-related decision-making. Moreover, alternative virtual spaces can offer separate and thematic communication spaces, based on either the target audience (i.e., civil protection stakeholders coordination compared to vulnerable communities communication) or the guiding material (i.e., how to use equipment, how to navigate to shelters, how to perform vaccination). Furthermore, SSC&C IoT infrastructure can collect real time data and integrate physical and virtual space (i.e., via positioning determination).

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q8/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23518

[3.5.9] ITU-T Y.MetaExpSys – Requirements of Metaverse Experience System for Tourist Places

This draft Recommendation addresses the challenges in the tourism sector by detailing requirements of a metaverse-enabled experience system for tourist places. The system leverages metaverse technologies, IoT sensors, and data analytics to revolutionize visitor experiences through immersive virtual tours, interactive information overlays, and real-time navigation. It also addresses accessibility issues by providing virtual access to those unable to visit physical locations. Additionally, the system supports dynamic content creation and remote collaboration, enabling stakeholders to develop and manage engaging metaverse experiences. The draft Recommendation aims to increase visitor engagement, improve accessibility, and enhance operational efficiency, contributing to the sustainable development of the tourism sector.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q2/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22103

[3.5.10] ITU-T Y.PM-FUSG – Technical framework and use cases of the power metaverse for future urban smart grids

This draft Recommendation outlines the requirements and the technical framework of the power metaverse for future urban smart grids. The Appendix presents several use cases that demonstrate how metaverse technology can be applied to optimize the power system from the perspectives of users, the grid and the power supply side. Each illustrated use case provides a detailed description of assumptions and service scenarios. These use cases contribute to the identification of the requirements of the power metaverse for future urban smart grids.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q2/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22101

[3.5.11] ITU-T Y.meta-Ed – Requirements and functional architecture for IoT-enabled multilingual and immersive education system

Equitable access to advanced digital education is essential for bridging the educational divide. Emerging technologies such as IoT, metaverse, AR and VR, are significantly transforming Teaching-Learning Materials (TLM) by enabling immersive, experiential and engaging educational environments. However, to fully realize the benefits of these innovations, there is an urgent need for standardization, particularly in the development of metaverse-enabled educational systems. Without such standards, the potential of IoT, AR/VR and metaverse platforms to support inclusive education may remain unrealized. Metaverse-based education offers the potential to transcend geographical barriers by delivering high-quality, learner-centric content, immersive and interactive learning experiences. Yet in the absence of common standards, there is a significant risk of fragmented systems, lack of interoperability, privacy and security issues and exclusion of non-dominant languages. This proposed architectural framework aims to define the functional requirements for IoT-enabled multilingual and immersive education systems.

▸ Standard Organization: ITU-T SG20 | STATUS: Under study | Question: Q8/20 | URL: https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23520

[3.5.12] ISO 37120:2018 – Sustainable cities and communities – Indicators for city services and quality of life

This standard defines indicators for measuring city service performance and quality of life, establishing standardized metrics for comparing city performance across different dimensions. It addresses inconsistent city performance measurement across different cities. These standardized city performance indicators can serve as a KPI reference framework for citiverse deployments, enabling consistent measurement of city performance, comparison across districts, and prediction of how policy changes will impact quality of life metrics.

▸ Standard Organization: ISO/TC 268 | STATUS: Published (2018-07, Ed.2) | URL: https://www.iso.org/standard/68498.html

[3.5.13] ISO 37122:2019 – Sustainable cities and communities – Indicators for smart cities

This standard defines indicators specifically for smart city performance, extending ISO 37120 with technology-focused city indicators. It addresses the need to measure smart city implementation progress and outcomes. These smart city indicators can serve as a technology-focused metrics reference for citiverse deployments, measuring the adoption, performance, and impact of digital and AI technologies across city services within the virtual city environment.

▸ Standard Organization: ISO/TC 268 | STATUS: Published (2019) | URL: https://www.iso.org/standard/69050.html

[3.5.14] ISO 37123:2019 – Sustainable cities and communities – Indicators for resilient cities

This standard defines indicators for measuring city resilience, establishing metrics for assessing city ability to absorb, recover from, and adapt to shocks and stresses. It addresses resilience measurement gaps in generic city indicator standards. These resilience indicators can serve as a metrics reference for citiverse resilience simulation scenarios, thereby enabling cities to test

resilience scenarios (flooding, earthquakes, heatwaves) within the virtual city environment and measure resilience improvements.

▸ Standard Organization: ISO/TC 268 | STATUS: Published (2019) | URL: https://www.iso.org/standard/70492.html

4 Standardization Gap Analysis

This section identifies 36 standardization gaps across the citiverse architecture, including two highest priority gaps, 27 high priority gaps, and seven medium priority gaps.

4.1 Priority assessment methodology

Standard Inventory Assessment Framework. The current edition applies four dimensions qualitatively:

- Maturity and readiness
- Citiverse relevance
- Interoperability and openness
- Governance and trust alignment.

A complete quantitative scoring matrix covering all inventory entries, including scoring evidence, weights and classification thresholds, is planned for a subsequent revision. This inventory assessment framework is distinct from the gap-priority methodology applied below. Descriptions of standards are distinguished from the report's assessment of their potential citiverse applications. Gap classifications and priorities represent the report's qualitative analysis, rather than determinations issued by the respective standards bodies.

Gap-priority methodology. Gaps are prioritized qualitatively according to their impact on interoperability, urgency for large-scale deployment, current market fragmentation, and regulatory or safety implications.

The gap-priority methodology is applied qualitatively to the 36 identified gaps.

Priority Level Definitions:

- **Highest priority**: Gaps that either block foundational cross-platform citiverse deployment or materially constrain safety-critical, multi-agency urban operations, and require immediate standardization action.
- **High priority**: Gaps required for scalable, secure, interoperable citiverse operation.
- **Medium priority**: Gaps that enhance functionality, accessibility, and sustainability.

Gap Type Definitions:

- **Normative gap**: No directly applicable normative standard exists for the identified citiverse-specific function, even where general foundational standards are available.
- **Profile/interface gap**: Relevant standards exist, but no citiverse-specific profile, interface mapping or cross-domain integration specification has been developed.

- **Conformance/implementation gap**: Standards exist, but conformance test methods, evaluation metrics, maturity models or implementation guidance are missing.

4.2 Cross-cutting standards gaps

4.2.1 Cross-cutting technical support standards gaps

Gap | [G01] Cross-domain semantic interoperability framework for citiverse

Highest Priority (IEEE 2874-2025 provides the foundational protocol/hypergraph layer; existing city semantic models such as ISO/IEC 30182:2017 and ISO/IEC 5087-1:2023 provide upper-ontology foundations, but their integrated application profiles, cross-departmental mapping rules and conformance testing within the citiverse architecture remain incomplete).

▸ GAP TYPE: Profile/interface gap (ITU-T SG20 under-study items initiated: Y.Interop-DPM, Y.MinInterop, YSTR.GenAI-Sem-Interop. These address data-processing and management, as well as minimum-interoperability building blocks; the gap lies in their integrated application profiles, cross-departmental mapping rules and conformance testing within the citiverse architecture). ETSI TC DATA defines NGSI-LD as a cross domain interoperability layer applicable to cities. It should be noted that the Minimal Interoperability Mechanisms, structured according to Recommendation ITU-T Y.4505, are being developed by OASC and specified by ETSI in EN 304 182 to help address this gap.

▸ CORE CONTENT: Top-level semantic interoperability framework spanning all layers of the citiverse stack, enabling complete interoperability across different vendor platforms, city deployments, and domains (e.g., transport, energy, public safety). It would define unified data semantics, model interfaces, and AI model invocation protocols across layers.

▸ IMPACT: Without this framework, citiverse deployments risk remaining vendor-specific silos with limited cross-platform asset exchange. Cross-domain city data may not be combined consistently, constraining cross-domain AI analytics and simulation.

Gap | [G02] End-edge-cloud collaborative computing scheduling interface and capability grading standards for city digital twins – High Priority

▸ GAP TYPE: Profile/interface gap (ITU-T SG20 work initiated: Recommendations ITU-T Y.4509, Y.4486, Y.4494).

▸ CORE CONTENT: Standardized architecture and interfaces for scheduling computation across end devices (sensors, IoT gateways), edge nodes, and cloud resources to meet citiverse latency and performance requirements for large-scale 3D rendering and real-time twin simulation scenarios.

▸ IMPACT: Without this, computing resources across the full chain cannot be dynamically allocated optimally. Immersive experiences and real-time AI inference face significant barriers to scaling to city-scale deployments; large-scale immersive scenario operation stability is difficult to assure consistently.

Gap | [G03] Unified inter-layer interface specifications for citiverse technology stacks – High Priority

- GAP TYPE: Profile/interface gap (SG20 virtual-physical integration work initiated: Recommendations ITU-T Y.4239, Y.4240).

- CORE CONTENT: Standardized interfaces between the five technology layers to enable modular, interchangeable layer implementations. Unified specification for four categories of inter-layer interfaces: data access, capability service, model interaction, and regulatory docking.

- IMPACT: Without this, cross-layer integration costs remain high and end-to-end interoperability is weakened. Scattered single-domain API specifications cannot form a unified inter-layer interaction baseline, preventing modular procurement and vendor competition.

Gap | [G04] Urban digital twin data product exchange and data space integration framework – High Priority

- GAP TYPE: Profile/interface gap (aligned with ISO/IEC 30151, ISO/IEC 30152); see also CEN-CLC/JTC 25 work on trusted data transactions and MIM3.

- CORE CONTENT: Unified framework for cross-domain data circulation covering data extraction, ownership confirmation, valuation, transactions, and data space integration. It would enable standardized extraction and exchange of digital twin data components.

- IMPACT: Without this, closed-loop data commercialization and sustainable operational models for citiverse may be difficult to achieve. Data "silos" are harder to break down, preventing the formation of a data commercialization ecosystem and constraining cross-domain data economies.

4.2.2 Governance System Standards Gaps

Gap | [G05] Unified citiverse conformance testing and certification framework – High Priority

- GAP TYPE: Conformance/implementation gap (testing frameworks exist but require citiverse-specific profiling); examples include the NGSI-LD conformance test suite and the ETSI qualification and conformance scheme for MIMs 0, 1, 2, 3, 6, 7 and 8 (MIM-Q).

- CORE CONTENT: Standardized conformance testing programme and certification framework to ensure consistent implementation and interoperability certification across citiverse platforms and components.

