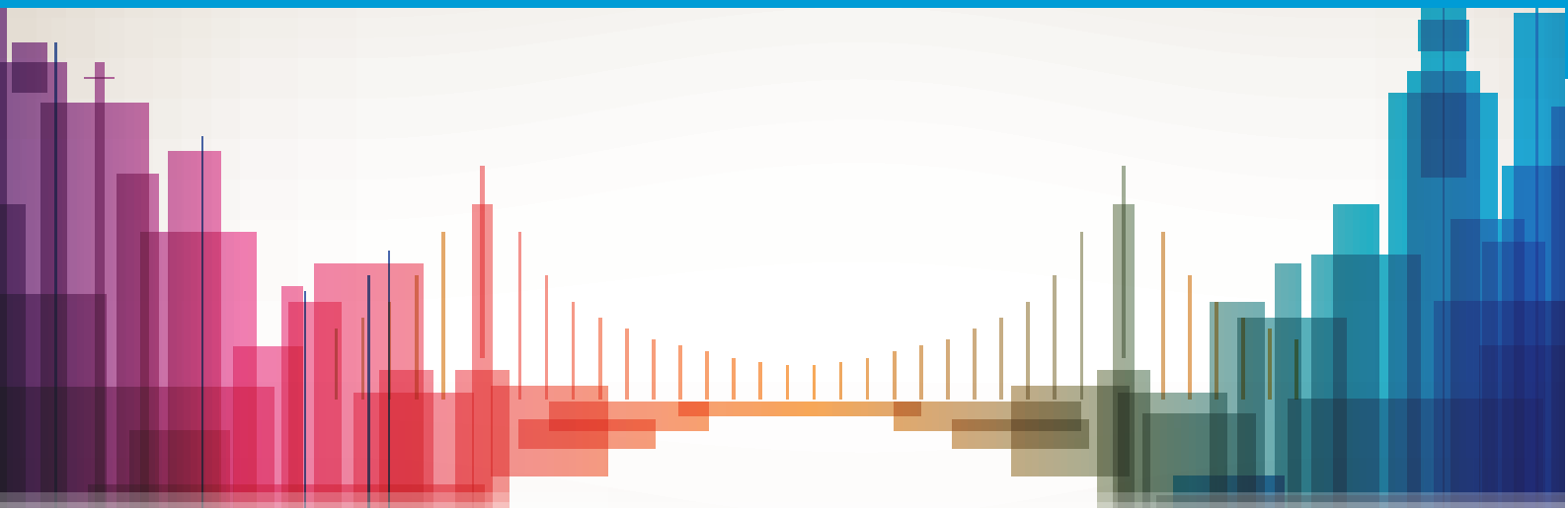
Autonomous urban systems in Songdo, Republic of Korea

Case study of the U4SSC Guide to autonomous cities and AI: The next frontier of urban transformation



Convention on Biological Diversity

United Nations ECLAC

Food and Agriculture Organization of the United Nations

UNIDO

ITU

UNDP

United Nations Economic Commission for Africa

UNECE

UNESCO United Nations Educational, Scientific and Cultural Organization

UN environment programme

UNEP FINANCE INITIATIVE

United Nations Framework Convention on Climate Change

unitar United Nations Institute for Training and Research

UN-HABITAT FOR A BETTER URBAN FUTURE

United Nations Department of Economic and Social Affairs

UN 4 PARTNERSHIPS

UNU EGOV

UN Tourism

UN WOMEN

WORLD METEOROLOGICAL ORGANIZATION

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Foreword

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Disclaimer

The opinions expressed in this publication are those of the authors and do not necessarily represent the views of their respective organizations or U4SSC members. In line with the U4SSC principles, this report does not promote the adoption and use of Smart City technology. It advocates for policies encouraging responsible use of information and communications technologies (ICTs) that contribute to the economic, environmental and social sustainability as well as the advancement of the 2030 Agenda for Sustainable Development and the Pact for the Future and its Global Digital Compact.

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Contents

Abbreviations and acronyms

Abbreviation	Full Form
5G	Fifth-generation mobile network
AI	Artificial Intelligence
AQI	Air Quality Index
AV	Autonomous Vehicles
BACnet	Building Automation and Control Network
CO2	Carbon dioxide
EV	Electric Vehicle
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation (European Union)
IBD	International Business District
IFEZ	Incheon Free Economic Zone
ICT	Information and Communication Technology
IoT	Internet of Things
IT	Information Technology
KPI	Key Performance Indicators
LEED	Leadership in Energy and Environmental Design
MaaS Platform	Mobility as a Service Platform
NIST	National Institute of Standards and Technology
PII	Personally Identifiable Information
PPP	Public-Private Partnership
SDG	Sustainable Development Goals
U-City	Ubiquitous City
V2X	Vehicle to Everything

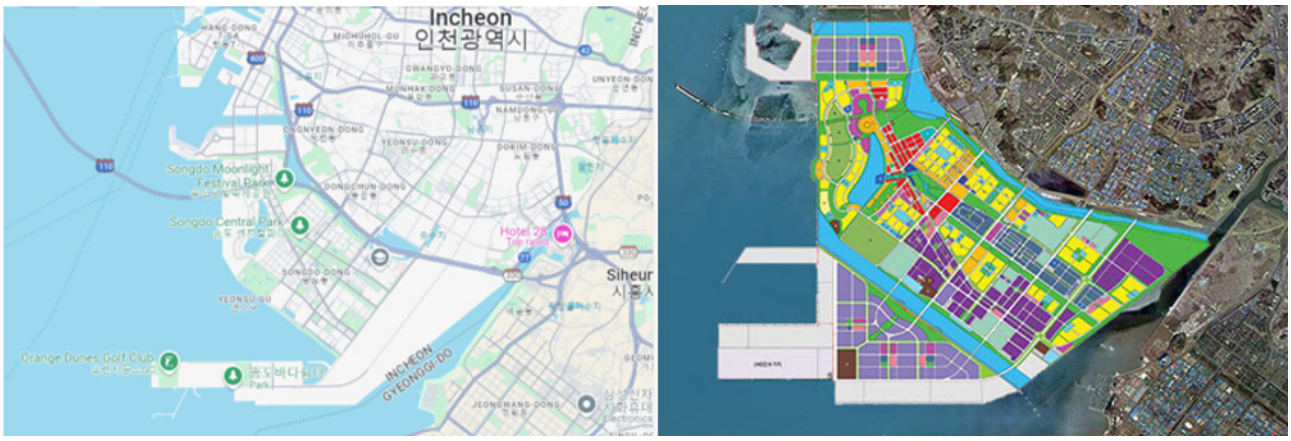
Executive summary

Autonomous cities are urban areas where various technological systems, particularly artificial intelligence (AI) and the Internet of Things (IoT), are integrated to allow the city to run with minimal human intervention. These cities use data-driven decision-making and automation to enhance transportation, infrastructure management, energy use, and other services. A case study on autonomous cities in Songdo International Business District, Republic of Korea involves understanding how autonomous technology can impact human experience, environment, and city operational efficiency.

1 Introduction

Songdo International Business District (IBD) is a smart city in Incheon, Republic of Korea, developed on reclaimed land along the Yellow Sea. It is part of the Incheon Free Economic Zone (IFEZ) and is one of the most prominent examples of a smart, sustainable city built from the ground up.

Figure 1: Songdo IBD (Source: Author)



Songdo spanned 600 hectares and was planned with a focus on sustainability, green spaces, and advanced technology integration. The city has wide, green avenues, and over 40 per cent of the area is dedicated to open space and parks, including the iconic Central Park, inspired by its New York namesake.

