

Article

Development of Smart Mobility Infrastructure in Saudi Arabia: A Benchmarking Approach

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Abstract: Smart mobility systems offers solutions for traffic congestion, transport management, emergency, and road safety. However, the success of smart mobility lies in the availability of intelligent transportation infrastructure. This paper studied smart mobility systems in three Asia-Pacific countries (South Korea, Singapore, and Japan) to highlight the major strategies leading their successful journey to become smart cities for aspiring countries, such as the Kingdom of Saudi Arabia (KSA), to emulate. A robust framework for evaluating smart mobility systems in the three countries and Saudi Arabia was developed based on the indicators derived from the smart mobility ecosystem and three major types of transport services (private, public, and emergency). Sixty indicators of smart mobility systems were identified through a rigorous search of the literature and other secondary sources. Robots, drones, IoT, 5G, hyperloop tunnels, and self-driving technologies formed part of the indicators in those countries. The study reveals that the three Asia-Pacific countries are moving head-to-head in terms of smart mobility development. Saudi Arabia can join these smarter countries through inclusive development, standardization, and policy-driven strategies with clear commitments to public, private, and research collaborations in the development of its smart mobility ecosystem. Moreover, cybersecurity must be taken seriously because most of the smart mobility systems use wireless and IoT technologies, which may be vulnerable to hacking, and thus impact system safety. In addition, the smart mobility system should include data analytics, machine learning, and artificial intelligence in developing and monitoring the evaluation in terms of user experience and future adaptability.



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1. Introduction

The population of urban areas is continuously growing throughout the world. The present urban population is about 53% of the world's population and it is likely to reach 67% in 2050. Presently, urban travel constitutes more than half (64%) of the total travel being made and this figure is expected to double by 2050 [1]. This surge in the population and travel demand comes with enormous mobility challenges including the change in travel behavior and increased demand for speed, convenience, and service predictability. Hence the need for developing a more intelligent transportation infrastructure [1,2].

To achieve this, the concept of a smart city and smart mobility needs to be implemented [3]. Smart mobility integrates information and technology into the transportation system to enable efficient mobility in an area [4,5]. Currently, automatically smarter transportation systems are being developed as a result of advancements in digital technology, which leads to more efficient, intelligent, and environmentally friendly mobility (smart mobility) [3,6]. Smart mobility can be seen as an intelligent transport system (ITS) that offers solutions for traffic management, information providers, road-vehicle collaboration, emergency, and more importantly, safety [7].

In KSA, the need for a safe, secure, and convenient transportation system through ITS cannot be over-emphasized. The Saudi Vision 2030 outlines the government's dream of a

smart Saudi Arabia in 2030, which include building a more sustainable and resilient transportation system [8]. Further to the adoption of this vision, several smart cities equipped with various intelligent infrastructures are actively evolving. Riyadh is KSA's capital and financial hub and has adopted many smart city initiatives to ensure the success of Saudi Arabia's Vision 2030. The 176 km Metro project in the city is equipped with automatic electrification, Wi-Fi services, LED lighting, and surveillance cameras [9]. Furthermore, a central traffic monitoring and control system was installed to provide sustainable management solutions for high traffic volume often experienced in the city.

However, despite this development, traffic congestion and accidents are among the major issues Riyadh city is facing. According to the Interior Ministry, the annual cost of accidents in the Kingdom is estimated to be around SAR 21 billion [10]. Thus, the widespread and continuous implementation of smart mobility policies and initiatives through ITS and intelligent infrastructure that were successfully implemented elsewhere will go a long way in achieving the vision of a smart Saudi Arabia. Hence the need for a benchmarking study to highlight the strengths and weaknesses of the existing intelligent transportation infrastructure systems in the KSA with a view to achieving the goals of Saudi Vision 2030 and Smart Saudi Arabia. A benchmarking study can be achieved through the use of appropriate smart mobility indicators. Many indicators for benchmarking smart mobility have been proposed by many studies including those related to public transport, private transport, and emergency transport [6,11,12]. Some studies also further grouped the indicators based on accessibility, sustainability, and innovation [11].

Although many studies assessed smart mobility around the globe, there is little information about studies on the evaluation of the smart mobility system in KSA in comparison with other advanced countries. Therefore, a comprehensive smart mobility evaluation framework to measure the smart mobility system in KSA is needed. Additionally, South Korea, Japan, and Singapore have been identified as worldwide leaders in terms of smart mobility. One of the most remarkable elements of mobility in these nations is the extensive use of smart technologies and the influence they have on people's quality of life in terms of ease of travel, reduced congestion, and enhanced safety and dependability of transportation services [13].