- IMPACT: Without this, the ability to verify that different vendors' implementations truly conform to citiverse standards is lacking, undermining trust and interoperability. Cities may find it difficult to evaluate and compare platform offerings.

Gap | [G06] AI-generated 3D city model provenance and rights expression metadata standards – High Priority

- GAP TYPE: Profile/interface gap (W3C PROV-O, C2PA standards exist; citiverse-specific profiling required).

- CORE CONTENT: Technical standards for content provenance, fingerprinting, and machine-readable rights expression metadata for AI-generated city-level 3D models, scenes, and simulation results. This would enable transparent tracking of content origin and usage rights.

- IMPACT: Without this, the authenticity, traceability, and proper attribution of AI-generated city assets may be difficult to establish reliably. Core technical bottlenecks for citiverse content ecosystem integrity and commercial operation remain unaddressed.

Gap | [G07] City-specific AI fairness assessment metrics and bias testing methodology for urban governance decision systems – High Priority (general AI bias standards exist: ISO/IEC TR 24027, TS 12791, IEEE 7003; urban-domain specialization remains a gap)

- GAP TYPE: Profile/interface gap (IEEE 7003, ISO/IEC TR 24027 exist; city-specific metrics required).

- CORE CONTENT: Scenario-specific AI ethics guidelines and bias testing frameworks for urban governance AI systems, covering algorithmic fairness assessment and compliance audit for AI-assisted urban governance decision-making.

- IMPACT: Without this, city-level AI governance lacks a dedicated basis. Existing general AI ethics standards cannot cover the specialized needs of urban governance scenarios, risking algorithmic discrimination in public resource allocation.

Gap | [G08] City-level AI algorithm registration and audit interface standards – High Priority

- GAP TYPE: Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified).

- CORE CONTENT: Technical specifications for algorithm registration, compliance audit indicators, and automated audit interfaces tailored to urban governance AI algorithms, covering scenario classification, registration procedures, and on-site verification rules.

- IMPACT: Without this, regulatory authorities cannot carry out efficient and unified algorithm supervision. General AI management system standards lack city-scenario-specific technical implementation rules.

Gap | [G09] Citiverse-specific virtual asset classification and lifecycle security – High Priority (IEEE P2048.203 in development covers blockchain interconnection security; citiverse virtual asset definition and lifecycle security remain a gap)

- GAP TYPE: Profile/interface gap (aligned with IEEE P2048.201/.202/.204).

- CORE CONTENT: Unified security management for blockchain-based digital assets covering accounts, data, and commodity circulation. It would address the complete lifecycle of circulating digital commodities in a blockchain-based metaverse.

- IMPACT: Without this, the trust framework for the citiverse virtual economy may be difficult to establish. Digital commodities (virtual property, digital twin licences, AI-generated content) may be difficult to issue, trade and transfer securely, increasing fraud risks and making regulatory compliance difficult to assure.

Gap | [G10] Interoperability framework of digital public infrastructure (DPI) for smart cities – High Priority

- GAP TYPE: Profile/interface gap (SG20 DPI work initiated: Y.sf-dpi-ssc, Y.diwi-reqts, YSTR. DPI-BP).

- CORE CONTENT: Framework for interoperability of digital public infrastructure (DPI) components (digital identity, data exchange, payments) that underpin citiverse platforms, enabling consistent DPI integration across city services and virtual environments.

- IMPACT: Without this, DPI components across different cities and regions remain fragmented, preventing seamless cross-jurisdiction citiverse services. Citizens cannot use a single digital identity across different city citiverse deployments.

Gap | [G11] Trustworthiness evaluation specifications for IoT and digital twin systems in smart cities – High Priority

- GAP TYPE: Conformance/implementation gap (aligned with the proposed ITU-T Y.Sup. trust-SG20).

- CORE CONTENT: Guidelines for trust technologies in IoT, digital twins, and smart sustainable cities, providing a systematic framework for trustworthiness assessment and governance of citiverse systems.

- IMPACT: Without this, the credibility of citiverse systems may be difficult to assure systematically. Citizen and government trust in virtual city environments remains a barrier to adoption.

Gap | [G12] Green computing metrics for citiverse-specific infrastructure (rendering, digital twin runtime, edge computing) – Medium Priority (ISO 14064 and ITU-T L-series provide general carbon/energy baselines; citiverse-specific green computing metrics remain a gap)

- GAP TYPE: Conformance/implementation gap (ISO/IEC 30134 provides data-centre energy metrics; citiverse-specific metrics for rendering, digital-twin runtime and edge infrastructure required).

- CORE CONTENT: Metrics for measuring and optimising the environmental impact of running large-scale citiverse infrastructure, addressing the unique high energy consumption characteristics of 3D twin systems.

- IMPACT: Without this, the environmental sustainability of citiverse may be difficult to measure and optimize. General low-carbon standards may not be sufficient for the unique computing energy consumption characteristics of 3D twin systems.

4.3 Vertical technology stack layer gaps

4.3.1 Layer 1: Network & connectivity layer gaps

Gap | [G13] Immersive media SLA and QoS assurance specifications for city-scale multi-user citiverse scenarios – High Priority

- GAP TYPE: Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified).

- CORE CONTENT: Standardized SLA definitions and QoS mechanisms tailored to immersive media traffic characteristics for city-scale XR interaction and 3D streaming scenarios.

- IMPACT: Without this, core network foundation for immersive experience is lacking. General XR QoS specifications exist, but lack specialized SLA details for city-scale large-space, multi-user concurrent scenarios. Network operators cannot guarantee service quality for citiverse immersive applications.

Gap | [G14] Computing power network-aware scheduling interface and routing signalling specifications for immersive urban services – High Priority

- GAP TYPE: Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified).

- CORE CONTENT: Network routing that is aware of computing resource availability for optimal edge-cloud task placement, enabling dynamic scheduling of computing power resources.

- IMPACT: Without this, end-edge-cloud collaborative efficiency is compromised. Computing resource utilization is low, and large-scale immersive scenario operation stability is difficult to assure consistently.

Gap | [G15] Citiverse profile and interoperability mapping for mobile spatial anchor and digital asset services – High Priority

- GAP TYPE: Profile/interface gap (aligned with 3GPP TS 23.437, TS 23.438).

- CORE CONTENT: Citiverse-specific refinement of mobile spatial anchor and digital asset services for city-scale deployments, enabling consistent spatial positioning and digital asset management across mobile devices and platforms.

- IMPACT: Without this, ubiquitous mobile access to citiverse services across the city is constrained. Cross-platform AR spatial positioning may be difficult to unify; mobile virtual identities and assets face barriers to interoperating across different citiverse instances.

4.3.2 Layer 2: Digital infrastructure & platform layer gaps

Gap | [G16] City digital infrastructure platform capability assessment and maturity grading – High Priority

- GAP TYPE: Conformance/implementation gap (SG20 maturity-model work under revision: Recommendation ITU-T Y.4904-Rev).

▸ CORE CONTENT: Standardized capability maturity model for assessing and grading city digital infrastructure platforms (including digital twin platforms and DPI), covering spatial capability, AI integration, interoperability, and other dedicated dimensions.

▸ IMPACT: Without this, core basis for platform selection and acceptance is lacking. General digital twin maturity models are reusable, but specialized platform capability assessment specifications for citiverse scenarios are still needed. Cities cannot make informed procurement decisions.

Gap | [G17] Digital twin federation and interconnection interface – High Priority

▸ GAP TYPE: Profile/interface gap (aligned with Recommendations ITU-T Y.4224, Y.4489, Y.4605).

▸ CORE CONTENT: Existing standards define federation requirements (Recommendation ITU-T Y.4224), reference architecture with functional entities and interfaces (Recommendation ITU-T Y.4489), and information-exchange models with message structures (Recommendation ITU-T Y.4605). NGSI-LD defines federation and distribution mechanisms applicable to city deployments. However, a complete implementation profile covering protocol bindings, API schemas, conformance test methods, and cross-vendor deployment guidance for city-scale digital twin federation remains unavailable.

▸ IMPACT: Without this, core prerequisite for cross-city interconnection and federated operation is missing. District, departmental, and domain-specific digital twins face barriers to federating into the unified city-scale citiverse.

Gap | [G18] AI model interoperability and deployment interface specifications for city digital twin platforms – High Priority

▸ GAP TYPE: Profile/interface gap (SG20 AI model deployment metadata work under study).

▸ CORE CONTENT: Framework for orchestrating multiple AI models across different city domains within the digital twin platform, enabling coordinated AI inference and decision-making across city services.

▸ IMPACT: Without this, AI models across different domains operate in isolation, preventing cross-domain intelligence. The full potential of AI-enabled citiverse may be difficult to realize.

Gap | [G19] Urban digital twin system fidelity metrics and assessment – High Priority

▸ GAP TYPE: Conformance/implementation gap (ISO/IEC TR 30138 under development; SG20 visualization work under study).

▸ CORE CONTENT: Citiverse-specific fidelity metrics including similarity, resolution, synchronization latency, and LoD classification for city-scale twins, establishing a credibility baseline for the correspondence between twin systems and the physical world.

▸ IMPACT: Without this, there is no unified measurement baseline for assessing digital twin accuracy. The credibility of simulation results for urban governance may be difficult to verify consistently, affecting citiverse reliability in governance-level decision-making.

Gap | [G20] Full-lifecycle data governance specifications for city digital twin platforms – Medium Priority

- GAP TYPE: Conformance/implementation gap (SG20 data processing/governance work ongoing); MIM-Q includes evidence rules for data-quality assertions.

- CORE CONTENT: End-to-end data governance processes covering data quality, lineage, retention, and archiving for city-level digital twin platforms.

- IMPACT: Without this, internal data management level of platforms is compromised. Data consistency, traceability, and availability within the platform is difficult to assure consistently, affecting data assetization and value release.

4.3.3 Layer 3: Data & analytics layer gaps

Gap | [G21] Cross-domain urban spatiotemporal data fusion output format and quality assessment standards – High Priority

- GAP TYPE: Profile/interface gap (SG20 data fusion work under study: Y.AIoT-dfs-arc, Recommendation ITU-T Y.4499).

- CORE CONTENT: Standardized output formats, semantic mapping rules and quality assessment methods for fusing spatiotemporal data across different city domains, enabling unified representation of city data across the digital twin; NGSI-LD information model and API allows integration, query and notification related to spatiotemporal information.

- IMPACT: Without this, the full value of multidomain city data may remain difficult to unlock. Cross-domain AI analytics and simulation remain difficult due to fragmented data representation.