Songdo's vision is to be a centre for global businesses, offering advanced infrastructure, tax incentives, and a business-friendly environment. It aims to serve as a technology and business innovation platform, with initiatives to support startups and technology-driven industries.

2 Background and context

Songdo is designed to be one of the greenest cities in the world, with a target of significantly reducing carbon emissions and energy consumption. The development prioritizes ample green spaces, parks, and waterways to promote sustainability and improve residents' quality of life by ensuring that most buildings in the district meet international environmental standards for energy efficiency and green construction. Songdo aims to be a globally recognized smart city by integrating IoT solutions for traffic management, energy optimization, water conservation and waste management. It uses real-time data analytics to monitor and manage city operations, making them more efficient and user-friendly. It also provides intelligent transportation systems, focusing on reducing dependency on private vehicles and enhancing public transportation options. Songdo seeks to provide a balanced urban environment that promotes well-being, with wide pedestrian-friendly streets, parks, and facilities that support a healthy lifestyle. The development provides smart

home systems and integrated digital platforms, from waste disposal to entertainment services that make day-to-day living easier for residents. Songdo is developing world-class educational institutions, cultural centres and recreational facilities to attract a diverse and vibrant population. The city also fosters a hyper-connected environment, with a high-speed fibre-optic network to facilitate seamless communication and business operations.

Songdo has been evolving significantly, especially in the context of technological advancements and AI adoption. Built from scratch as a model for future urban living, the city continues to integrate cutting-edge technologies to enhance its infrastructure and services. Songdo utilizes AI-powered systems for traffic management, energy distribution and waste management. AI-driven sensors monitor traffic flow in real time, thereby reducing congestion and improving transportation efficiency. Similarly, AI-based systems optimize energy consumption, allowing for smarter use of electricity and reducing the overall carbon footprint. The city's buildings are equipped with AI systems that adjust lighting, temperature and security based on occupancy and time of day. Smart homes in Songdo come with integrated AI assistants that help residents manage household tasks, control appliances, and provide recommendations for improving energy efficiency. AI is being adopted in Songdo's healthcare system for predictive analytics and personalized medicine. AI models analyse patient data to predict potential health issues and suggest preventative measures.

The city also deploys AI for public safety, using facial recognition and pattern recognition systems to monitor public spaces and respond to incidents faster. AI plays a role in Songdo's sustainability efforts by managing resources more efficiently. This includes water conservation, energy optimization in public and private spaces, and waste-to-energy initiatives, all monitored and controlled by AI systems. Songdo is increasingly incorporating AI in its mobility systems, particularly with autonomous vehicles and AI-driven public transportation networks. AI enables real-time adjustments to routes based on traffic and demand, enhancing the reliability of transport services. AI-based simulations and predictive modelling are used to plan future expansions and projects, ensuring that urban growth remains sustainable and aligns with environmental goals.

3 AI strategy in Songdo

Songdo has been a model for smart city innovation since its inception in the early 2000s, but the formal integration of AI as a key component of its strategy evolved more recently. It was initially designed as a Ubiquitous City (U-City), with a focus on information technology and connectivity, aiming for a fully networked infrastructure. Early systems focused on smart building controls, IoT, and automated infrastructure management, laying the foundation for AI integration.

By the late 2010s, the Republic of Korea's broader national AI strategy, which aimed to position the country as a leader in AI by 2030, greatly influenced Songdo's approach. Public-private partnerships

were strengthened to accelerate AI adoption. Large corporations like LG CNS, KT Corporation, and Cisco helped integrate AI for urban management and smart city services, such as:

- AI-powered public safety systems using facial recognition and behavioural analytics.
- Healthcare AI solutions that analyse patient data for predictive health management.
- Autonomous mobility projects incorporating AI for traffic optimization and autonomous driving.

AI became a key part of Songdo's energy sustainability goals, enabling smarter energy distribution and consumption patterns, aligning with the Republic of Korea's push for green growth.

Around 2015, with the rise of AI and big data analytics, Songdo began to formally integrate AI-driven technologies into its smart systems. AI started being applied to traffic management, energy grids, and waste management, optimizing these systems through predictive analytics and automation. This marked the beginning of Songdo's transition from merely a connected city to one that actively leverages AI for real-time decision-making.

From 2020 onwards, the Republic of Korea announced a more formal AI-driven smart city model under its Smart City 2.0 initiative, in which Songdo plays a crucial role. AI strategies in Songdo now emphasize:

- **Citizen-centric AI**: Improving the daily life of residents through personalized services and better resource management.
- **AI in public services**: Enhancing services such as waste collection, energy use, and public transport through real-time AI systems that respond dynamically to urban needs.
- **AI in urban planning**: Using AI to simulate future growth and make data-driven decisions in city expansion and infrastructure projects.
- **AI and sustainability**: Leveraging AI for achieving carbon neutrality, including waste-to-energy and water management systems.

4 Songdo autonomous system

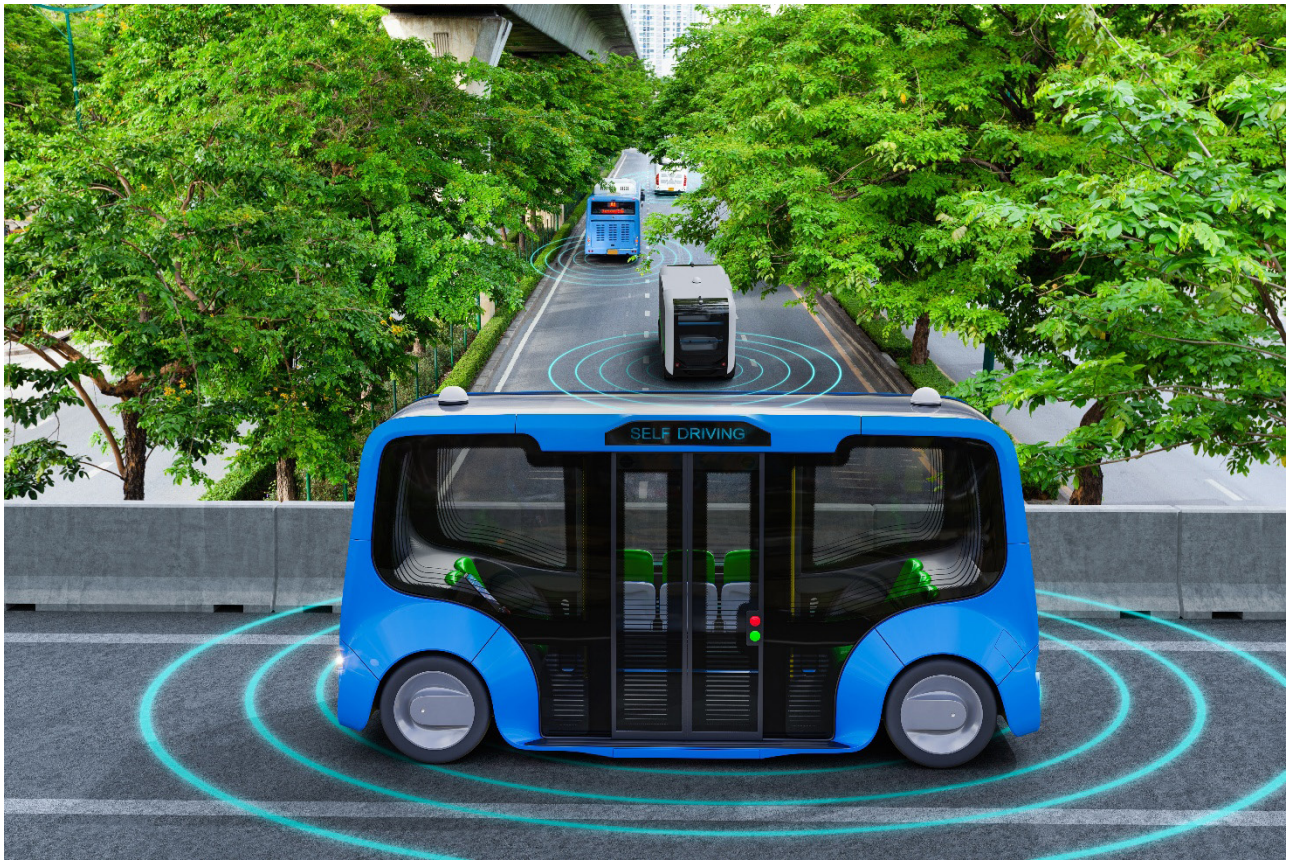
Songdo's autonomous systems are central to its smart city infrastructure, focusing on automating services across mobility, energy, and city management to create a more efficient, sustainable, and liveable environment. Here's an overview of the key autonomous systems in Songdo:

Autonomous transportation

Songdo has been a testbed for autonomous vehicles, with self-driving cars and buses being piloted as part of the city's public transportation network. These vehicles are equipped with advanced AI,

sensors, and machine learning algorithms to navigate the urban landscape, avoid obstacles, and make real-time adjustments based on traffic and pedestrian movement.

Figure 2: Autonomous shuttle bus in Songdo (Source: Adobe stock)



Autonomous shuttles operate on fixed routes, integrating with smart traffic management systems to optimize travel time and reduce congestion. The system is designed to adapt routes based on demand, thereby ensuring the efficient use of public transportation. Songdo integrates different modes of transportation – like AVs, bicycles and electric scooters, into a seamless MaaS platform. Residents can access real-time transportation data and book various autonomous or traditional transport services through a single app.

Smart traffic management

The city employs AI-powered traffic systems that monitor intersections, vehicle movement and congestion patterns in real time. These systems automatically adjust traffic signals and reroute vehicles to optimize traffic flow and minimize delays. Songdo's infrastructure is equipped with V2X technology, enabling vehicles to communicate with each other and with traffic systems. This communication allows AVs to adjust speed, anticipate traffic conditions, and make decisions that enhance road safety and efficiency.

Figure 3: AI-based traffic management (Source: Author)

Autonomous building management systems

Songdo's high-rise buildings and residential complexes are equipped with autonomous systems for managing lighting, heating, cooling and security. AI systems automatically adjust these parameters based on occupancy, time of day and energy usage to maximize comfort and energy efficiency. Buildings in Songdo are integrated with a central control system that autonomously manages resources like water, electricity, and air quality. The system tracks usage patterns and predicts future needs, reducing energy consumption and waste.

Autonomous waste management

Songdo has an automated pneumatic underground waste disposal system that uses air pressure to transport waste directly from homes and offices to processing centres. This autonomous system eliminates the need for traditional garbage trucks and optimizes waste processing, including sorting and recycling. The system also uses AI to monitor waste levels in real-time and adjust collection schedules automatically to ensure efficient waste management and minimal environmental impact.

Autonomous energy management

Songdo's power infrastructure includes a smart grid system that autonomously manages energy distribution, balancing supply and demand. AI algorithms predict peak usage times and allocate resources efficiently, so reducing the city's carbon footprint. Autonomous energy systems optimize heating, cooling, and electricity in buildings based on real-time data about occupancy and weather conditions. These systems help reduce energy consumption and contribute to the city's sustainability goals.

Autonomous public safety

Songdo employs autonomous surveillance systems that use AI to monitor public spaces. These systems use facial recognition, behavioural analysis, and anomaly detection to identify potential security risks and alert authorities. These systems are keys in the emergency response system that autonomously detect accidents or unusual activities (e.g., fires or medical emergencies) and dispatch first responders without human intervention

Autonomous urban planning and maintenance

AI systems monitor infrastructure like roads, bridges and public buildings, predicting when maintenance is needed. This autonomous approach helps reduce downtime and ensures the infrastructure remains in optimal condition. Songdo uses AI simulations to model urban growth and infrastructure needs. These systems help city planners make data-driven decisions about future developments, ensuring sustainable and efficient growth.

Autonomous retail and logistics

Drones and autonomous delivery vehicles are used in Songdo to transport goods from retailers and warehouses to homes and businesses. These systems are integrated with AI for route optimization and to ensure safe delivery. Retail outlets in Songdo use AI to manage inventory, track customer behaviour, and automate checkout processes through autonomous systems like cashier-less stores.

Figure 4: Autonomous logistics management in Songdo

Songdo's autonomous systems, powered by AI and advanced technologies, are transforming the way the city operates. These systems span across multiple sectors – transportation, energy, waste, public safety and urban planning, working together to create a city that is self-managing, highly efficient and sustainable. The integration of autonomous technology in Songdo is key to its vision of a future-ready, fully optimized smart city.

5 Implementation of the autonomous system

Songdo International Business District (IBD) has been designed as a smart city that incorporates various autonomous systems and cutting-edge technologies to promote sustainability, energy efficiency and innovation, aligning its development closely with the United Nations Sustainable Development Goals (SDGs). The autonomous systems implemented in Songdo support a wide range of functions, from energy management to transportation and public services, in alignment with specific SDGs.

Initial development phase (2003-2015)

In its initial phase (2003-2009), Songdo was built with advanced ICT infrastructure such as fibre-optic networks to support autonomous systems and real-time data collection across the city. The city incorporated adaptive street lighting that adjusts based on foot traffic and environmental conditions, thereby reducing energy waste; smart water systems; and district heating and cooling to enhance efficiency and reduce carbon footprints. These systems were central to Songdo's alignment with SDG 7 (Affordable and Clean Energy) and SDG 6 (Clean Water and Sanitation). In addition, from 2010 to 2015 Songdo adopted green building practices (LEED-certified buildings) and IoT-based sensors to monitor energy consumption, air quality, and traffic. This aligns with SDG 11 (Sustainable Cities and Communities) by promoting sustainable urban living.

Expansion of autonomous transportation and mobility (2015-2020)

In the period (2015-2017) Songdo implemented an integrated smart transportation system that includes autonomous buses and smart traffic management systems. These initiatives contribute to reducing emissions from transportation and aligning with SDG 13 (Climate Action). From 2018-2020, Songdo built charging stations for electric vehicles (EVs) and incorporated autonomous parking systems. The city's autonomous buses, in conjunction with ride-sharing systems, aim to reduce congestion and reduce the carbon footprint, further contributing to SDG 11. AI-powered optimization of public transit schedules was introduced to match real-time demand with supply, reducing idle times and fuel consumption.

Smart resource management and sustainability (2020-2025)

From 2020 to 2023, the district cooling and heating systems in Songdo incorporated AI-based energy demand forecasting and real-time energy optimization. These systems contribute to SDG

7 by improving energy efficiency and reducing greenhouse gas emissions. Songdo implemented an automated waste collection system using pneumatic tubes that transport waste underground to a central facility for sorting and recycling. This aligns with SDG 12 (Responsible Consumption and Production) by promoting efficient waste management and reducing landfill use. From 2023 to 2025, Songdo started to implement real-time monitoring and control of water usage, leak detection, and automated water distribution systems to help achieve SDG 6 (Clean Water and Sanitation) by promoting efficient water use and reducing wastage.