In this study, smart mobility development in three Asia-Pacific countries and KSA are compared using a benchmarking framework developed using methodologies outlined in previous research [6,11,12]. The study hinges on three important questions: (i) How do Japan, Singapore, and South Korea govern interventions in smart mobility? (ii) What are the most appropriate indicators and indices to study smart mobility? (iii) What are the smart mobility developments in Japan, Singapore, and South Korea?

In an attempt to answer these questions, the concept of smart mobility in terms of the technologies involved are first discussed with a special focus on intelligent transportation system (ITS), intelligent infrastructure, and intelligent vehicles. Secondly, several studies that used smart mobility indicators were reviewed, and the most applicable indicators were selected. The indicators were grouped according to the smart mobility ecosystem proposed by [14] and three transportation subsystems, namely private transportation, public transportation, and emergency transportation.

The smart mobility ecosystem includes: (i) User experience; (ii) existing smart mobility modes; (iii) emerging technology; (iv) data analytics; (v) infrastructure; and (vi) governance and regulations [15]. These indices are further combined into a composite smart mobility index, which indicates an overall development of smart mobility in a particular country. These indices allow a comparison of the smart mobility infrastructure development in three Asia-Pacific countries and KSA.

This paper is organized as follows: Section 2 presents the concept of intelligent transportation systems, intelligent infrastructure, and intelligent vehicle technologies as they are applied to smart mobility development; Section 3 outlines the indicator selection and index construction process for this study; Section 4 presents the results and a discussion of the evaluation of the smart mobility development in the selected countries; and Section 5 is

the conclusions and suggestions for the appropriate steps for the development of smart mobility in KSA and further studies.

2. Intelligent Transportation System (ITS)

The intelligent transportation system (ITS) is attracting great attention in many countries (e.g., Singapore, South Korea, Japan, China, EU countries, and the USA), and in academia and industry. This is because it makes the transportation sector more sustainable, efficient, and convenient and reduces climate change's effects on traffic. ITSs integrate information and communication technologies (ICT) with transportation infrastructure [15]. The system collects data from sensors and equipment implanted in vehicles and infrastructure and gives contextual information for making inferences about the state of the transportation system at any given time and location.

The information derived from ITS could be used to offer information and alert services that can improve efficiency in managing resources and people's convenience in urban areas. Smart mobility implementation through ITSs reduces delays due to traffic congestion, fuel consumption, carbon emissions, and economic losses [15]. When ITS is integrated into the transportation system's infrastructure, and in vehicles, it will improve safety and mobility and enhances the productivity of the system. This integration can be achieved through the use of advanced communications technologies, such as wireless and wireline communications-based information and electronics technologies.

ITS have vast applications in smart mobility and is majorly categorized into traffic management, maintenance management, telematics, and infotainment [16]. Traffic management involves optimizing urban transport systems by reducing travel time, fuel consumption, emergency routes guidance, and traffic control. It also includes traffic signals and public transportation control systems. Maintenance management operates using real-time data exchange for continuous monitoring and assessment of the conditions of ITS infrastructure. Telematics is applied in monitoring the performance of onboard vehicle units that are providing driving assistance services in autonomous vehicles. Infotainment is the combination of information and entertainment, offering Internet-based services to passengers to increase their journey comfort. The ITS systems consist of intelligent infrastructure systems and intelligent vehicle systems.

2.1. Intelligent Infrastructure

Intelligent infrastructure leverages technological advancement to collect, store, and analyze data on nearly all parts of city operations. The availability of low-cost sensors, internet connectivity, and inexpensive cloud computing makes it easy for city authorities to connect transportation infrastructure and other amenities to the Internet of things. Intelligent infrastructure harnesses the capacity of artificial intelligence, the latest sensing technology, pervasive computing, and wide-range connectivity to transform the world. This transformation becomes possible through a compound relationship between humans, technologies, and their environments. Intelligent infrastructure combines the physical and virtual aspects of places and people to form autonomous system senses, learns the human's cognitive and physical states, and adapts to their environments [17].

Intelligent transport infrastructure can transform the future of transportation systems where human and other technology-based systems are interconnected and dependent on each other and where new knowledge and insights into the system are created through data mobilization and information integration [17]. In the context of transportation, intelligent infrastructure collects transport-related data, processes it, and transforms the acquired data into timely, accurate, and relevant information in order to make the transportation system efficient, safer, and convenient. This will allow the system to drive autonomic responses and adapt to changing conditions.