Gap | [G22] Urban spatial foundation model evaluation metrics and training data governance specifications – High Priority

- GAP TYPE: Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified).

- CORE CONTENT: Standards for adapting general AI foundation models to specific urban governance scenarios, covering training data compliance and spatial reasoning explainability requirements.

- IMPACT: Without this, foundation models and urban spatial integration lack specialized specification guidance. Generated content compliance and accuracy are unassured; cities cannot reliably deploy foundation models for governance applications.

Gap | [G23] Cross-modal sensor data fusion quality validation standards – Medium Priority

- GAP TYPE: Conformance/implementation gap (SG20 multisensor fusion work exists: Recommendations ITU-T Y.4487 and ITU-T Y.4604).

- CORE CONTENT: Standardized quality metrics and automated validation processes for cross-modal fusion of multisource heterogeneous sensor data (cameras, LiDAR, radar, environmental sensors) in urban scenarios.

- IMPACT: Without this, manual verification of massive urban sensing data is inefficient. The accuracy and timeliness of the underlying data input to the twin system is difficult to assure consistently, affecting all upstream citiverse capabilities.

4.3.4 Layer 4: Virtual world construction layer gaps

Gap | [G24] City-scale 3D scene streaming protocol and data format standards – High Priority

- GAP TYPE: Profile/interface gap (component standards exist – OGC 3D Tiles, MPEG immersive media, glTF, 3GPP XR streaming, WebXR – but no integrated citiverse-specific city-scale scene streaming profile combining spatial tiling, dynamic updates, adaptive delivery and cross-platform conformance).

- CORE CONTENT: Optimized streaming protocols and standards for city-scale 3D scenes that adapt to device capability and network conditions, enabling efficient delivery of massive 3D city models.

- IMPACT: Without this, rendering city-scale 3D models on client devices with limited memory and bandwidth is challenging. User experience across different devices and network conditions is inconsistent.

Gap | [G25] Cross-platform virtual identity interoperability – High Priority

- GAP TYPE: Profile/interface gap (IEEE 3812.1-2023 published, P3812.2 in development; cross-platform identity roaming remains unresolved).

- CORE CONTENT: Standards enabling avatars, virtual identities, and permissions to move seamlessly across different virtual environments and platforms.

- IMPACT: Without this, unified cross-platform user experience is missing. Avatars and virtual identities may be difficult to port between citiverse platforms.

Gap | [G26] Immersive-scenario accessibility – Medium Priority

- GAP TYPE: Conformance/implementation gap (Recommendation ITU-T Y.4246 already specifies accessibility requirements for metaverse services supporting IoT; W3C WCAG and EN 301 549 cover Web 2D. The gap lies in XR test methods, cross-device implementation profiles and application-level conformance, not in the absence of immersive accessibility requirements).

- CORE CONTENT: Verifiable XR test methods, cross-device implementation profiles and application-level conformance assessment for immersive services, building on Recommendation ITU-T Y.4246 accessibility requirements and extending WCAG/EN 301 549 coverage to haptic, spatial-audio and inclusive interaction in XR-based citiverse services.

- IMPACT: Without agreed XR test methods and cross-device implementation profiles, conformance to immersive accessibility requirements cannot be verified consistently across platforms, risking uneven access for persons with disabilities and weakening inclusive-governance commitments.

Gap | [G27] Urban-service capability assessment for AI-driven digital humans (dialogue, multilingual, public service knowledge) – High Priority

- GAP TYPE: Conformance/implementation gap (IEEE 3079.3-2023 covers visual quality assessment; urban service capability assessment remains a gap).

- CORE CONTENT: Citiverse-specific capability classification, interface standards, and performance assessment for service-oriented AI digital humans deployed in urban public service roles.

- IMPACT: Without this, digital human applications in urban public services remain fragmented. There is no unified assessment or interoperability baseline across vendors, leading to duplicated development and high integration costs.

Gap | [G28] AI-generated city virtual content quality, trustworthiness and compliance validation standards – High Priority

- GAP TYPE: Conformance/implementation gap (SG20 visualization precision work partially addresses).

- CORE CONTENT: Validation standards for authenticity, spatial accuracy, and compliance of AI-generated citiverse urban scene content, covering geometric accuracy, semantic consistency, and spatial topology correctness.

- IMPACT: Without this, generated content spatial accuracy and compliance risks may be difficult to manage. AI-generated urban scenes have risks of spatial distortion and semantic deviation; they may not be suitable for direct use for governance-level decision-making simulation, restricting the value of generative AI in citiverse.

Gap | [G29] VR/AR/MR integration reference model for citiverse immersive urban services – Medium Priority

- GAP TYPE: Conformance/implementation gap (aligned with ISO/IEC NP 23620-2).

- CORE CONTENT: Reference model for integrating VR, AR, and MR systems within citiverse, providing a standardized framework for immersive technology integration across the virtual city environment.

- IMPACT: Without this, different immersive technologies in citiverse integration are highly fragmented. VR/AR/MR systems cannot be consistently integrated, limiting the potential for rich, diverse immersive experiences in the virtual city.

Gap | [G30] OGC 3D Tiles 2.0 and 3D city model interoperability and migration – Medium Priority

- GAP TYPE: Profile/interface gap (OGC 3D Tiles 1.x published; 2.0 is a proposed community-standard work item, not yet an approved standard).

- CORE CONTENT: Standards and guidelines for migrating from 3D Tiles 1.x to 2.0, and for ensuring interoperability between 3D Tiles 2.0 and other 3D city model formats (CityGML, I3S), enabling smooth transition of city 3D data assets.

▸ IMPACT: Cities with existing 3D Tiles 1.x deployments face unclear migration paths if 2.0 is adopted. The proposed 2.0 features (glTF 2.1 integration, voxels, temporal dynamic tiles) would require standardized migration and interoperability approaches to prevent fragmentation of 3D city data assets.

4.3.5 Layer 5: Application scenario layer gaps

Gap | [G31] Urban planning immersive simulation and decision support scenario standards – High Priority

▸ GAP TYPE: Normative gap (SG20 simulation work under study).

▸ CORE CONTENT: Standardized scenario definitions and validation methods for digital twin urban planning simulations, covering immersive collaborative planning simulation, multistakeholder review, and citizen participation channels.

▸ IMPACT: Without this, core deployment scenario standards are missing. This directly determines the value and uptake of technology deployment, and prevents cities from comparing or reusing planning simulation results.

Gap | [G32] Multisystem interoperability and linkage for emergency response (command, IoT sensing, digital twin simulation, communication) – Highest Priority

▸ GAP TYPE: Profile/interface gap (IEEE 2888.4-2023 covers VR disaster training architecture; SG20 metaverse emergency work under study; multisystem linkage remains a gap).

▸ CORE CONTENT: Standards for multiagency emergency response coordination through digital twin platforms, covering immersive emergency drill and collaborative response simulation.

▸ IMPACT: Without this, coordinated use of citiverse capabilities in emergency response may remain fragmented across agencies and systems, limiting their effectiveness in safety-critical scenarios.

Gap | [G33] Intelligent transportation real-time optimization and signal linkage – High Priority

▸ GAP TYPE: Normative gap (Recommendation ITU-T Y.4225 provides a high-level ITS digital twin framework, but citiverse-specific normative technical requirements for real-time optimization algorithms, signal-control interfaces and multimodal predictive analytics remain underdeveloped).

▸ CORE CONTENT: Standards for real-time traffic optimization and signal control through citiverse digital twins, supporting multimodal transport twin fusion and simulation and predictive analysis.

▸ IMPACT: Without this, core deployment scenario lacks refined specifications for immersive simulation and collaborative dispatch. The full potential of citiverse for intelligent transportation may be difficult to realize.

Gap | [G34] Citizen immersive government service interface specification – High Priority

- GAP TYPE: Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified).

- CORE CONTENT: Standardized interface patterns for delivering government services through immersive environments, supporting virtual government hall specifications and accessible public service interactions.

- IMPACT: Without this, digital transformation of government services through citiverse is hampered. Universal value demonstration is limited; service quality across different city citiverse deployments is inconsistent.

Gap | [G35] Cross-departmental service collaboration interface and data exchange specifications for citiverse platforms – High Priority

- GAP TYPE: Profile/interface gap (SG20 multiparty collaboration work under study: Y.IoT-CMP-VR and Y.Interop-DPM).

- CORE CONTENT: Standards for orchestrating cross-departmental workflows through the citiverse platform, enabling coordinated service delivery across city departments.

- IMPACT: Without this, the value of citiverse as cross-domain coordination platform is limited. Government departments remain in silos even within the virtual city environment.

Gap | [G36] Human-machine collaboration interface and handover protocol standards for urban AI-assisted governance – Medium Priority

- GAP TYPE: Profile/interface gap (SG20 human-AI collaboration work under study: Y.IoT-HAC).

- CORE CONTENT: Clear boundaries between AI automated decisions and human decision-making, with standardized handover protocols for AI-assisted urban governance scenarios.

- IMPACT: Without this, the boundary between AI auxiliary decision-making and human final decision-making is unclear. There is a lack of standardized intervention paths and responsibility definition for decision-making risks.

4.4 Gap priority summary

Table 4: Gap Priority Summary

Priority	Count	Description
Highest Priority	2	Block foundational cross-platform citiverse deployment or materially constrain safety-critical multi-agency urban operations; should be addressed in the next standardization work-programme cycle.
High Priority	27	Required for scalable, secure, interoperable citiverse operation; mix of normative, profile/interface and conformance/implementation gaps.
Medium Priority	7	Enhance functionality, accessibility and sustainability; mostly conformance/implementation and profile gaps.

Table 4: Gap Priority Summary (continued)

Priority	Count	Description
Total	36	–

5 Conclusions and Next Steps

This report maps the AI-enabled citiverse standardization landscape through a five-layer technology stack, two cross-cutting dimensions and two cross-layer support modules. Within this architecture, it catalogues 201 entries and, through a qualitative gap-priority assessment covering interoperability impact, deployment urgency, market fragmentation, and regulatory and safety implications, identifies 36 standardization gaps.

Three conclusions stand out.

First, the standards base is substantial but uneven. Foundations are well established at the network and data layers, and good at the platform layer. At the virtual world construction layer, underlying coding is mature but interaction interoperability is insufficient. At the application scenario layer, dedicated standards are severely lacking. Standardization is strongest where the technology is generic and weakest where cities actually apply it.