Full integration of autonomous public services (2025-2030)

Starting from 2025 and up to 2027, Songdo plans to implement AI-assisted public health systems with real-time data on air quality, disease outbreaks, and healthcare demand. The city will also adopt autonomous emergency services (e.g., drones and autonomous ambulances) to enhance the responsiveness and efficiency of public services, aligned with SDG 3 (Good Health and Well-being). From 2028 to 2030, The integration of AI-driven governance systems to optimize resource allocation and public service delivery will align with the broader goal of SDG 16 (Peace, Justice, and Strong Institutions) by promoting transparent and effective institutions. Autonomous learning platforms and community engagement tools will empower residents with real-time information about sustainability practices and energy usage, further promoting SDG 4 (Quality Education).

6 Songdo autonomous system rollout challenges and mitigation

Implementing autonomous systems in Songdo, while ground-breaking, has not been without challenges. These challenges arise from the complexities of integrating cutting-edge technologies, building public trust, ensuring cybersecurity, and aligning with long-term sustainability goals. Here's an overview of some of the key challenges encountered during Songdo's implementation of autonomous systems and the strategies used to address them:

Integration of technologies

One of the biggest challenges was integrating a wide range of technologies across different domains (transportation, energy, water, waste management, public safety) into a seamless, interoperable system. Various platforms for IoT, AI, and control systems had to work in concert to provide real-time data collection, processing, and automated decision-making. Songdo developed a centralized data platform to integrate IoT, AI, and smart infrastructure data into a unified system. This allows for smooth communication between different autonomous systems, enhancing coordination across sectors like energy management, transportation, and building automation. The adoption of open communication protocols like BACnet and Modbus across building management and energy systems allowed for seamless integration with third-party solutions and future technology upgrades.

Cybersecurity concerns

As a highly connected smart city, Songdo faced significant risks of cyberattacks that could disrupt critical infrastructure such as energy grids, autonomous transport systems, or public services. Autonomous systems, which rely on data exchange and automation, are particularly vulnerable to threats like hacking, data breaches and unauthorized access. Songdo has implemented multilayered cybersecurity measures, including strong encryption, regular network penetration testing, and continuous monitoring. These measures are reinforced by firewalls and intrusion detection systems to safeguard the network. AI algorithms were integrated into the city's infrastructure to monitor network traffic and detect unusual patterns that could indicate potential security breaches, so allowing for a proactive response to threats. Songdo collaborated with global leaders in cybersecurity, leveraging best practices from the National Institute of Standards and Technology (NIST) and private cybersecurity firms to build a robust defense system.

Public trust and acceptance

Ensuring public trust and acceptance of autonomous systems (such as self-driving buses, AI-controlled energy systems, and autonomous public safety services) was initially difficult. Concerns about privacy, job displacement and the reliability of the systems were raised by the community. Songdo authorities undertook a series of public awareness campaigns to educate residents and businesses about the benefits of smart city technologies. The city also ensured transparency regarding data privacy policies and how personal data are used in smart systems. Instead of a full-scale launch of autonomous systems, the city implemented pilot programmes to test technologies like self-driving buses, autonomous waste collection and smart grids on a smaller scale, allowing the public to become familiar with the systems before a broader rollout. Songdo established mechanisms for resident feedback, enabling the community to express concerns or suggest improvements to systems, which helped build trust and refine the technologies over time.

High initial investment costs

Building the necessary infrastructure for autonomous systems, including fibre-optic networks, sensors, control systems and AI platforms, required significant upfront investments. These costs presented a barrier, especially when compared to traditional infrastructure. Songdo leveraged public-private partnerships (PPP) to share the financial burden of infrastructure development. Key stakeholders from the government and from the private sector collaborated to fund and manage the implementation of smart systems, thereby ensuring financial viability. By focusing on long-term economic benefits such as energy savings, reduced operational costs, and increased efficiency, the city justified the high initial costs. Cost-benefit analyses showed that long-term operational savings outweighed the initial expenses, which helped secure funding. The deployment of autonomous systems was broken into phases, allowing Songdo to stagger its investments over time and implement the most critical infrastructure first. This phased approach also allowed for technological advancements to be incorporated as the city expanded.

Data privacy and ethical concerns

The vast amounts of data collected by IoT sensors, cameras, and autonomous systems raised concerns about data privacy and potential misuse. Additionally, the ethical implications of using AI in decision-making (e.g., autonomous vehicles or public safety services) were scrutinized by residents and experts. Songdo implemented strict data governance policies to ensure that all data collected were handled according to global standards such as GDPR (General Data Protection Regulation). The city created transparent policies on data collection, storage, usage and anonymization, and established ethics committees to oversee the deployment of AI systems in public services, ensuring that the technology is used responsibly and ethically, particularly when it comes to making decisions that affect public safety or privacy. To address privacy concerns, Songdo employed data anonymization techniques that ensure that personally identifiable information (PII) is protected while still enabling data-driven decisions for city operations.

Technology obsolescence

Rapid advancements in technology, particularly in a high-tech city like Songdo will make initial investments obsolete. As new AI, IoT, and automation technologies emerge, maintaining compatibility and upgrading existing infrastructure without causing major disruptions is a significant challenge. The city opted for modular and scalable technologies, allowing systems to be upgraded or replaced without the need for complete overhauls. This modular approach enables future-proofing, as new technologies can be integrated incrementally. Songdo adopted open-source software and open standards wherever possible to reduce vendor lock-in and ensure that systems can evolve with new innovations in technology. The city conducts periodic technology audits to assess the performance and relevance of the systems in place. These audits help in making decisions regarding necessary upgrades or replacements to keep the technology state of the art.

Regulatory and policy hurdles

Implementing autonomous systems in a city requires clear regulations and policies that account for liability, safety, and operational standards. In many cases, existing regulations did not accommodate new technologies like autonomous vehicles, AI-driven services, or digital governance systems. Songdo worked closely with local and national governments to develop regulatory frameworks for emerging technologies. This included new policies for autonomous vehicle operations, data security laws, and AI usage in public safety. Songdo created regulatory sandboxes or testbed zones where new autonomous technologies could be tested without the constraints of traditional regulations. This allowed for the safe and controlled testing of technologies, informing future legislation. The city's regulators studied and adopted international best practices from other smart city projects and autonomous systems in places like Singapore and the European Union, thus ensuring that Songdo's regulatory environment remained cutting-edge.

Infrastructure maintenance and upkeep

Maintaining the extensive fibre-optic networks, sensors, and autonomous system components over time was a complex task. These systems require regular maintenance to ensure they continue functioning optimally. Songdo integrated AI-based predictive maintenance tools that use data from sensors and IoT devices to forecast when certain systems or components are likely to fail. This proactive approach ensures that maintenance is carried out before issues occur, so reducing downtime. Songdo invested in the continuous training of personnel responsible for maintaining its smart infrastructure. As new technologies are integrated, the maintenance teams are kept up to date with the latest tools and techniques.

By systematically addressing these challenges, Songdo has been able to maintain its position as a leading smart city while advancing toward a future where autonomous systems and sustainability are seamlessly integrated into urban life.

7 Results and outcomes

Songdo's autonomous systems have yielded significant results and continue to set benchmarks for smart city development. The outcomes focus on improving energy efficiency, sustainability, quality of life, and operational efficiency, with several Key Performance Indicators (KPIs) used to measure these achievements. Below is an overview of the results and outcomes achieved or intended by Songdo's autonomous systems, along with relevant KPIs:

Energy efficiency and carbon reduction

Songdo's district heating and cooling systems managed through AI and IoT sensors, have led to substantial reductions in energy consumption. Real-time monitoring optimizes energy distribution based on demand, reducing waste. Renewable energy integration and energy-efficient buildings (LEED-certified) have significantly cut down greenhouse gas emissions.