Intelligent transport infrastructure is the backbone of the intelligent transportation system. It enables the system to process the large amount of data often collected in real-time and provides efficient transportation services in urban areas where they are deployed [3].

ITS infrastructure comprises physical and spatial structural elements and ITS stations (functional elements in ITS architecture).

ITS stations are responsible for adding intelligence to the infrastructure. According to ETSI EN 302 665 [18], ITS stations may further be categorized into vehicle ITS stations (mobile); roadside ITS stations (fixed); personal ITS stations (mobile); and central ITS stations (fixed) [16]. These stations mainly consist of (i) a sensing unit, (ii) a computing unit, (iii) a communication unit, and (iv) a power unit. Traffic detection technologies, such as inductive loops, radio-frequency identification (RFID), light detection and ranging (LiDAR) sensors, radio-frequency identification (RFID), and automatic license plate detection cameras, are usually used as parts of the sensing units and other onboard sensing units.

The computing unit controls the computational processes. Communication devices such as beacons, transceivers, and routers formed the communication unit, while the power unit supplies the power-through renewable energy sources or panels or the electrical grid system [16]. In order to comply with traffic and safety regulations, ITS stations may include actuating and control devices to prevent hazardous conditions [16].

2.2. Intelligent Vehicles

Recently, vehicles are continuously being designed with increasing sophistication and are often equipped with Global Positioning Systems (GPS) and wireless communication devices. These technologies allow the vehicles to navigate, communicate, and transfer information to promote efficient human–vehicle interactions. It is based on these sophistications that the concept of autonomous/intelligent vehicles emerges. An intelligent vehicle must satisfy the minimum technology requirements for (i) the position and movement state of the vehicle, (ii) the environmental state of vehicle surroundings, (iii) navigational abilities, (iv) the condition of the driver and other passengers, and (v) vehicle-infrastructure communications [19].

Intelligent vehicles use cutting-edge technologies to enable autonomous driving abilities and enhance user experience. Intelligent vehicles can detect events in their environment and make inferences on route and navigation decisions without human interference. However, there are growing concerns that small faults in an intelligent car system might lead to a serious safety problem. These concerns trigger heavy investments in electronic systems from the automotive industry to ensure safety, comfort, and performance. Intelligent or autonomous vehicles (AVs) are already on the roads in many countries and these vehicles are already communicating with each other to ensure the safety of road users. Vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) are emerging as some of the smart mobility technologies enabling communication between vehicles, road infrastructure, and other objects to improve road safety, user convenience, and comfort [19].

Intelligent vehicles operate without drivers to serve passengers or carry goods. Equipped with a computerized control system, intelligent vehicles navigate autonomously from the moment a user initiates a mission and move safely over streets, roads, and other pavement surfaces [15,18]. In the process of delivering the mission, intelligent vehicles gather data from the environment while performing optimally to avoid any possible collisions with other elements of the environment. A typical example of an intelligent vehicle is the Google driverless car and G Mercedes S500 Intelligent Drive that traveled several kilometers autonomously. In the process, the vehicle successfully interacted with roundabouts, traffic congestions, traffic control devices, and pedestrians.

The advantages of intelligent/autonomous vehicles lie in having smooth traffic and higher road safety, passenger comfort, and fuel economy [15]. ITS infrastructure requires high computing power, analytical software, connectivity, and other features that enable communication between transportation infrastructure, vehicles, and people, leading to higher efficiencies and connected mobility. The connected mobility allows vehicle-to-anything (V2X) communication, which includes: vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-occupant, vehicle to a vulnerable road user, vehicle-to-environment, and vehicle-to-network. Connected mobility can improve the safety of our roads, reduce congestion,

and make them more eco-friendly because of the sophistication of intelligent vehicles in terms of data collection, storage, processing, and sharing mechanisms. Therefore, with the intelligent vehicle and other infrastructure capable of handling connected mobility in place, ITS applications, such as real-time navigation, traffic information dissemination, safety warnings, advanced driver assistance systems (ADAS), and self-driving, becomes possible [3].

The technologies highlighted above can transform our cities into intelligent environments where information and communication technologies create interactive environments that use communication to solve our daily problems and ensure better public management. An intelligent city is expected to deal with urban challenges, such as traffic congestion, security surveillance, environmental pollution, and natural disaster, through smart solutions that are based on big data. These solutions require state-of-the-art wireless communication, remote sensing, and data management infrastructure.