Second, most gaps call for adaptation rather than invention. 34 of the 36 gaps are profile/interface or conformance/implementation gaps: general standards exist, but they lack citiverse-specific interfaces, profiles, test methods or implementation guidance for city-scale deployment. Only 2 gaps, urban planning immersive simulation and decision support scenario standards and intelligent transportation real-time optimization and signal linkage, are normative gaps.

Third, two gaps carry the highest priority. Cross-domain semantic interoperability is the fundamental blocker for large-scale, cross-platform deployment, because without it, deployments remain vendor-specific silos and city data cannot be integrated consistently. Multisystem interoperability for emergency response is an essential scenario affecting citizen safety. Urban planning immersive simulation, while strategically important, is treated as a high-priority application-level gap rather than a deployment blocker. Governance and trust gaps cut across all layers and will affect whether cities can procure, compare and rely on citiverse systems.

The current edition has limits. The assessment is qualitative, and a full scoring matrix, adoption-evidence assessment and overlap and conflict analysis are planned for later updates. Where overlaps exist, for example between 3GPP SEAL and IEEE 2874 in spatial anchoring, both standards are included and reconciliation is deferred. Gap priorities are the report's own analysis, not determinations by standards bodies.

Based on these findings, five next steps are suggested.

1) **Initiate work on the priority gaps**. Relevant SDOs, such as ITU-T Study Group 20, are encouraged to start, coordinate or strengthen work on the two highest-priority gaps through new work items, revisions, profiles or implementation guidance. For the 27 high-priority gaps, it is advisable to distinguish between areas needing refinement of existing foundational standards and areas needing citiverse-specific profiles, interface mappings, conformance specifications or implementation guidance. This includes coordination

between ITU-T SG20 and ETSI TC DATA to keep Recommendation ITU-T Y.4505 and ETSI EN 304 182 aligned.

2) **Adapt existing standards to urban scenarios**. When revising existing standards, SDOs are encouraged to account for citiverse use cases and to consider application-specific annexes that provide parameter adaptation and use-case guidance, rather than developing new standards from scratch. This can shorten development time and lower the barrier to adoption.

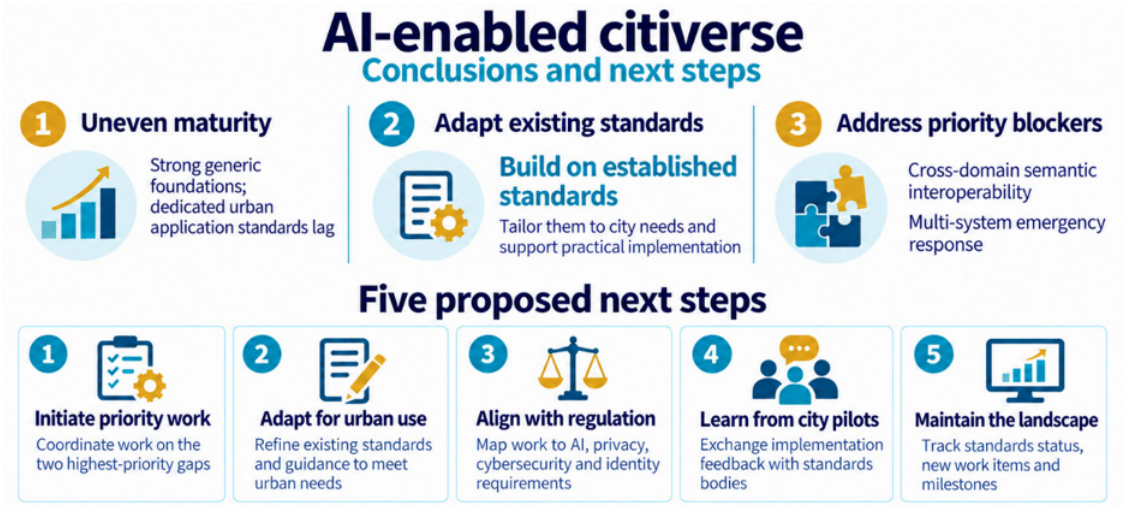
3) **Align with regulation**. Citiverse standardization should stay aligned with applicable regional frameworks, such as the EU AI Act, GDPR, NIS2 and emerging digital identity regulation, and equivalent frameworks in other regions. A standing mapping between work items and regulatory requirements should be maintained as part of the living document.

4) **Connect city pilots and standards development**. Cities deploying or planning pilots are encouraged to document the barriers they meet when applying existing standards and to channel this feedback to the relevant SDOs, including ITU-T Study Group 20. Standards developers are invited to seek input from pilot cities during draft consultation. Interoperability test events with pilot cities, such as ETSI Plugtests and collaboration through the Global Citiverse Initiative, can provide valuable opportunities to facilitate this engagement and support the development of standards that respond to cities' needs.

5) **Maintain the landscape annually**. The existing reporting team should keep the landscape as a living document and, where feasible, publish updates annually reflecting changes in standards status, new work items and publication milestones, without creating new institutional structures.

The standardization of the AI-enabled citiverse is a long-term and dynamic endeavour that requires sustained, open and pragmatic collaboration from stakeholders worldwide. The landscape will be updated annually, and contributions, comments and supplementary information from all concerned parties are welcome.

Figure 3: Conclusions and next steps



6 About the Discovering the Citiverse – Global Initiative on AI, Digital Twins and Virtual Worlds

Launched by ITU, UNICC, and Digital Dubai, the Discovering the Citiverse – Global Initiative on AI, Digital Twins and Virtual Worlds is a multistakeholder platform dedicated to shaping the next generation of the AI-enabled citiverse. A global coalition of more than 70 partners including cities, governments, UN agencies, standards bodies, industry, academia, and civil society, the Initiative is helping to build the governance architecture of the AI-enabled citiverse. The Initiative seeks to ensure that these technologies evolve in ways that are inclusive, interoperable, and human-centric, while contributing to the implementation of the Pact for the Future and its Global Digital Compact.

Serving as a neutral and action-oriented platform, it brings together public and private stakeholders to advance the responsible development and deployment of the AI-enabled citiverse. It provides blueprints, capacity-building resources, and a global peer network to support cities in moving from vision to scaled implementation.

The Initiative advances its mission through three strategic pillars, supported by dedicated tracks addressing key challenges and opportunities. This structure enables high-level global guidance and practical implementation across cities worldwide.

For more information, please visit: https://www.itu.int/citiverse/.



Meet the Supporters

Supporters are organizations that have expressed endorsement of the Initiative and actively participate in its activities. This includes, but is not limited to, participation in tracks, contribution of use cases, co-organization of events, provision of expertise, or public advocacy of the Initiative.




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Appendix 1: Core Standards Inventory

Number	Standard Reference & Title	Module	URL
1.1	ITU-T Y.4200 – Requirements for the interoperability of smart city platforms	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4200/en
1.2	ITU-T Y.4113 – Requirements of the network for the Internet of things	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4113/en
1.3	ITU-T Y.4201 – High-level requirements and reference framework of smart city platforms	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4201-201802-I
1.4	ITU-T Y.4464 – Framework of data sharing in IoT-based smart city platforms	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4464/en
1.5	ITU-T Y.4505 – Minimal Interoperability Mechanisms for smart and sustainable cities and communities	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4505/en
1.6	ITU-T Y.4560 – Blockchain-based data exchange and sharing for supporting Internet of things and smart cities and communities	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4560-202303-P/en
1.7	ITU-T Y.4561 – Blockchain-based Data Management for supporting Internet of things and smart cities and communities	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4561/en
1.8	ITU-T Y.4812 – Interoperability of the identity of Internet of things devices across metaverse platforms	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4812/en
1.9	ITU-T Y.4240 – Interoperability for integrating virtual and physical worlds through digital twins in the metaverse	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4240/en
1.10	ITU-T Y.4246 – Accessibility requirements for metaverse services supporting Internet of things	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4246/en
1.11	ITU-T Y.4489 – Reference architecture of digital twin federation in smart cities and communities	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4489/en
1.12	ITU-T Y.4605 – Information exchange model for digital twin federation in smart cities and communities	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4605/en
1.13	ITU-T Y.4805 – Identifier service requirements for the interoperability of Smart City applications	Cross-layer Technical Foundation	https://www.itu.int/rec/T-REC-Y.4805/en
1.14	ITU-T Y.metaID – Framework and requirements for identity visualization in and across metaverse	Cross-layer Technical Foundation	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22081

(continued)

Number	Standard Reference & Title	Module	URL
1.15	ITU-T Y.Interop-DPM – Integrated Interoperability framework for Data Processing and Management	Cross-layer Technical Foundation	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22028
1.16	ITU-T Y.citiverse-ai-reqts – Requirements for AI-enabled interoperability in citiverse	Cross-layer Technical Foundation	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23498
1.17	ISO/IEC 30141:2024 – Internet of Things (IoT) – Reference Architecture	Cross-layer Technical Foundation	https://www.iso.org/standard/88800.html
1.18	ISO/IEC 21823-1:2019 – Internet of things (IoT) – Interoperability for IoT systems – Part 1: Framework	Cross-layer Technical Foundation	https://www.iso.org/standard/71885.html
1.19	ISO/IEC 21823-2:2020 – Internet of things (IoT) – Interoperability for IoT systems – Part 2: Transport interoperability	Cross-layer Technical Foundation	https://www.iso.org/standard/80986.html
1.20	ISO/IEC 21823-3:2021 – Internet of things (IoT) – Interoperability for IoT systems – Part 3: Semantic interoperability	Cross-layer Technical Foundation	https://www.iso.org/standard/83752.html
1.21	ISO/IEC 21823-4:2022 – Internet of things (IoT) – Interoperability for IoT systems – Part 4: Syntactic interoperability	Cross-layer Technical Foundation	https://www.iso.org/standard/84773.html
1.22	ISO/IEC 21823-5 – Internet of things (IoT) – Interoperability for IoT systems – Part 5: Behavioural and policy interoperability	Cross-layer Technical Foundation	https://www.iso.org/standard/83852.html
1.23	oneM2M TS-0001 – Functional Architecture	Cross-layer Technical Foundation	https://www.onem2m.org/technical/published-specifications
1.24	ETSI GS MEC 003 – Multi-access Edge Computing (MEC); Framework and Reference Architecture	Cross-layer Technical Foundation	https://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/
1.25	ETSI GS MEC 012 – MEC; Radio Network Information API	Cross-layer Technical Foundation	https://www.etsi.org/deliver/etsi_gs/MEC/001_099/012/
1.26	OGC SensorThings API – Part 1: Sensing	Cross-layer Technical Foundation	https://www.ogc.org/standard/sensorthings/
1.27	OGC API – Features	Cross-layer Technical Foundation	https://ogcapi.ogc.org/features/