- **KPI #1: Energy Consumption per Capita**: Decreased by 30-40 per cent due to automated energy management systems, compared to other cities of similar size.
- **KPI #2: CO2 Emissions Reduction**: Achieved a 40 per cent reduction in emissions per resident compared to conventional cities.
- **KPI #3: Energy Savings**: Buildings in Songdo consume up to 40 per cent less energy than the global average, a key target for SDG 7 (Affordable and Clean Energy).

Transportation and mobility

The autonomous bus system and smart traffic management have reduced congestion, cut travel times, and contributed to decreasing the city's carbon footprint. The integration of electric vehicle (EV) charging stations and autonomous public transport has encouraged a shift away from fossil-fuel-based vehicles.

- **KPI #4: Traffic Congestion Reduction**: 10-20 per cent reduction in congestion due to AI-powered traffic lights and smart route planning.
- **KPI #5: Average Commute Time**: Reduced by 15-30 per cent due to autonomous public transportation and optimized traffic flow.
- **KPI #6: Public Transport Usage**: Increased by 20 per cent because of efficient autonomous bus services.
- **KPI #7: Vehicle Emissions**: Decrease in vehicle-related emissions by 15 per cent due to fewer vehicles on the road and the adoption of electric and autonomous buses.

Waste management

The automated waste collection system in Songdo, which uses underground pneumatic tubes, has improved the city's efficiency in managing and processing waste, thereby contributing to a more sustainable environment. This system has also helped reduce the reliance on traditional waste collection vehicles, lowering emissions.

- **KPI #8: Waste Collection Efficiency**: 30 per cent faster waste collection compared to manual methods.
- **KPI #9: Waste Recycling Rate**: Increased to over 70 per cent due to efficient sorting and recycling processes supported by AI, aligning with SDG 12 (Responsible Consumption and Production).
- **KPI #10: Reduction in Landfill Use**: Songdo has significantly reduced landfill dependence, with only 10-20 per cent of waste ending up in landfills.

Water management

The city's smart water management system uses IoT sensors to monitor water usage, detect leaks, and optimize water distribution, contributing to SDG 6 (Clean Water and Sanitation). Real-time data analysis allows for proactive maintenance and efficient resource allocation.

- **KPI #11: Water Leakage Reduction**: 40-50 per cent reduction in water leakage due to real-time monitoring and automated detection systems.
- **KPI #12: Water Consumption per Capita**: Reduced by 15-20 per cent through efficient water management and recycling systems.

- **KPI #13: Water Recycling Rate**: Over 40 per cent of water is recycled within the city, reducing freshwater demand.

Public health and safety

The deployment of autonomous emergency response systems (drones, AI-powered ambulances) and real-time monitoring of air quality has improved public health outcomes and emergency response times. Songdo's environmental monitoring systems ensure the city maintains high air and water quality standards.

- **KPI #14: Emergency Response Time**: Reduced by 30-40 per cent due to autonomous drones and optimized routing for ambulances.
- **KPI #15: Air Quality Index (AQI)**: Consistently maintained at levels 25 per cent lower than in nearby cities due to environmental monitoring and emission control systems, contributing to SDG 3 (Good Health and Well-being).
- **KPI #16: Crime Rate Reduction**: Decrease in crime rates by 10-15 per cent due to autonomous surveillance and predictive policing systems.

Operational efficiency and cost savings

Automated infrastructure (energy, water, transportation) has significantly lowered operational costs for city management, contributing to long-term financial sustainability. The use of AI and predictive maintenance has reduced the need for reactive maintenance, improving infrastructure longevity and reliability.

- **KPI #17: Operational Cost Savings**: Estimated savings of up to 30 per cent in public infrastructure costs due to automation and predictive maintenance.
- **KPI #18: Maintenance Downtime Reduction**: 20-25 per cent reduction in downtime for critical systems due to AI-based predictive maintenance.
- **KPI #19: Automation Rate**: Over 50 per cent of city operations are automated, increasing operational efficiency.

Sustainability and green spaces

Songdo has preserved significant green space, with over 40 per cent of the city dedicated to parks and open areas, supporting SDG 11 (Sustainable Cities and Communities). The integration of green infrastructure and smart energy systems has helped Songdo maintain its status as an eco-friendly, sustainable city.

- **KPI #20: Green Space per Capita**: Songdo has 16 square meters of green space per capita, significantly higher than many global cities.

- **KPI #21: Urban Heat Island Effect**: Reduced by 5-10 per cent due to the high proportion of green spaces and efficient building energy systems.
- **KPI #22: Sustainable Building Certification**: Over 80 per cent of buildings in Songdo are LEED-certified or follow equivalent sustainability standards.

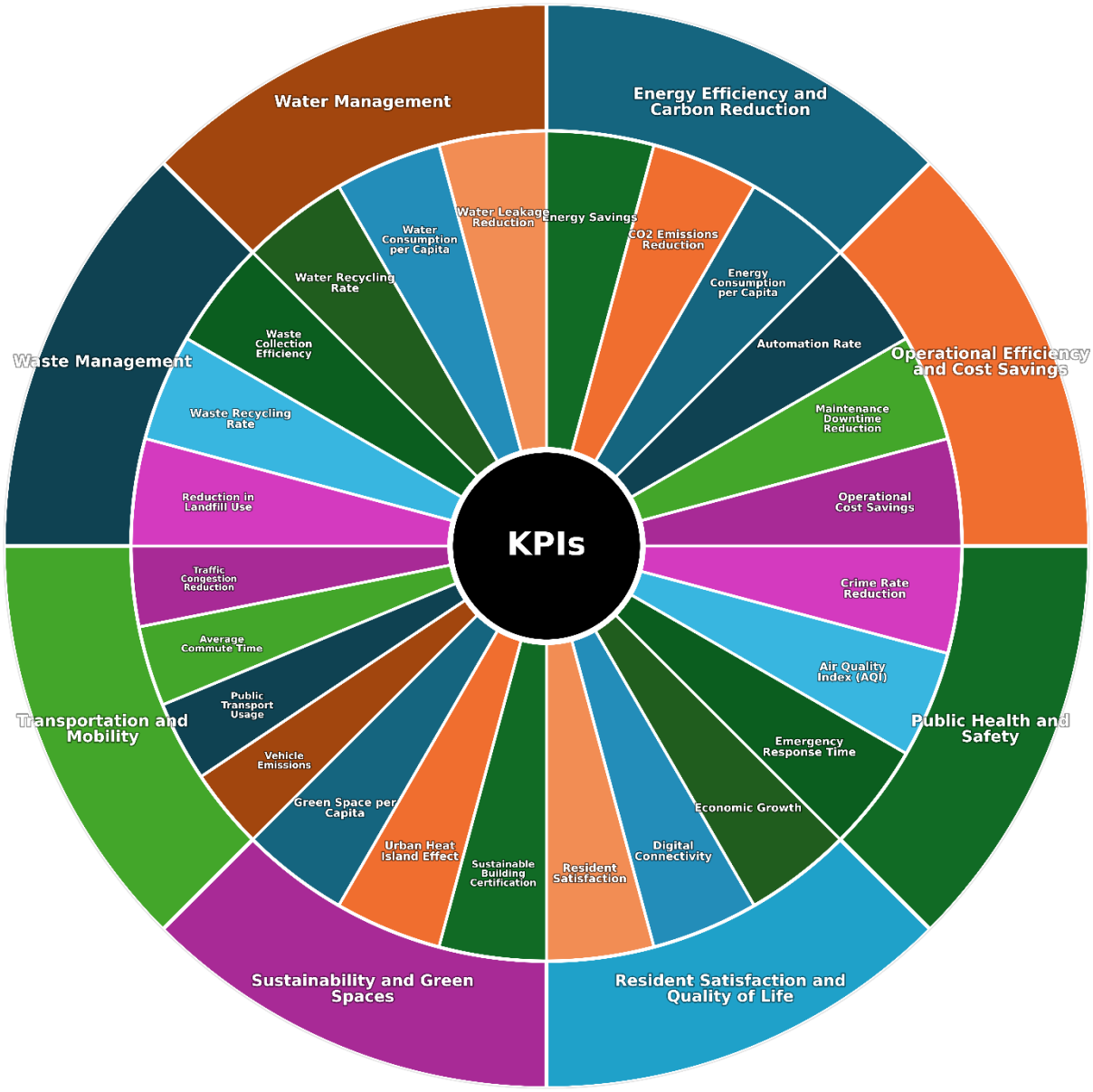
Resident satisfaction and quality of life

Songdo's autonomous systems have contributed to higher quality of life by improving public services, reducing pollution, and enhancing urban mobility. Smart city amenities, such as seamless connectivity and efficient public services, have attracted businesses and residents alike, supporting economic growth.