3. Methods

3.1. Data

This study used secondary sources of information in data collection due to resource limitations. The data were collected from several sources, including webpages of transport authorities, agencies and statistics, reports and publications, and some other international-ranking publications. In the first instance, the webpages of transportation agencies in the respective countries were accessed using the Google search engine. The indicator names, country names, and/or city names were used as keywords. The search for the keywords was repeated many times by different people independently. Most of the web pages provided enough information for the study. However, finding the extent or coverage of a particular indicator in some countries was the main challenge. In such situations, several sources of information were used, including news publications.

The major sources of the data were: the Ministry of Land, Infrastructure, Transport, and Tourism [20] and the Universal Traffic Management System [21] for Japan; the Ministry of Land, Infrastructure, and Transport [22], Korean Expressway Cooperation [23], Korea-ITS [24], and the Korean Transport Institute [25] for Korea; the Land Transport Authority [26], Intelligent Transportation Society of Singapore (ITSS) [27], and the Centre of Excellence for Testing & Research of AVs [27] for Singapore; and the Ministry of Transport, The Saher System [28], and the Saudi Public Transport Company [27] for Saudi Arabia.

3.2. Building a Smart Mobility Evaluation Framework for the Three Asia-Pacific Countries and KSA

Several studies have used composite indicators to measure the performance of transportation systems [11,28]. This study used secondary sources of information in data collection due to some resource limitations. The data were collected from several sources including webpages of transport authorities, agencies and statistics, reports and publications, and some other international-ranking publications. In the first instance, the webpages of transportation agencies in the respective countries were accessed using Google search engine and the indicator names, country names, and/or city names were used as keywords and mined using Google search with keywords of the indicators, country names, and/or city names. To ensure accuracy and robustness in the collected data, the web search was repeated by different people independently. Most of the web pages provided enough information for the study. However, finding the extent or coverage of a particular indicator in some countries was the main challenge. In such situations, several sources of information were used, including news publications.

Using the Google Search Engine, webpages of city authorities, research institutions, services providers, related companies, consultant reports, and news agencies were utilized to obtain data [6,13,29]. Overall, nine (9) different indices were estimated from sixty (60) selected indicators. These indices were selected based on the smart mobility ecosystem [13] and the three main transportation subsystems. The indices include data and analytics, emerging technology, existing smart mobility modes, governance and regulation,

infrastructure, user experience, public transport, private transport, and emergency transport. These indices are aggregated into a composite Smart Mobility Index for each country. The indicators were selected based on their measurability, availability, interpretability, and their individual impact on smart mobility [30].

The units of the indicators are percentages, extent of coverage, and number indicators where possible. The extent of coverage is categorized into full coverage (FC = 1), partial coverage (PC = 0.66), trial period (TP = 0.33), and not available (NA = 0). However, when information about an indicator is not sufficient, the on (Available (A) or Yes = 1) and off (Not available (NA) or No = 0) values were used as shown in Table 1. Other units of indicators used are scores from other organizations that had access to the data from the countries involved. The data for the set of selected indicators of smart mobility infrastructure used in this study are presented in Table 1 to show the samples of the data. The remaining indicators are provided in Supplementary Information Table S1.

Table 1. Indicators for smart mobility infrastructure.

Country	Internet Coverage	Laboratories	Test Beds	Connected and Autonomous Vehicles	Surveillance	GIS	ITS Traffic Management Center
Japan (JPN)	92.70%	YES	YES	3.233	A	A	FC
Korea (KOR)	96.50%	YES	YES	3.525	A	A	FC
Singapore (SGP)	89.73%	YES	YES	3.379	A	A	FC
Saudi Arabia (SAU)	92.50%	NO	NO	1	A	A	TP
Country	Road Network	Electric Vehicle Charging	Smart Motorways	Smart Parking Facilities	Traffic Signs and Signals	Intermodal Mobility Hubs	Internet of Things (IoT)
Japan (JPN)	1.13	44	YES	FC	FC	YES	FC
Korea (KOR)	3.23	50	YES	FC	FC	YES	FC
Singapore (SGP)	4.79	42	YES	FC	FC	YES	FC
Saudi Arabia (SAU)	10.3	20	NO	PC	FC	NO	PC

The individual indicators have different units; therefore, each indicator result was rescaled using z-score normalization in order to be aggregated into indices for smart mobility.