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Number	Standard Reference & Title	Module	URL
1.28	OGC API – Processes	Cross-layer Technical Foundation	https://ogcapi.ogc.org/processes/
1.29	ISO 19177-1:2026 – Geographic information – Geospatial application programming interface (API) for tiles – Part 1: Core	Cross-layer Technical Foundation	https://www.iso.org/standard/88296.html
1.30	ISO/TR 23262:2021 – GIS (geospatial) / BIM interoperability	Cross-layer Technical Foundation	https://www.iso.org/standard/78821.html
1.31	ETSI TS 104 175 – Data Solutions (DATA); NGSI-LD Core API	Cross-layer Technical Foundation	https://www.etsi.org/deliver/etsi_ts/104100_104199/104175/01.01.01_60/ts_104175v010101p.pdf
1.32	ETSI TS 104 178 – Data Solutions (DATA); NGSI-LD Information Model	Cross-layer Technical Foundation	https://www.etsi.org/deliver/etsi_ts/104100_104199/104178/01.01.01_60/ts_104178v010101p.pdf
1.33	ETSI EN 304 181 – Data Solutions (DATA); AI-based EU Local Digital Twin reference architecture	Cross-layer Technical Foundation	https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=74885
1.34	ETSI EN 304 182 – MIM key specifications Smart City platforms and Local Digital Twins	Cross-layer Technical Foundation	https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=74886
1.35	IDS-RAM 4.0 – International Data Spaces Reference Architecture Model	Cross-layer Technical Foundation	https://internationaldataspaces.org/ram/
1.36	IEEE 2874-2025 – Standard for Spatial Web Protocol, Architecture and Governance	Cross-layer Technical Foundation	https://standards.ieee.org/ieee/2874/10375/
1.37	ISO/IEC 5087 series – Information technology – City data model	Cross-layer Technical Foundation	https://www.iso.org/standard/80718.html
1.38	ISO 19111 / 19115 / 19157 – Geographic information foundations	Cross-layer Technical Foundation	https://www.iso.org/committee/54914.html
1.39	IEC 62443 series – Industrial automation and control systems security	Cross-layer Technical Foundation	https://webstore.iec.ch/en/publication/7033

(continued)

Number	Standard Reference & Title	Module	URL
1.40	IEEE 2888.1-2023 / 2888.2-2023 / 2888.4-2023 – Sensor/actuator interfaces and VR disaster response	Cross-layer Technical Foundation	https://standards.ieee.org/standard/2888_1-2023.html
1.41	IEEE 3079.3-2023 – Framework for Evaluating the Quality of Digital Humans	Cross-layer Technical Foundation	https://standards.ieee.org/ieee/3079.3/10893/
1.42	NIST AI Risk Management Framework (AI RMF 1.0)	Cross-layer Technical Foundation	https://www.nist.gov/itl/ai-risk-management-framework
1.43	W3C Web of Things (WoT) Architecture	Cross-layer Technical Foundation	https://www.w3.org/TR/wot-architecture/
1.44	OGC GeoPose 1.0 – Geographic information – GeoPose – Part 1: A geospatial pose standard for XR	Cross-layer Technical Foundation	https://www.ogc.org/standards/geopose/
1.45	OGC API – Moving Features 1.0	Cross-layer Technical Foundation	https://www.ogc.org/standards/ogc-api-moving-features/
1.46	OGC API – Environmental Data Retrieval	Cross-layer Technical Foundation	https://ogcapi.ogc.org/edr/
1.47	ISO 19650-1:2018 / 19650-2:2018 – Organization and digitization of information about buildings and civil engineering works – BIM information management	Cross-layer Technical Foundation	https://www.iso.org/standard/68078.html
1.48	ISO/IEC 30182:2017 – Smart city concept model – Guidance for establishing a model for data interoperability	Cross-layer Technical Foundation	https://www.iso.org/standard/53302.html
1.49	ISO/IEC 30146:2019 – Smart city ICT indicators	Cross-layer Technical Foundation	https://www.iso.org/standard/70302.html
1.50	ISO/IEC 30145-1:2021 / 30145-2:2020 / 30145-3:2020 – Smart city ICT reference framework	Cross-layer Technical Foundation	https://www.iso.org/standard/76371.html
1.51	W3C PROV-O – PROV Ontology: Provenance Data Model and Ontology	Cross-layer Technical Foundation	https://www.w3.org/TR/prov-o/
1.52	IEEE 2413-2019 – Standard for an Architecture Framework for the Internet of Things	Cross-layer Technical Foundation	https://standards.ieee.org/standard/2413-2019.html
2.1	ITU-T Y.4900 – Overview of key performance indicators in smart sustainable cities	Governance System	https://www.itu.int/rec/T-REC-Y.4900-201608-I/en

(continued)

Number	Standard Reference & Title	Module	URL
2.2	ITU-T X.2012 – Security measures for digital twin system of smart cities	Governance System	https://www.itu.int/rec/T-REC-X.2012-202410-I/en
2.3	ITU-T Y.4806 – Security capabilities supporting safety of the Internet of things	Governance System	https://www.itu.int/rec/T-REC-Y.4806/en
2.4	ITU-T Y.SSC-AISE-sec – Security capabilities and guidelines for artificial intelligence service exposure for smart sustainable cities	Governance System	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23994
2.5	ITU-T Y.diwi-reqts – Requirements of digital identity wallet interoperability for smart city services	Governance System	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23496
2.6	ITU-T FG-MV-034 – Metaverse terminology and definitions	Governance System	https://www.itu.int/en/ITU-T/focusgroups/mv/Pages/default.aspx
2.7	ETSI TS 104 179 – Data Solutions (DATA); NGSI-LD Provenance and Integrity	Governance System	https://www.etsi.org/deliver/etsi_ts/104100_104199/104179/01.01.01_60/ts_104179v010101p.pdf
2.8	ETSI TS 104 312 – Data Solutions (DATA); Data Quality Metrics: Measurement Methodologies and Assessment Procedures	Governance System	https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=78853
2.9	ETSI EN 304 311 – Data Solutions (DATA); Data Quality Metrics: Framework and Definitions	Governance System	https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=78851
2.10	ISO/IEC 27001:2022 – Information security, cybersecurity and privacy protection – Information security management systems – Requirements	Governance System	https://www.iso.org/standard/27001
2.11	ISO/IEC 27701:2025 – Information security, cybersecurity and privacy protection – Privacy information management systems – Requirements and guidance	Governance System	https://www.iso.org/standard/27701
2.12	ISO/IEC 38505-1:2017 – Information technology – Governance of IT – Governance of data – Part 1: Application of ISO/IEC 38500 to the governance of data	Governance System	https://www.iso.org/standard/56639.html

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Number	Standard Reference & Title	Module	URL
2.13	ISO/IEC 42001:2023 – Information technology – Artificial intelligence – Management system	Governance System	https://www.iso.org/standard/81230.html
2.14	ISO/IEC 23894:2023 – Information technology – Artificial intelligence – Guidance on risk management	Governance System	https://www.iso.org/standard/77304.html
2.15	IEEE 7000-2021 – Standard Model Process for Addressing Ethical Concerns during System Design	Governance System	https://standards.ieee.org/standard/7000-2021.html
2.16	IEEE P7016 – Standard for Ethically Aligned Design and Operation of Metaverse Systems	Governance System	https://standards.ieee.org/ieee/7016/
2.17	IEEE 3812.1-2023 – IEEE Standard for General Requirements for Identity Framework for Metaverse	Governance System	https://standards.ieee.org/ieee/3812.1/
2.18	IEEE P2048 – Standard for Metaverse: Terminology, Definitions, and Taxonomy	Governance System	https://standards.ieee.org/ieee/2048/11169/
2.19	IEEE P2048.201 – Security Specification of Blockchain-based Metaverse Accounts	Governance System	https://standards.ieee.org/ieee/2048.201/
2.20	IEEE P2048.202 – Security Specifications of Blockchain-Based Metaverse Data	Governance System	https://standards.ieee.org/ieee/2048.202/
2.21	W3C Decentralized Identifiers (DIDs) v1.0	Governance System	https://www.w3.org/TR/did-core/
2.22	W3C Verifiable Credentials Data Model v2.0	Governance System	https://www.w3.org/TR/vc-data-model-2.0/
2.23	ISO/IEC 5259-1:2024 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 1: Overview, terminology and examples	Governance System	https://www.iso.org/standard/81088.html
2.24	ISO/IEC 5259-2:2024 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 2: Data quality measures	Governance System	https://www.iso.org/standard/81860.html
2.25	ISO/IEC 5259-3:2024 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 3: Data quality management requirements and guidance	Governance System	https://www.iso.org/standard/81861.html

(continued)

Number	Standard Reference & Title	Module	URL
2.26	ISO/IEC 5259-4:2024 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 4: Data quality process framework	Governance System	https://www.iso.org/standard/81862.html
2.27	ISO/IEC 5259-5:2025 – Artificial intelligence – Data quality for analytics and machine learning (ML) – Part 5: Data quality governance framework	Governance System	https://www.iso.org/standard/81863.html
2.28	ISO/IEC 5338:2023 – Information technology – Artificial intelligence – AI system lifecycle processes	Governance System	https://www.iso.org/standard/81118.html
2.29	ISO/IEC 42005:2025 – Information technology – Artificial intelligence – AI system impact assessment	Governance System	https://www.iso.org/standard/42005
2.30	ISO/IEC 42006:2025 – Information technology – Artificial intelligence – Requirements for bodies providing audit and certification of AI management systems	Governance System	https://www.iso.org/standard/42006
2.31	ISO/IEC 12792:2025 – Information technology – Artificial intelligence – Transparency taxonomy	Governance System	https://www.iso.org/standard/84111.html
2.32	ISO/IEC 38507:2022 – Information technology – Governance of IT – Governance implications of the use of artificial intelligence by organizations	Governance System	https://www.iso.org/standard/80007.html
2.33	ISO/IEC 40500:2025 – Information technology – W3C Web Content Accessibility Guidelines (WCAG) 2.2	Governance System	https://www.iso.org/standard/91029.html
2.34	ISO/IEC TR 5469:2024 – Artificial intelligence – Functional safety and AI systems	Governance System	https://www.iso.org/standard/81283.html
2.35	ISO/IEC TS 12791:2024 – AI – Treatment of unwanted bias in classification and regression machine learning tasks	Governance System	https://www.iso.org/standard/81229.html
2.36	ISO 37101:2016 (Amd 1:2024) – Sustainable development in communities – Management system – Requirements with guidance for use	Governance System	https://www.iso.org/standard/61885.html
2.37	ISO/IEC 27400:2022 – Cybersecurity – IoT security and privacy – Guidelines	Governance System	https://www.iso.org/standard/44373.html
2.38	IEEE 7014-2024 – Standard for Ethical Considerations in Emulated Empathy in Autonomous and Intelligent Systems	Governance System	https://standards.ieee.org/standard/7014-2024.html