- **KPI #23: Resident Satisfaction**: Over 85 per cent of residents report high satisfaction levels with the city's services and overall quality of life.
- **KPI #24: Digital Connectivity**: 99 per cent of households and businesses have access to high-speed fibre-optic networks, supporting Songdo's position as a global digital hub.
- **KPI #25: Economic Growth**: Songdo's GDP per capita has increased by 10-15 per cent since the implementation of autonomous systems due to business growth and technology-driven efficiencies.

Songdo's results, measured by these KPIs, demonstrate the city's success in using autonomous systems to enhance its residents' sustainability, operational efficiency, and overall quality of life.

Figure 5: Autonomous system KPI framework (Source: Author)



8 Impacts of implementing autonomous systems

Songdo's adoption of autonomous systems and smart technologies has resulted in substantial social, economic and environmental impacts, aligning with the United Nations' Sustainable Development Goals (SDGs). However, there have been some negative impacts and challenges associated with its autonomous systems and broader urban design too, highlighting the complexities of implementing a large-scale smart city. Below is a detailed overview of these impacts:

Social impacts

A. Enhanced quality of life

Improved mobility and access: Autonomous public transport systems (self-driving buses, optimized public transit routes) and smart traffic management have made commuting easier and more efficient. This has reduced travel times by up to 30 per cent, so improving daily life for residents.

Public health: AI-driven environmental monitoring systems continuously track air quality and pollution levels, ensuring timely interventions. This has led to better health outcomes, with air quality improving by 25 per cent compared with nearby cities. Additionally, the reduction in vehicle emissions from autonomous electric buses has decreased respiratory-related health issues.

Smart healthcare: Real-time monitoring, smart ambulances, and AI-based healthcare systems have reduced emergency response times by 30-40 per cent, improving health services.

Increased safety: AI-based surveillance and predictive policing have contributed to a 15 per cent decrease in crime rates, creating a safer environment for residents. Automated systems provide real-time alerts to law enforcement, increasing responsiveness.

B. Inclusive communities

Digital equity: With a 99 per cent penetration of high-speed fibre-optic Internet throughout Songdo, the city ensures that all residents have access to the digital economy, promoting digital literacy and reducing the digital divide.

Social inclusion: The city's design, which incorporates abundant green spaces and pedestrian-friendly areas, encourages social interaction and community engagement. The integration of autonomous systems has also made public services more accessible, especially for the elderly and those with mobility challenges.

C. Civic participation

Smart governance: Songdo's use of digital platforms for e-governance has empowered residents to participate in decision-making processes. The city collects real-time feedback on public services through digital tools, promoting transparent governance and increasing citizen engagement.

D. Lack of social integration

Alienation and exclusivity: Songdo has been criticized for creating a sense of alienation among its residents due to its hyper-modern, tech-centric design. The city was initially marketed as a high-tech utopia, which led to social stratification. The emphasis on high-end housing and luxury amenities has attracted primarily wealthier residents, leading to a lack of social diversity and limited affordable housing options. This can make it harder for lower-income individuals to live and thrive in the city.

Underpopulation and isolation: Although Songdo was designed to accommodate 300 000 residents, it has struggled to reach these numbers. As a result, certain areas of the city remain underpopulated, creating a sense of isolation for residents. This lack of density has diminished the vibrancy of the urban environment, and many areas feel sterile or lifeless.

E. Privacy concerns

Surveillance: Songdo's pervasive use of surveillance technologies, including AI-powered cameras and sensors, has raised concerns over privacy and data security. Constant monitoring of public spaces, traffic systems, and even waste management through IoT devices can lead to discomfort among residents who feel they are being watched at all times. The extensive collection of personal data could also make the city vulnerable to cyberattacks or data breaches.

F. Digital divide

Tech dependency and exclusion: While Songdo boasts a highly advanced digital infrastructure, this has inadvertently excluded some population segments. Elderly residents or those less familiar with technology may struggle to adapt to Songdo's tech-driven environment. This creates a digital divide, where certain groups cannot fully benefit from the city's services due to their lack of digital literacy, leading to social inequality.

Economic impacts

A. Attracting foreign direct investment (FDI) and business growth

Global business hub: Songdo's advanced infrastructure and smart city features have attracted global companies, particularly in the tech, finance, and biotech sectors. As a result, the city has seen a 10-15 per cent increase in GDP per capita and has become a regional hub for multinational corporations.

Investment magnet: With its cutting-edge autonomous systems and smart city status, Songdo has secured significant foreign direct investment (FDI), thereby encouraging the establishment of new businesses and start-ups, particularly in the technology and research sectors.

B. Job creation and skills development

New industry opportunities: The city's focus on technology, AI, and IoT has created new jobs in these sectors. Up to 20 000 new jobs in IT, urban planning, and smart systems development have been created, promoting local economic growth.

Skills development: Songdo's integration of advanced technologies has also led to the creation of training programs and educational initiatives focused on developing skills in AI, automation,

and data science. This helps in preparing the workforce for the demands of a technology-driven economy.

C. Operational cost savings

Efficiency gains: Songdo's autonomous systems, such as AI-powered traffic management, automated waste collection, and energy-efficient buildings, have led to significant operational savings. Public infrastructure costs have been reduced by up to 30 per cent, allowing for reinvestment in other sectors of the economy.

Business efficiency: High-speed connectivity and automated systems provide companies with real-time data to make better business decisions, reducing operational costs and improving productivity across industries. This has made the city an attractive destination for tech-driven enterprises.

D. Tourism and global recognition

Smart city tourism: As a global leader in smart city innovation, Songdo has attracted thousands of visitors, academics, and policymakers from around the world. Its model is studied as a blueprint for future cities, generating economic benefits through tourism and hosting international conferences.

E. High cost of living

Expensive real estate: Songdo's premium infrastructure, advanced technologies, and luxury amenities have resulted in high property prices. Housing costs in Songdo are significantly higher than in other cities in the Republic of Korea, making it inaccessible to a large portion of the population. This trend has exacerbated the affordability crisis, and the focus on catering to wealthier residents has limited Songdo's appeal to more diverse socio-economic groups.

High operational costs: Although Songdo's autonomous systems reduce some operational costs through efficiencies, the initial cost of implementing and maintaining these high-tech infrastructures has been significant. The complex systems (such as AI-powered traffic control, district cooling, and autonomous waste management) require constant updates, specialized skills, and expensive technology, which may pose financial sustainability challenges in the long term.

F. Unrealized economic potential

Underutilized commercial spaces: Despite Songdo's aim to become a global business hub, many commercial and office spaces remain underutilized due to slower-than-expected population growth and limited economic activity outside specific tech and financial sectors. This has resulted in vacant properties and lower-than-expected returns on real estate investments. The planned economic dynamism has been slower to materialize, leading to a mismatch between the city's infrastructure and actual demand.