3.3. Composite Indicator Development and Analysis

The smart mobility index for measuring the smart mobility development in Japan, Singapore, South Korea, and Saudi Arabia was developed using “COINr”, a package for building, analyzing, and visualizing composite indicators written in R statistical programming language [31]. COINr takes the indicator data, then processes and performs necessary analysis to form a single object called a “COIN”. COINr includes several functions used for building/analyzing composite indicators, including normalization methods, either for all indicators or for each individually; weighting using manual, PCA weights, or correlation methods; and several aggregation methods for aggregating indicators at different aggregation level. COINr includes detailed indicator statistics, visualization tools, and data imputation methods [32].

3.3.1. Normalization of Indicators

Normalization is the operation of bringing indicators onto comparable scales so that they can be aggregated more fairly. In this study, normalization of the indicators was done using z-scores transformation, which uses the mean and standard deviation as reference points as follows:

$$x_{min} = \frac{x - \mu_x}{\delta_x} \times a + b, \quad (1)$$

where x , is the normalized indicator value, μ_x and δ_x are the mean and standard deviation of x . The indicator is first re-scaled so that its mean and standard deviation are zero and one, respectively. Then, it is scaled by a factor a and moved by a distance b . Z-scores are generally less sensitive to outliers because the standard deviation is less dependent on an outlying value [31].

3.3.2. Aggregation and Weighting

Aggregation is the operation of combining multiple indicators into one value. It is normally done on normalized data, unless the indicators are on similar scales. Composite indicators often have a hierarchical structure that necessitates multiple aggregations. Overall, aggregating indicators is a form of information compression to combine many indicator values into one. The indicator data are presented and made available alongside aggregate values, then aggregate (index) values can complement indicators and be used as a useful tool for summarizing the underlying data and identifying overall trends and patterns. Many aggregation methods involve weighting the indicators/aggregates in the aggregation. To aggregate, weights need first to be specified, but to adjust weights effectively it is necessary to aggregate.

This chicken and egg conundrum is best solved by aggregating initially with a trial set of weights, perhaps equal weights, then seeing the effects of the weighting and making any weight adjustments necessary. The most straightforward and widely-used approach to aggregation is the weighted arithmetic mean. Denoting the indicators as $x_i \in \{x_1, x_2, \dots, x_d\}$ the weighted arithmetic mean is calculated as:

$$y = \frac{1}{\sum_{i=1}^d w_i} \sum_{i=1}^d x_i w_i \quad (2)$$

where the w_i are the weights corresponding to each x_i . Here, if the weights are chosen to sum to 1, it will simplify the weighted sum of the indicators. In any case, the weighted mean is scaled by the sum of the weights, so weights operate relative to each other [30].

Clearly, if the index has more than two levels, then there will be multiple aggregations. For example, three groups of indicators may give three separate aggregate scores. These aggregate scores would then be fed back into the weighted arithmetic mean above to calculate the overall index. The arithmetic mean has “perfect compensability”, meaning that a high score in one indicator will perfectly compensate for a low score in another [31]. Figure 1 presents the structure of the smart mobility evaluation framework utilized in this study.

3.4. Smart Mobility Development in Asia-Pacific Countries and Saudi Arabia

Smart mobility employs Intelligent Transport Systems (ITS) to ensure that transportation is safe, smart, and green through the use of various combinations of modern technologies. These technologies are being deployed across the Asia-Pacific region in countries such as Japan, South Korea, and Singapore as global ITS leaders [19]. These countries have developed and tested many technologies in connected and autonomous vehicles (CAVs) and mobility-as-a-service (Maas) platforms. ITS is revolutionizing transport in the Asia-Pacific region through the deployment of cutting-edge information technology (IT)-based communications and control technologies. These technologies enhance traffic flow and provide real-time traffic information and automatic payment systems. Recently, developed state-of-the-art smart mobility technology, cooperative-ITS (C-ITS) is one of the trending terminologies in these countries [19].

Smart mobility solutions support countries in achieving the Sustainable Development Goals (SDGs). The C-ITS is a new paradigm for the next-generation ITS focusing on safety, mobility, and sustainability through V2V, V2I, and V2P communication [31]. When fully deployed, these technologies will help in improving safety and mobility while reducing the health and environmental impacts of vehicular emissions. The effectiveness of smart

mobility and ITS solutions depends largely on an all-inclusive regulatory framework that outlines the responsibilities of all the stakeholders, including the public and private sectors, and the R&D community in ITS development and operation. Furthermore, regulations integrate current and emerging technologies seamlessly. In the Asia-Pacific region, the successes of Japan, Singapore, and South Korea in the planning, development, and operation of smart mobility could largely be attributed to the well-developed and adequate smart mobility and ITS policies, regulations, and guidelines [6].