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Number	Standard Reference & Title	Module	URL
2.39	IEEE 7010-2020 – Standard for Well-Being Metrics for Artificial Intelligence and Autonomous Systems	Governance System	https://standards.ieee.org/standard/7010-2020.html
2.40	IEEE 7009-2024 – Standard for Fail-Safe Design of Autonomous and Semi-Autonomous Systems	Governance System	https://standards.ieee.org/standard/7009-2024.html
2.41	IEEE 7003-2022 – Standard for Algorithmic Bias Considerations	Governance System	https://standards.ieee.org/standard/7003-2022.html
2.42	IEEE 7002-2022 – Standard for Data Privacy Process	Governance System	https://standards.ieee.org/standard/7002-2022.html
2.43	W3C ODRL – ODRL Information Model and Vocabulary	Governance System	https://www.w3.org/TR/odrl-model/
2.44	ISO/IEC 25059:2023 – Software engineering - Systems and software Quality Requirements and Evaluation (SQuaRE) - Quality model for AI systems	Governance System	https://www.iso.org/standard/80655.html
2.45	ISO/IEC TR 24028:2020 – Information technology – Artificial intelligence – Overview of trustworthiness	Governance System	https://www.iso.org/standard/73528.html
2.46	ISO/IEC TR 24027:2021 – Information technology – Artificial intelligence – Bias in AI systems and AI aided decision making	Governance System	https://www.iso.org/standard/73527.html
2.47	IEEE 2089-2021 – Standard for Age Appropriate Design Process for AI Systems	Governance System	https://standards.ieee.org/standard/2089-2021.html
2.48	IEEE 7001-2021 – IEEE Standard for Transparency of Autonomous Systems	Governance System	https://standards.ieee.org/standard/7001-2021.html
2.49	ETSI TS 104 309 – Data Solutions (DATA); MIM-Q; Qualification and Conformance Scheme	Governance System	https://portal.etsi.org/webapp/WorkProgram/Report_WorkItem.asp?WKI_ID=78847
3.1.1	ITU-T Y.2501 – Computing power network – Framework and architecture	Layer 1: Network & Connectivity	https://www.itu.int/rec/T-REC-Y.2501-202109-I/en
3.1.2	ITU-T Y.4700 – Smart sustainable cities – Deployment guidelines for ubiquitous sensor network applications and services	Layer 1: Network & Connectivity	https://www.itu.int/rec/T-REC-Y.4700/en

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Number	Standard Reference & Title	Module	URL
3.1.3	ITU-T Y.4247 – Requirements of smart city communication network system	Layer 1: Network & Connectivity	https://www.itu.int/rec/T-REC-Y.4247-202606-P
3.1.4	ITU-T Y.4509 – Functional architecture of AI-enabled device-edge-cloud collaborative services for IoT and smart city	Layer 1: Network & Connectivity	https://www.itu.int/rec/T-REC-Y.4509/en
3.1.5	3GPP TS 22.156 – Mobile Metaverse Services; Stage 1 (Release 19)	Layer 1: Network & Connectivity	https://www.3gpp.org/DynaReport/22156.htm
3.1.6	3GPP TS 23.434 – Service Enabler Architecture Layer for Verticals (SEAL); Functional architecture and information flows	Layer 1: Network & Connectivity	https://www.3gpp.org/DynaReport/23434.htm
3.1.7	3GPP TS 23.437 – SEAL; Spatial map and Spatial anchors (Release 19)	Layer 1: Network & Connectivity	https://www.3gpp.org/DynaReport/23437.htm
3.1.8	3GPP TS 23.438 – SEAL; Digital assets (Release 19/20)	Layer 1: Network & Connectivity	https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=4372
3.1.9	3GPP TS 23.501 – System architecture for the 5G System (5GS)	Layer 1: Network & Connectivity	https://www.3gpp.org/DynaReport/23501.htm
3.1.10	3GPP TS 29.437 – SEAL; Metaverse Enablement Services; Stage 3 (Release 19)	Layer 1: Network & Connectivity	https://www.3gpp.org/DynaReport/29437.htm
3.1.11	3GPP TS 26.118 – Virtual Reality (VR) profiles for streaming applications	Layer 1: Network & Connectivity	https://www.3gpp.org/DynaReport/26118.htm
3.1.12	3GPP TS 26.119 – Media Capabilities for Augmented Reality	Layer 1: Network & Connectivity	https://www.3gpp.org/DynaReport/26119.htm
3.1.13	IEEE 802.11bf – Wi-Fi Sensing	Layer 1: Network & Connectivity	https://standards.ieee.org/ieee/802.11bf/11574/
3.1.14	IETF RFC 8655 – Deterministic Networking (DetNet) Architecture	Layer 1: Network & Connectivity	https://www.rfc-editor.org/rfc/rfc8655.html
3.1.15	IEEE 1918.1-2024 – Tactile Internet: Application Scenarios, Definitions and Terminology, Architecture, Functions, and Technical Assumptions	Layer 1: Network & Connectivity	https://standards.ieee.org/standard/1918_1-2024.html

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Number	Standard Reference & Title	Module	URL
3.1.16	IEEE 802.11be-2024 – Wireless LAN Enhancements for Extremely High Throughput (EHT)	Layer 1: Network & Connectivity	https://standards.ieee.org/standard/802_11be-2024.html
3.1.17	IEEE 802.1 TSN Series – Time-Sensitive Networking	Layer 1: Network & Connectivity	https://1.ieee802.org/tsn/
3.1.18	IEEE 1588-2019 – Precision Clock Synchronization Protocol for Networked Measurement and Control Systems	Layer 1: Network & Connectivity	https://standards.ieee.org/standard/1588-2019.html
3.1.19	IEEE 1451.0-2017 – Standard for a Smart Transducer Interface for Sensors and Actuators	Layer 1: Network & Connectivity	https://standards.ieee.org/standard/1451_0-2017.html
3.2.1	ITU-T Y.4201-Rev – High-level requirements and reference framework of smart city platforms (Revision)	Layer 2: Digital Infrastructure & Platform	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22088
3.2.2	ITU-T Y.4239 – Reference model for integrating virtual and physical worlds through digital twins in the metaverse	Layer 2: Digital Infrastructure & Platform	https://www.itu.int/rec/T-REC-Y.4239/en
3.2.3	ITU-T Y.4241 – Common requirements and capability framework of digital twin for smart complex and campus	Layer 2: Digital Infrastructure & Platform	https://www.itu.int/rec/T-REC-Y.4241-202605-P
3.2.4	ITU-T Y.4237 – Requirements and capability framework of digital twin for intelligent water conservancy system	Layer 2: Digital Infrastructure & Platform	https://www.itu.int/rec/T-REC-Y.4237/en
3.2.5	ITU-T Y.4513 – Requirements and functional architecture for blockchain-based sustainable and cooperative digital twin creation system	Layer 2: Digital Infrastructure & Platform	https://www.itu.int/rec/T-REC-Y.4513/en
3.2.6	ITU-T Y.4515 – Functional framework of an IoT platform for metaverse applications	Layer 2: Digital Infrastructure & Platform	https://www.itu.int/rec/T-REC-Y.4515/en
3.2.7	ITU-T Y.4600 – Requirements and capabilities of a digital twin system for smart cities	Layer 2: Digital Infrastructure & Platform	https://www.itu.int/rec/T-REC-Y.4600/en
3.2.8	ITU-T Y.4224 – Requirements for digital twin federation in smart cities and communities	Layer 2: Digital Infrastructure & Platform	https://www.itu.int/rec/T-REC-Y.4224-202311-I
3.2.9	ITU-T Y.aidt-reqts – Requirements of AI integrated digital twin for cities and communities	Layer 2: Digital Infrastructure & Platform	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23966
3.2.10	ISO/IEC 30173:2023 – Digital twin – Concepts and terminology	Layer 2: Digital Infrastructure & Platform	https://www.iso.org/standard/81442.html

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Number	Standard Reference & Title	Module	URL
3.2.11	ISO/IEC 30186:2025 – Digital twin – Maturity model and guidance for a maturity assessment	Layer 2: Digital Infrastructure & Platform	https://www.iso.org/standard/53306.html
3.2.12	ISO/IEC 30187:2026 – Internet of Things (IoT) – Evaluation indicators for IoT systems	Layer 2: Digital Infrastructure & Platform	https://www.iso.org/standard/53307.html
3.2.13	ISO/IEC 30188:2026 – Digital twin – Reference architecture	Layer 2: Digital Infrastructure & Platform	https://www.iso.org/standard/53308.html
3.2.14	ISO/IEC 30151 – Digital twin – Extraction and transactions of data components	Layer 2: Digital Infrastructure & Platform	https://www.iso.org/standard/89834.html
3.2.15	ISO/IEC 30152 ED1 – IoT and digital twins – Guidance on the connection to data spaces	Layer 2: Digital Infrastructure & Platform	https://www.iso.org/standard/89835.html
3.2.16	ISO/IEC 30153 ED1 – Digital Twin – Guidelines for digital entity modelling	Layer 2: Digital Infrastructure & Platform	https://www.iso.org/standard/89836.html
3.2.17	ISO/IEC 30194:2024 – Internet of things (IoT) and digital twin – Best practices for use case projects	Layer 2: Digital Infrastructure & Platform	https://www.iso.org/standard/53314.html
3.2.18	ISO/IEC CD TR 30138 – Digital Twin – Fidelity metric of digital twin system (under development)	Layer 2: Digital Infrastructure & Platform	https://www.iso.org/standard/53258.html
3.2.19	IEEE 2888.3-2024 – IEEE Standard for Orchestration of Digital Synchronization Between Cyber and Physical Worlds	Layer 2: Digital Infrastructure & Platform	https://standards.ieee.org/standard/2888.3-2024.html
3.2.20	IEEE 2302-2021 – Standard for Inter-cloud Interoperability and Federation	Layer 2: Digital Infrastructure & Platform	https://standards.ieee.org/standard/2302-2021.html
3.2.21	IEEE 1934-2018 – Standard for Adoption of OpenFog Reference Architecture for Fog Computing	Layer 2: Digital Infrastructure & Platform	https://standards.ieee.org/standard/1934-2018.html
3.3.1	ITU-T Y.4614 – Energy data model for city-level energy management platform	Layer 3: Data & Analytics	https://www.itu.int/rec/T-REC-Y.4614-202605-P
3.3.2	ITU-T Y.C&D-SCP-req – Requirements for centralized and decentralized data flow control on smart city platforms	Layer 3: Data & Analytics	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23984
3.3.3	ITU-T Y.DPM-DT – Requirements of data processing and management for digital twin-based smart cities and communities	Layer 3: Data & Analytics	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23558