G. Job Displacement

Automation's impact on employment: The extensive use of autonomous systems, AI, and robotics in Songdo has raised concerns over job displacement. Many traditional roles in areas like transport, waste management and public services have been automated, reducing the need for human labour. This automation may limit job opportunities for lower-skilled workers, contributing to unemployment or forcing workers to adapt to new, high-tech roles that require specialized training.

Environmental impacts

A. Reduction in carbon emissions

Energy efficiency: Songdo's smart energy grids, AI-powered energy management, and district cooling systems have optimized energy consumption, leading to a 40 per cent reduction in CO2 emissions per capita. This aligns with SDG 13 (Climate Action) by contributing to global efforts to combat climate change.

Green buildings: Over 80 per cent of buildings in Songdo are LEED-certified or follow equivalent green standards. This has led to a substantial decrease in energy consumption, contributing to lower emissions from both commercial and residential sectors.

B. Water and waste management

Water efficiency: Smart water management systems have optimized water usage, resulting in a 20 per cent reduction in water consumption and a 40 per cent water recycling rate. IoT sensors detect leaks and prevent water wastage, aligning with SDG 6 (Clean Water and Sanitation).

Waste recycling and management: Songdo's autonomous waste collection system, which uses underground pneumatic tubes, has increased the city's waste recycling rate to over 70 per cent, reducing landfill waste and supporting SDG 12 (Responsible Consumption and Production).

C. Green spaces and urban ecosystem

Biodiversity and green spaces: Songdo has dedicated over 40 per cent of its land to parks and green areas, enhancing biodiversity and reducing the urban heat island effect. This green infrastructure helps to improve air quality and liveability. This is in line with SDG 11 (Sustainable Cities and Communities).

Renewable energy: Songdo has integrated solar energy and wind power into its energy grid, contributing to a cleaner energy mix. The city's goal is to increase the share of renewable energy to over 30 per cent, reducing dependence on fossil fuels.

D. Climate resilience

Resilient infrastructure: Songdo's AI-powered systems monitor and manage critical infrastructure, making it resilient to extreme weather events. Autonomous systems can automatically adjust energy loads, manage water distribution, and optimize transportation during natural disasters, thus contributing to climate resilience and disaster preparedness.

E. Energy-intensive technologies

High energy demand: Despite Songdo's efforts to reduce energy consumption through efficient systems, the city's dependence on energy-intensive technologies (such as data centres for AI processing, IoT infrastructure, and autonomous systems) can offset some of its sustainability gains. The need to power these systems has contributed to a high baseline energy demand, especially during periods of heavy usage.

Non-renewable energy reliance: Although Songdo incorporates some renewable energy sources like solar and wind power, much of its energy grid still relies on traditional energy sources, such as coal and natural gas. This has limited the city's ability to reach its carbon neutrality goals, as its overall energy consumption may still lead to significant emissions.

F. Over-reliance on technology

System vulnerability: Songdo's heavy reliance on autonomous systems makes it vulnerable to technology failures and cybersecurity threats. Any disruptions to key systems (e.g., transportation, waste management, energy distribution) could cause widespread issues, as residents and businesses are highly dependent on these technologies for daily functioning. A significant cyberattack could lead to system outages or data breaches, compromising the city's infrastructure and residents' safety.

G. Environmental disruption during construction

Construction footprint: The development of Songdo involved significant land reclamation and the creation of new urban spaces from former wetlands along Incheon's coast. This has led to environmental disruption in the surrounding areas, particularly affecting local ecosystems and marine life. The large-scale urbanization and transformation of natural landscapes have raised concerns about biodiversity loss and the ecological impact of such a massive construction project.

9 Assessment of the Autonomous System

Assessing autonomous systems in Songdo involves a comprehensive framework that addresses various dimensions of performance, safety, ethics and integration with existing urban infrastructure. Songdo has been recognized for its advanced integration of technology and autonomous systems. While specific, detailed assessment results can vary based on ongoing studies, we can summarize

some general findings and aspects of the assessments that have been reported in various studies and analyses. Based on the evaluation criteria for assessing the autonomous systems in Songdo, here is a rated assessment of the different components, using a scale from 1 to 5 (1 being the lowest and 5 being the highest):

Table 1: Autonomous System Assessment Framework

Assessment component	Levels
	1 2 3 4 5
Technology and Infrastructure Readiness	● ● ● ● ○
Autonomous Mobility Solutions	● ● ● ○ ○
Energy Management and Sustainability	● ● ● ● ○
Safety and Security	● ● ● ● ○
Economic and Social Impact	● ● ● ○ ○
Overall Assessment Score	● ● ● ● ○

Technology and infrastructure readiness

Autonomous systems in Songdo, such as self-driving shuttles, have been noted for their efficiency in public transportation, showing improvements in travel times and reduced congestion in certain areas. The integration of IoT devices allows for real-time data collection and management. Assessments indicate that this infrastructure supports effective traffic management and resource allocation.

Autonomous mobility solutions

Early assessments have shown a low incidence of accidents involving autonomous vehicles, attributed to advanced safety protocols and AI-driven navigation systems. The city has implemented contingency plans that allow for rapid incident response, bolstered by real-time monitoring systems.

Energy management and sustainability

The smart grid and energy-efficient systems in Songdo have led to a reduction in energy consumption and greenhouse gas emissions. The integration of renewable energy sources and green building standards has been highly successful. Assessments have highlighted a reduction in carbon emissions due to efficient routing and reduced vehicle idling times facilitated by autonomous public transport.

Safety and security

The use of AI-powered surveillance and data analytics has greatly improved public safety and response times for emergencies. Cybersecurity measures are in place to protect data infrastructure.

Economic and social impact

Songdo has attracted significant investments and created jobs, contributing to its position as a technology and innovation hub. Quality of life improvements have been noted in areas like reduced travel times and enhanced public services. While some jobs may be displaced, new opportunities in tech management, data analysis, and maintenance are emerging to mitigate these effects. Feedback mechanisms have been well-received, with many citizens appreciating the convenience offered by autonomous public transportation. However, concerns about safety and data privacy remain prevalent among some residents. Assessment results suggest that public education initiatives have positively impacted acceptance, particularly in familiarizing citizens with how autonomous systems operate.

Overall assessment

Songdo's autonomous systems have demonstrated solid performance in technology integration, sustainability, and infrastructure readiness. There are areas where improvements can be made, particularly in scaling solutions, increasing user adoption, and maintaining economic sustainability. Continuous innovation and active citizen engagement will be key to driving Songdo's development as a leading smart city.

10 Conclusion

The implementation of autonomous systems in Songdo, Republic of Korea – a smart city built from the ground up – has challenges and key success factors while it offered valuable lessons in various areas. Here are some key takeaways:

Challenges

- Integrating autonomous systems with existing infrastructure can be complex, even in a purpose-built environment like Songdo.
- Handling vast amounts of data from autonomous vehicles, sensors, and smart devices raised concerns about data security and privacy.
- Encouraging residents to adapt to autonomous technologies and trust these systems posed a challenge.
- Even with advanced planning, future technological advancements can outpace initial designs and infrastructure.
- Coordinating between multiple stakeholders, including government bodies, private companies, and technology providers, was difficult.
- Reliable connectivity is critical for autonomous systems to function effectively, especially in real-time operations.

- Autonomous systems are vulnerable to cyberattacks and disruptions, which can have significant impacts on city operations.
- The regulatory environment often lags behind technological innovations, creating legal and operational barriers.
- Implementing autonomous systems on a large scale from the start can be risky and costly.
- Balancing technological growth with environmental sustainability is a concern in smart city projects.