Figure 1. Structure of the smart mobility evaluation framework.

3.4.1. Japan

The Japanese ITS was designed for people, roads, and vehicles to be fully integrated to resolve traffic congestion, traffic accidents, and their resulting environmental impacts. The ITS systems in Japan, VICS (Vehicle Information and Communication System), and Electronic Toll Collection (ETC) service are recognized as the most advanced ITS (Intelligent Transport System) solutions available in the world [33]. Such an achievement hinges on the continuous Japanese Government's efforts in research and development, collaboration, and partnership with private industries and organizations, which resulted in the establishment of many development areas and user services.

The VICS collects and processes road traffic information and transmits real-time information on traffic, travel time, and congestion to navigation systems to improve driver convenience, which is then transmitted via radio wave and infrared beacons and FM in text, simple graphics, and maps. Japan-ITS took a new turn in 2014, when the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) unveiled a new C-ITS project called

“ETC2.0.” Big data analytics and cloud technologies were incorporated into the ETC system to include safe driving support, weather notifications, traffic jam information, and dynamic route guidance. Bidirectional data communication exists between the onboard device and the roadside infrastructure [6]. The C-ITS system transmits the in-vehicle information (IVI) using VICS with a radio frequency of 2.4 GHz [16].

The various ITS projects in Japan are executed under the Universal Traffic Management System (UTMS). The main goal of UTMS is to make Japanese roads safer, more comfortable, and more sustainable with the help of ICT gadgets that allow communications between individual vehicles and traffic management systems. UTMS services disseminate real-time traffic information to drivers, which allows for proactive traffic management, safe driving support, prompt emergency responses, and efficient public and freight transport. UTMS includes Advanced Mobile Information Systems (AMIS); Fast Emergency Vehicle Preemption Systems (FAST); Help Systems for Emergency Life-Saving and Public Safety (HELP); Public Transportation Priority Systems (PTPS); Mobile Operation Control Systems (MOCS); Driving Safety Support Systems (DSSS); Pedestrian Information and Communication Systems (PICS); and Dynamic Route Guidance Systems (DRGS). The Advanced Mobile Information Systems (AMIS) contains infrared beacon devices onboard to provide real-time traffic information to drivers using roadside display boards, in-vehicle radios, and other media. AMIS ensures natural dispersion of the traffic flows, alleviates traffic congestion, and eases driver’s stresses. Another infrared beacon-based system is the Fast Emergency Vehicle Preemption System (FAST), which was conceived to reduce accidents involving emergency vehicles and improve the life-saving rate and criminal arrest rate. The system detects emergency vehicles and prioritizes them at signalized intersections to shorten their response time [21].

A UTMS service related to emergency response is the HELP (Help System for Emergency Life-Saving and Public Safety). The HELP system assists emergency vehicles in conducting rapid response rescue activities. It immediately reports information about the location of incidents involving traffic accidents, vehicle breakdowns, and sudden illnesses to rescue organizations. The Public Transportation Priority Systems (PTPS) gives priority to public transportation modes at signalized intersections. The PTPS encourages people to switch from cars to public transport modes by reducing travel times and increasing user convenience. The Mobile Operation Control Systems (MOCS) was designed for the efficient management of bus, freight, sanitation, and other services operations by providing accurate time and locations of the vehicles. Information about air pollution and noise from traffic is being collected through Environment Protection Management Systems (EPMS) to coordinate and manage traffic signals and provide route guidance, with a view to reducing the environmental impacts of traffic [34].

The Driving Safety Support Systems (DSSS) are designed to assist drivers in safe driving using various detection sensors. These sensors detect vehicles and other road users not visible to the driver’s sight, and the DSSS alerts the drivers using traffic display boards or onboard vehicle units. DSSS is categorized as Level I or Level II. The DSSS level I use roadside equipment, and the position and speed of the vehicles to detect the possibility of dangerous situations in the road traffic environment and supply safe driving support information to the drivers via onboard devices. These systems improve driver behavior through a learning effect. The DSSS level II systems use infrared beacon devices at accident-prone intersections [35]. These systems include enhancements systems for traffic signal and stop sign recognition, prevention of rear-end, and crossing collision prevention. The Pedestrian Information and Communication Systems (PICS) provide safety information for the elderly and physically challenged persons at intersections using voice. Recently, PICS was improved to control traffic signals at intersections using smart devices and transmit pedestrian signal information to mobile phones via Bluetooth [21].