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Number	Standard Reference & Title	Module	URL
3.3.4	ITU-T Y.FML-AISF – Federated machine learning-based artificial intelligence software framework with block-chain-driven edge data sharing	Layer 3: Data & Analytics	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23546
3.3.5	ITU-T Y.Sup.DAM-SCC – Supplement to ITU-T Y.4223 - Use cases of data asset management in smart cities and communities	Layer 3: Data & Analytics	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23985
3.3.6	ISO/IEC 25012:2008 – Software engineering – Software product Quality Requirements and Evaluation (SQuaRE) – Data quality model	Layer 3: Data & Analytics	https://www.iso.org/standard/35736.html
3.3.7	ISO/IEC 22989:2022 – Information technology – Artificial intelligence – Artificial intelligence concepts and terminology	Layer 3: Data & Analytics	https://www.iso.org/standard/74296.html
3.3.8	C2PA 2.1 – Content Provenance and Authenticity Specification	Layer 3: Data & Analytics	https://spec.c2pa.org/specifications/specifications/2.1/specs/_attachments/C2PA_Specification.pdf
3.3.9	ISO/IEC 23053:2022 – Information technology – Artificial intelligence – Framework for AI systems using machine learning	Layer 3: Data & Analytics	https://www.iso.org/standard/74437.html
3.4.1	ITU-T Y.4519 – Functional architecture of visualization system in digital twin for smart sustainable cities and communities	Layer 4: Virtual World Construction	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22090
3.4.2	ITU-T Y.DT-SSC-CVP – Classification of visualization precision levels for digital twin systems in smart sustainable cities	Layer 4: Virtual World Construction	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22057
3.4.3	ITU-T YSTR.Acc-Tools – Tools for accessible interactions in IoT-enabled immersive environments and virtual worlds for smart sustainable cities and communities	Layer 4: Virtual World Construction	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=24007
3.4.4	ITU-T YSTR.BP-DTw – Best Practices for Graphical Digital Twins of Smart Cities	Layer 4: Virtual World Construction	https://www.itu.int/epublications/ru/publication/itu-t-ystr-bp-dtw-2023-02-best-practices-for-graphical-digital-twins-of-smart-cities

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Number	Standard Reference & Title	Module	URL
3.4.5	ISO/IEC 5927:2024 – Augmented and virtual reality safety – Guidance on safe immersion, set up and usage	Layer 4: Virtual World Construction	https://www.iso.org/standard/81847.html
3.4.6	ISO 9241-820:2024 – Ergonomics of human-system interaction – Part 820: Ergonomic guidance on interactions in immersive environments	Layer 4: Virtual World Construction	https://www.iso.org/standard/83673.html
3.4.7	ISO/IEC 23090-5:2026 – Coded representation of immersive media – Part 5: Visual volumetric video-based coding (V3C) and video-based point cloud compression (V-PCC)	Layer 4: Virtual World Construction	https://www.iso.org/standard/91546.html
3.4.8	ISO/IEC 23090-6:2021 – Coded representation of immersive media – Part 6: Immersive media metrics	Layer 4: Virtual World Construction	https://www.iso.org/standard/79417.html
3.4.9	ISO/IEC 23090-12:2025 – Coded representation of immersive media – Part 12: MPEG immersive video (MIV)	Layer 4: Virtual World Construction	https://www.iso.org/standard/83558.html
3.4.10	ISO/IEC 23090-14:2025 – Coded representation of immersive media – Part 14: Scene description	Layer 4: Virtual World Construction	https://www.iso.org/standard/90191.html
3.4.11	ISO/IEC 23090-29:2026 – Coded representation of immersive media – Part 29: Video-based dynamic mesh coding (V-DMC)	Layer 4: Virtual World Construction	https://www.iso.org/standard/85254.html
3.4.12	ISO/IEC 19774:2019 – Information technology – Computer graphics and image processing – Humanoid animation (H-Anim)	Layer 4: Virtual World Construction	https://www.iso.org/standard/74298.html
3.4.13	ISO/IEC 37200:2022 – Information technology – Computer graphics and image processing – Mixed and augmented reality – Content model for virtual human	Layer 4: Virtual World Construction	https://www.iso.org/standard/80917.html
3.4.14	ISO/IEC 18039:2019 – Information technology – Computer graphics, image processing and environmental data representation – Mixed and augmented reality (MAR) reference model	Layer 4: Virtual World Construction	https://www.iso.org/standard/74297.html
3.4.15	ISO/IEC 12113:2022 – Information technology – Runtime 3D asset delivery format – Khronos glTF™ 2.0	Layer 4: Virtual World Construction	https://www.iso.org/standard/83990.html

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Number	Standard Reference & Title	Module	URL
3.4.16	ISO/IEC 19775-1:2023 (X3D) – Information technology – Computer graphics and image processing – Extensible 3D (X3D) – Part 1: Architecture and base components	Layer 4: Virtual World Construction	https://www.iso.org/standard/82562.html
3.4.17	ISO/IEC 19775-2:2015 – Information technology – Computer graphics, image processing and environmental data representation – Extensible 3D (X3D) – Part 2: Scene Access Interface	Layer 4: Virtual World Construction	https://www.iso.org/standard/60500.html
3.4.18	ISO/IEC 3721:2023 – Information model for Mixed and Augmented Reality contents	Layer 4: Virtual World Construction	https://www.iso.org/standard/81207.html
3.4.19	OGC CityGML 3.0 – City Geography Markup Language 3.0	Layer 4: Virtual World Construction	https://www.ogc.org/standard/citygml/
3.4.20	OGC 3D Tiles 1.1	Layer 4: Virtual World Construction	https://www.ogc.org/standard/3dtiles/
3.4.21	OGC IndoorGML – Indoor Geography Markup Language	Layer 4: Virtual World Construction	https://www.ogc.org/standard/indoorgml/
3.4.22	OGC InfraGML 1.0 – Infrastructure Geography Markup Language	Layer 4: Virtual World Construction	https://www.ogc.org/standard/infragml/
3.4.23	ISO 16739-1:2024 – Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries	Layer 4: Virtual World Construction	https://www.iso.org/standard/84123.html
3.4.24	W3C WebXR Device API	Layer 4: Virtual World Construction	https://www.w3.org/TR/webxr/
3.4.25	OpenXR 1.0	Layer 4: Virtual World Construction	https://www.khronos.org/openxr/
3.4.26	W3C WebGPU – Web Graphics Processing Unit API	Layer 4: Virtual World Construction	https://www.w3.org/TR/webgpu/
3.4.27	OGC CityJSON 2.0 – CityJSON encoding for 3D city models	Layer 4: Virtual World Construction	https://www.ogc.org/standard/cityjson/

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Number	Standard Reference & Title	Module	URL
3.4.28	IEEE 2048.101-2023 – IEEE Standard for Augmented Reality on Mobile Devices – General Requirements for Software Framework, Components, and Integration	Layer 4: Virtual World Construction	https://standards.ieee.org/ieee/2048.101/
3.4.29	ETSI GS ARF 003 – Augmented Reality Framework (ARF); AR framework architecture	Layer 4: Virtual World Construction	https://www.etsi.org/deliver/etsi_gs/ARF/001_099/003/
3.4.30	ISO/IEC TS 5147:2023 – Information technology – Computer graphics, image processing and environmental data representation – Guidelines for representation and visualization of smart cities	Layer 4: Virtual World Construction	https://www.iso.org/standard/80918.html
3.4.31	IEEE P2048.121 – Standard for Service-oriented AI-based Digital Human	Layer 4: Virtual World Construction	https://standards.ieee.org/ieee/2048.121/
3.4.32	IEEE 3079-2020 – Recommended Practice for Reducing the Effects of Motion Sickness in Virtual Reality Environments	Layer 4: Virtual World Construction	https://standards.ieee.org/ieee/3079/7156/
3.4.33	IEEE P2888.6 – Standard for Holographic Visualization for Interfacing Cyber and Physical Worlds	Layer 4: Virtual World Construction	https://standards.ieee.org/project/2888.6.html
3.4.34	IEEE 2888.5-2024 – Standard for Virtual Training System Evaluation Methods	Layer 4: Virtual World Construction	https://standards.ieee.org/standard/2888_5-2024.html
3.4.35	IEEE 3333.1.4-2022 – Recommended Practice for Quality Assessment of Light Field and Holographic Display Systems	Layer 4: Virtual World Construction	https://standards.ieee.org/standard/3333_1_4-2022.html
3.4.36	IEEE P3079.1 – Standard for Motion-to-Photon Latency Measurement in Virtual Reality Environments	Layer 4: Virtual World Construction	https://standards.ieee.org/project/3079.1.html
3.4.37	IEEE P2048.2 – Standard for Metaverse: Framework	Layer 4: Virtual World Construction	https://standards.ieee.org/ieee/2048.2/
3.5.1	ITU-T Y.4205 – Requirements and reference framework for smart city operation centres	Layer 5: Application Scenario	https://www.itu.int/rec/T-REC-Y.4205/en
3.5.2	ITU-T Y.4215 – Requirements and common framework for crowdsourcing in smart sustainable cities	Layer 5: Application Scenario	https://www.itu.int/rec/T-REC-Y.4215/en
3.5.3	ITU-T Y.4225 (formerly Y.dt-ITS) – Requirements and capability framework of digital twin for intelligent transport system	Layer 5: Application Scenario	https://www.itu.int/rec/T-REC-Y.4225/en