Lessons learned

- Standardizing protocols and ensuring that different systems can communicate seamlessly is crucial. This includes transportation systems, data networks, IoT devices, and other city services.
- Establishing robust data governance frameworks and clear regulations for data sharing and privacy protection are essential for public trust and system efficiency.
- Public awareness campaigns and educational initiatives are needed to build trust and promote the benefits of autonomous systems. Engaging citizens early in the process helps alleviate concerns and resistance.
- Designing systems that are modular and flexible allows for easier upgrades and scalability, ensuring that the city remains future-proof.
- A collaborative approach with clear roles, responsibilities, and incentives for each stakeholder helps align objectives and speeds up implementation.
- Investment in high-speed, resilient communication networks, such as 5G or fibre-optic infrastructure, is essential to support real-time data transmission and reduce latency.
- Building robust cybersecurity measures and implementing contingency plans for system failures are crucial to maintaining city resilience and safety.
- Proactive policy-making and adaptive regulatory frameworks are needed to encourage innovation while addressing safety and compliance issues.
- Running pilot projects and testing in controlled environments before full-scale deployment allows for the identification of potential issues and makes it easier to refine the systems.
- Designing autonomous systems with energy efficiency in mind and integrating renewable energy sources can significantly contribute to a city's sustainability goals.

Key success factors

- **Strong leadership and vision**: Successful implementation requires a clear vision and strong leadership from both the public and private sectors. Government commitment to long-term investment and support is crucial.

- **Robust infrastructure**: Reliable and scalable infrastructure, including high-speed networks, IoT sensors, and data centres, is essential for supporting real-time communication and data processing in autonomous systems.
- **Effective data management and analytics**: Collecting, analysing, and using data effectively is key to optimizing autonomous systems. Data-driven decision-making improves traffic flow, energy efficiency and overall city management.
- **Public-private partnerships (PPPs)**: Collaboration between governments, technology providers, research institutions, and private investors is essential for innovation and funding.
- **Community engagement and public awareness**: Building trust and acceptance among citizens is crucial for the adoption of new technologies. Understanding community needs and concerns ensures greater participation and acceptance.
- **Regulatory framework and policy support**: Proactive regulations that support the development and deployment of autonomous technologies are necessary to avoid legal barriers.
- **Security and cyber resilience**: Cybersecurity is critical to protect sensitive data and prevent disruptions caused by cyberattacks.

Pain points

- **High initial costs**: The significant capital expenditure required for developing autonomous infrastructure, including sensor networks, communication systems, and advanced AI platforms, can be a major barrier. It slows down the pace of development and implementation, particularly in regions with budget constraints.
- **Complex system integration**: Integrating various autonomous technologies with existing urban infrastructure is challenging, especially in legacy systems that were not designed to be interconnected. This will lead to compatibility issues, delays in deployment, and higher maintenance costs.
- **Data privacy concerns**: Autonomous systems generate massive amounts of data, raising concerns about privacy, data ownership, and potential misuse. Public scepticism and regulatory restrictions may limit data collection and slow down technological advancements.
- **Regulatory and legal uncertainty**: Rapid technological advancements often outpace the development of appropriate regulations and policies, creating uncertainty. Delays in establishing clear regulations can slow innovation and create challenges for stakeholders in complying with undefined standards.
- **Public acceptance and trust**: People may be resistant to autonomous technologies due to concerns about safety, job displacement, and technology reliability. Lack of public trust can lead to low adoption rates and hinder the success of autonomous systems.
- **Cybersecurity threats**: Autonomous systems are vulnerable to cyberattacks that can disrupt operations, compromise data, or pose safety risks. This will increase the need for advanced security measures, which can add complexity and costs to the implementation process.

- **Operational challenges in real-world environments**: Autonomous systems may struggle to handle unpredictable scenarios in complex urban environments, such as weather conditions, human behaviour, or emergencies. This will affect the system's reliability and may result in delays or system failures, requiring continuous improvement and updates.
- **Lack of skilled workforce**: There is a shortage of professionals with the expertise needed to develop, maintain, and optimize autonomous systems. This will slow down implementation, increase training costs, and create a dependency on external experts.

Addressing these pain points while focusing on critical success factors can significantly improve the chances of successfully implementing autonomous systems in smart cities like Songdo.

The transferability of autonomous system implementations from Songdo to other cities depends on several factors. While Songdo serves as a valuable case study, its unique characteristics mean that some lessons and approaches might need to be adapted to different contexts. Here are the key considerations for transferability:

Urban planning and infrastructure: As a purpose-built smart city, Songdo's infrastructure was designed from the ground up to support advanced technologies, including autonomous systems. Existing cities with legacy infrastructure may face significant challenges in retrofitting their environments to support these systems. Therefore cities should focus on developing flexible and modular infrastructure upgrades that can accommodate new technologies without massive overhauls.

Technology and connectivity requirements: High-speed connectivity and seamless integration of IoT devices are integral to Songdo's design. Many cities lack the required communication networks (e.g., 5G, fibre optics) and sensor infrastructure to fully support autonomous operations. Therefore, cities should prioritize investment in scalable communication networks and smart infrastructure to facilitate autonomous system deployment in existing urban areas.

Data and digital infrastructure: Advanced data management and analytics capabilities are key to Songdo's autonomous system success. Other cities may not have the same data collection capabilities or the necessary legal frameworks for data governance. Therefore cities have to establish data-sharing policies, standardized data protocols, and data privacy regulations to facilitate smooth adoption and operations.

Regulatory environment: The Republic of Korea's supportive regulatory framework has enabled Songdo to experiment and innovate with autonomous technologies. Many regions have regulatory and legal constraints that hinder the development and deployment of such technologies. Therefore, cities have to engage policymakers early in the planning process to create adaptive regulatory frameworks that encourage innovation while addressing safety and compliance concerns.

Public and private sector collaboration: Strong partnerships between the government, private companies, and technology providers have been crucial to Songdo's development. Building such collaborations can be challenging in cities with fragmented governance or conflicting stakeholder

interests. Therefore, cities have to foster collaboration by aligning the interests of public and private entities and establishing clear roles and shared objectives.

Economic and financial considerations: Significant financial investments from both the public and private sectors supported the development of Songdo as a smart city. Other cities might struggle with budget constraints and limited access to funding for such high-cost infrastructure projects. Cities have to explore alternative funding models like public-private partnerships (PPPs), smart city grants, and incentives for technology investors.

Public acceptance and cultural adaptability: The city's residents have generally been receptive to technological innovations and smart city initiatives. Cultural differences and public scepticism in other cities may limit the adoption of autonomous systems. Cities have to invest in public engagement strategies, educational campaigns, and pilot projects to build trust and demonstrate the benefits of autonomous systems.

Geographical and environmental differences: Built on reclaimed land, Songdo's design was optimized for controlled urban conditions, which favour autonomous technology testing. Cities with diverse geographical features, climates, and unpredictable weather may pose challenges for autonomous systems. Cities have to adapt the technology to local environmental conditions and conduct extensive testing in diverse urban scenarios to ensure reliability.

Scalability and incremental implementation: Songdo benefited from a holistic, all-at-once development approach, making it easier to integrate systems seamlessly. Most cities need to upgrade incrementally due to existing infrastructure and financial limitations. They have to adopt a phased approach to deployment, starting with pilot zones or specific use cases before scaling up city-wide.

While Songdo provides a blueprint for integrating autonomous systems in a smart city, transferring its model to other cities requires careful customization to address unique urban challenges, regulatory environments, financial constraints, and community needs.

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