Japan’s Strategic Innovation Promotion Program (SIP) focuses on the C-ITS systems, including autonomous driving and safety support systems that can be further developed in collaboration with the private sector. The main focus of the SIP program includes the

development of advanced navigation information and field operational tests with enhanced information and sensing technologies. Other areas include the development of advanced technologies for Human Machine Interface (HMI) and enhanced security systems [36].

In order to cope with the rapid increase in traffic in the future, technical studies for the introduction of the V2X system in the 5.9 GHz band are being carried out. Twenty-five (25) use cases were developed in 2020. The requirements for DSRC in the 700 MHz band and for V2X communication in the 5.9 GHz band were defined using simulations in each of the cases. In order to realize advanced automated driving, several R&D projects about delivering traffic information have been conducted since 2020 [37].

3.4.2. Singapore

International ranking organizations, including the Institute of Management Development (IMD); the Singapore University of Technology and Design (SUTD); the International Institute for Management Development; KPMG's global ranking of leading technology innovation hubs outside of Silicon Valley/San Francisco in 2021; and KPMG Autonomous Vehicles Readiness Index 2020, ranked Singapore at the forefront of smart city innovations [38]. Singapore used three main strategies in achieving this feat: The implementation of smart mobility solutions, the development of ITS standards, and the establishment of collaborations in R&Ds [6].

Recently, the smart urban mobility program, which is a smart transport initiative in Singapore, uses smart technologies to enhance the public transport system and provide a comfortable, convenient, and reliable public transport system. These initiatives include connected and autonomous vehicles (CAVs), CETRAN, automatic electronic payment systems, on demand transport services, and open data analytics [37]. Under this initiative, Singapore is determined to optimize its limited land resources by providing reliable, safer, and comfortable vehicles, with enhanced transportation methods and systems [26]. Autonomous vehicles are a good candidate for this purpose. To date, many autonomous driving trials with cars, buses of different sizes, and trucks guided by transponders installed on the road have been and are being carried out. Furthermore, there are project trials on platooning with heavy vehicle leader-follower formations [39].

The Singapore Smart Nation initiative, launched in 2014 [40], was the backbone of this development, where both hard and soft infrastructures were conceived for the smart city. It also leads to the standardization of IoT usage and the Smart Nation Sensor Platform (SNSP) development, smart urban mobility, and other digital economy initiatives. The Smart Nation Platform is an enhanced connectivity network that allows companies and government agencies to develop innovations in smart services [39].

Smart Mobility 2030 includes ITS vision to move Singapore into an inclusive, integrated, and vibrant community through its ITS strategic plan [26,41]. The main objective of the vision is to meet transport challenges in a systematic and coordinated manner for smarter urban mobility in the future [26]). The deployment of ITS to over 160 km of expressways and tunnels significantly enhances the commuting experience of land transport users. The main ITS initiative includes: (i) Integrated, Real-Time Traffic Information, i-Transport, ITS Operations Control Centre (OCC), Expressway Monitoring and Advisory System (EMAS), Parking Guidance System, Green Man+, Junction Electronic Eyes, Traffic Scan, and Traffic Message Channel (TMC) [26,42].

The i-Transport is an integrated platform domiciled at ITS Operations Control Center (OCC) that connects all the ITS data, makes inferences, and shares the information for planning, traffic analysis, monitoring and evaluation, and incident management, as well as informed transport policies and travel decisions. The real-time information is then displayed on the Expressway Monitoring and Advisory System (EMAS), which is an incident management tool used for the prompt detection of accidents, vehicle breakdowns, and other incidents to ensure fast recovery of a normal traffic flow along the expressways. The traffic information from EMAS can be obtained through OneMotoring, MyTransport.SG

mobile app, @LTATrafficNews on Twitter, and broadcasts live on TrafficWatch (MediaCorp Radio) [43].