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Number	Standard Reference & Title	Module	URL
3.5.4	ITU-T Y.4236 – Requirements for real-time event monitoring and integrated management on smart city platforms	Layer 5: Application Scenario	https://www.itu.int/rec/T-REC-Y.4236/en
3.5.5	ITU-T Y.citiverse-reqts – Requirements of Citiverse platform for smart sustainable cities and communities	Layer 5: Application Scenario	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22087
3.5.6	ITU-T Y.4496 – Requirements and reference architecture for a smart public health emergency information system	Layer 5: Application Scenario	https://www.itu.int/rec/T-REC-Y.4496
3.5.7	ITU-T Y.4233 – Information and communication technology implementation framework for smart public health emergency management in smart and sustainable cities	Layer 5: Application Scenario	https://www.itu.int/rec/T-REC-Y.4233
3.5.8	ITU-T Y.IECC – Framework and requirements of interactive emergency communication within Citiverse	Layer 5: Application Scenario	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23518
3.5.9	ITU-T Y.MetaExpSys – Requirements of Metaverse Experience System for Tourist Places	Layer 5: Application Scenario	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22103
3.5.10	ITU-T Y.PM-FUSG – Technical framework and use cases of the power metaverse for future urban smart grids	Layer 5: Application Scenario	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=22101
3.5.11	ITU-T Y.meta-Ed – Requirements and functional architecture for IoT-enabled multilingual and immersive education system	Layer 5: Application Scenario	https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=23520
3.5.12	ISO 37120:2018 – Sustainable cities and communities – Indicators for city services and quality of life	Layer 5: Application Scenario	https://www.iso.org/standard/68498.html
3.5.13	ISO 37122:2019 – Sustainable cities and communities – Indicators for smart cities	Layer 5: Application Scenario	https://www.iso.org/standard/69050.html
3.5.14	ISO 37123:2019 – Sustainable cities and communities – Indicators for resilient cities	Layer 5: Application Scenario	https://www.iso.org/standard/70492.html

Appendix 2: Standards Gap Summary

This appendix provides a consolidated summary of the 36 standardization gaps identified in this report, organized by priority level.

Highest Priority Gaps (2):

- Cross-domain semantic interoperability framework for citiverse – Profile/interface gap
- Multisystem interoperability and linkage for emergency response – Profile/interface gap.

High Priority Gaps (27):

- End-edge-cloud collaborative computing scheduling interface and capability grading standards for city digital twins – Profile/interface gap
- Unified inter-layer interface specifications for citiverse technology stacks – Profile/interface gap
- Urban digital twin data product exchange and data space integration framework – Profile/interface gap
- Unified citiverse conformance testing and certification framework – Conformance/implementation gap
- AI-generated 3D city model provenance and rights expression metadata standards – Profile/interface gap
- City-specific AI fairness assessment metrics and bias testing methodology for urban governance – Profile/interface gap
- City-level AI algorithm registration and audit interface standards – Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified)
- Citiverse-specific virtual asset classification and lifecycle security – Profile/interface gap
- Interoperability framework of digital public infrastructure (DPI) for smart cities – Profile/interface gap
- Trustworthiness evaluation specifications for IoT and digital twin systems in smart cities – Conformance/implementation gap
- Immersive media SLA and QoS assurance specifications for city-scale multi-user citiverse scenarios – Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified)
- Computing power network-aware scheduling interface and routing signalling specifications for immersive urban services – Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified)
- Citiverse profile and interoperability mapping for mobile spatial anchor and digital asset services – Profile/interface gap
- City digital infrastructure platform capability assessment and maturity grading – Conformance/implementation gap
- Digital twin federation and interconnection interface – Profile/interface gap
- AI model interoperability and deployment interface specifications for city digital twin platforms – Profile/interface gap
- Urban digital twin system fidelity metrics and assessment – Conformance/implementation gap

- Cross-domain urban spatio-temporal data fusion output format and quality assessment standards – Profile/interface gap
- Urban spatial foundation model evaluation metrics and training data governance specifications – Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified)
- City-scale 3D scene streaming protocol and data format standards – Profile/interface gap
- Cross-platform virtual identity interoperability – Profile/interface gap
- Urban-service capability assessment for AI-driven digital humans – Conformance/implementation gap
- AI-generated city virtual content quality, trustworthiness and compliance validation standards – Conformance/implementation gap
- Intelligent transportation real-time optimization and signal linkage – Normative gap
- Citizen immersive government service interface specification – Profile/interface gap (foundational standards exist; no citiverse-specific profile or integrated specification identified)
- Cross-departmental service collaboration interface and data exchange specifications for citiverse platforms – Profile/interface gap
- Urban planning immersive simulation and decision support scenario standards – Normative gap.

Medium Priority Gaps (7):

- Green computing metrics for citiverse-specific infrastructure – Conformance/implementation gap
- Full-lifecycle data governance specifications for city digital twin platforms – Conformance/implementation gap
- Cross-modal sensor data fusion quality validation standards – Conformance/implementation gap
- Immersive-scenario accessibility – Conformance/implementation gap
- VR/AR/MR integration reference model for citiverse immersive urban services – Conformance/implementation gap
- OGC 3D Tiles 2.0 and 3D city model interoperability and migration – Profile/interface gap
- Human-machine collaboration interface and handover protocol standards for urban AI-assisted governance – Profile/interface gap.

Gap Type Definitions:

Normative gap: no directly applicable normative standard exists for the citiverse-specific function, even where general foundational standards are available. Profile/interface gap:

relevant standards exist but need citiverse-specific parameterization or interface mapping. Conformance/implementation gap: requirements exist but test methods, metrics or implementation guidance are missing.

Standards Gap Summary (36 gaps)

Number	Gap Name	Layer	Priority	Gap Type
Cross-Cutting Technical Support Standards Gaps				
1	Cross-domain semantic interoperability framework for citiverse	Cross-cutting Tech	Highest	Profile/interface gap
2	End-edge-cloud collaborative computing scheduling interface and capability grading standards for city digital twins	Cross-cutting Tech	High	Profile/interface gap
3	Unified inter-layer interface specifications for citiverse technology stacks	Cross-cutting Tech	High	Profile/interface gap
4	Urban digital twin data product exchange and data space integration framework	Cross-cutting Tech	High	Profile/interface gap
Governance System Standards Gaps				
5	Unified citiverse conformance testing and certification framework	Governance System	High	Conformance/implementation gap
6	AI-generated 3D city model provenance and rights expression metadata standards	Governance System	High	Profile/interface gap
7	City-specific AI fairness assessment metrics and bias testing methodology for urban governance	Governance System	High	Profile/interface gap
8	City-level AI algorithm registration and audit interface standards	Governance System	High	Profile/interface gap
9	Citiverse-specific virtual asset classification and lifecycle security	Governance System	High	Profile/interface gap
10	Interoperability framework of digital public infrastructure (DPI) for smart cities	Governance System	High	Profile/interface gap
11	Trustworthiness evaluation specifications for IoT and digital twin systems in smart cities	Governance System	High	Conformance/implementation gap

(continued)

Number	Gap Name	Layer	Priority	Gap Type
12	Green computing metrics for citiverse-specific infrastructure	Governance System	Medium	Conformance/implementation gap
Layer 1: Network & Connectivity Layer Gaps				
13	Immersive media SLA and QoS assurance specifications for city-scale multi-user citiverse scenarios	Layer 1: Network & Connectivity	High	Profile/interface gap
14	Computing power network-aware scheduling interface and routing signalling specifications for immersive urban services	Layer 1: Network & Connectivity	High	Profile/interface gap
15	Citiverse profile and interoperability mapping for mobile spatial anchor and digital asset services	Layer 1: Network & Connectivity	High	Profile/interface gap
Layer 2: Digital Infrastructure & Platform Layer Gaps				
16	City digital infrastructure platform capability assessment and maturity grading	Layer 2: Digital Infrastructure & Platform	High	Conformance/implementation gap
17	Digital twin federation and interconnection interface	Layer 2: Digital Infrastructure & Platform	High	Profile/interface gap
18	AI model interoperability and deployment interface specifications for city digital twin platforms	Layer 2: Digital Infrastructure & Platform	High	Profile/interface gap
19	Urban digital twin system fidelity metrics and assessment	Layer 2: Digital Infrastructure & Platform	High	Conformance/implementation gap
20	Full-lifecycle data governance specifications for city digital twin platforms	Layer 2: Digital Infrastructure & Platform	Medium	Conformance/implementation gap
Layer 3: Data & Analytics Layer Gaps				
21	Cross-domain urban spatiotemporal data fusion output format and quality assessment standards	Layer 3: Data & Analytics	High	Profile/interface gap

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Number	Gap Name	Layer	Priority	Gap Type
22	Urban spatial foundation model evaluation metrics and training data governance specifications	Layer 3: Data & Analytics	High	Profile/interface gap
23	Cross-modal sensor data fusion quality validation standards	Layer 3: Data & Analytics	Medium	Conformance/implementation gap
Layer 4: Virtual World Construction Layer Gaps				
24	City-scale 3D scene streaming protocol and data format standards	Layer 4: Virtual World Construction	High	Profile/interface gap
25	Cross-platform virtual identity interoperability	Layer 4: Virtual World Construction	High	Profile/interface gap
26	Immersive-scenario accessibility	Layer 4: Virtual World Construction	Medium	Conformance/implementation gap
27	Urban-service capability assessment for AI-driven digital humans	Layer 4: Virtual World Construction	High	Conformance/implementation gap
28	AI-generated city virtual content quality, trustworthiness and compliance validation standards	Layer 4: Virtual World Construction	High	Conformance/implementation gap
29	VR/AR/MR integration reference model for citiverse immersive urban services	Layer 4: Virtual World Construction	Medium	Conformance/implementation gap
30	OGC 3D Tiles 2.0 and 3D city model interoperability and migration	Layer 4: Virtual World Construction	Medium	Profile/interface gap
Layer 5: Application Scenario Layer Gaps				
31	Urban planning immersive simulation and decision support scenario standards	Layer 5: Application Scenario	High	Normative gap
32	Multisystem interoperability and linkage for emergency response	Layer 5: Application Scenario	Highest	Profile/interface gap
33	Intelligent transportation real-time optimization and signal linkage	Layer 5: Application Scenario	High	Normative gap

(continued)

Number	Gap Name	Layer	Priority	Gap Type
34	Citizen immersive government service interface specification	Layer 5: Application Scenario	High	Profile/interface gap
35	Cross-departmental service collaboration interface and data exchange specifications for citiverse platforms	Layer 5: Application Scenario	High	Profile/interface gap
36	Human-machine collaboration interface and handover protocol standards for urban AI-assisted governance	Layer 5: Application Scenario	Medium	Profile/interface gap

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