At the junctions with traffic lights, the presence of vehicles and pedestrians is detected through sensors laid beneath the road, and the real-time traffic data obtained are analyzed by the logic and algorithms in the Green Link Determining (GLIDE) system. The GLIDE system ensures variable timing of the traffic light based on the traffic volume [44]. The Green Man+ at these junctions extends the green man time by between 3 and 13 s for senior citizens and physically challenged people, depending on the width of the crossings. CEPAS-compliant senior citizen concession cards or PWD concession cards are tapped on the reader mounted above the standard push-button on the traffic light pole to activate the Green Man+ function [45]. The Junction Electronic Eyes (J-Eyes) system monitors traffic conditions and verifies incidents in real-time through a network of many surveillance cameras installed at the major traffic junctions to enable LTA to make informed decisions for managing incidents. At pedestrian crossings, signalized pedestrian crossing systems are installed and work based on safety, timing, and the demands of different road users. The use of existing parking facilities in the central business district and major shopping belts is optimized through real-time information on the parking space availability delivered by the Parking Guidance System (PGS). The information is delivered through roadside electronic information panels and other digital platforms, such as OneMotoring and myTransport.sg mobile application. TrafficScan provides real-time information on the average speed of traffic on roads to allow motorists to plan their route for a smooth journey. The Traffic Message Channel (TMC) delivers real-time traffic information to motorists, who can make use of mobile phones, portable navigation devices (PNDs), and in-vehicle navigation systems for dynamic route navigation. TMC is also used by commercial traffic service providers, which can broadcast real-time traffic messages to drivers on the road [46,47].

The main driver of the success of the Singapore journey in ITS is the collaboration between government institutions, academia, and private industries. For example, the standards for Dedicated Short-Range Communications (DSRC) to support the ITS development were developed jointly by the Committee on Autonomous Road Transport (CARTS); and four other organizations [6]. Furthermore, the CETRAN project was launched to develop standards for testing autonomous vehicles and certification [48].

The deployment of crash avoidance, real-time traffic routing, and network security related to 5G connected mobility was successful because of a collaboration between NTU and M1 Limited (M1). This collaboration succeeded in integrating 5G technology with vehicle-to-everything (C-V2X), which is being tested on real-life applications in public transport [49,50].

3.4.3. South Korea

ITS in Korea has reached an advanced stage despite late adoption by the government. Since then, the Korean government has been making substantial investments in the research, development, and deployment of ITS in the country, as well as supporting private businesses to develop advanced ITS technologies. The foundation for a nationwide ITS implementation was laid by establishing relevant standards and guidelines and revising laws that affect its implementation. In order to facilitate ITS development, a ten year national-level ITS basic plan was developed, which was billed to be reviewed every five years considering any changes of condition that might occur. Mayors and governors were also encouraged to establish a basic plan for ITS in their corresponding areas before embarking on an ITS project [24].

The research and development regarding ITS policies and planning are being conducted by the National Research and Development Institute, Korea Institute of Construction Technology (KICT), Korean Transport Institute (KOTI), and Korea Research Institute for Human Settlements (KRIHS). Another important player is the Korea-ITS tasked with the responsibility of establishing both local and international ITS standards, conducting workshops on ITS, and facilitating relations between private and public agencies involved in

ITS business [24]. The ITS system in Korea includes the Freeway (Expressway) Traffic Management System (FTMS), which operates and manages the traffic flow on the expressway. The Parking Information System (PIS) is an integrated parking guidance system consisting of wireless loop detectors, ultrasonic detectors, and an image analysis tool for number plate recognition [51,52]. It provides real-time parking information on board and/or on the road about the parking availability based on available parking space data collected from the detectors. Furthermore, the system detects illegal parking and charges the offenders automatically. The transport fare is being managed using the Automatic Fare Collection (AFC) system, which improves public transport passenger convenience. This system can be found in parking lots, taxis, subways, and buses [53]. Effective bus operation management and monitoring by public organizations and bus companies are made easier with the development of a Bus Information Management System (BIMS). BIMS is an information system designed to increase the modal share of buses in public transportation by providing real-time bus arrival time, the bus's current location, and incident information to the public based on data collected [54]. The real-time information about bus and adjacent subway arrival times, transfer and incident information, bus routes, and last bus/transfer information provided is disseminated through smartphones.

Freeway (Expressway) Traffic Management System (FTMS) [55] is an ITS system made to operate and manage the traffic flow on the expressway through Electronic Toll Collection System (ETCS) and DSRC technologies. It allows Non-Stop Payment at Tollgate and automatic fare deduction from inserted smart cards in onboard units (OBU) through the Hi-pass system. The Weigh in Motion (WIM) system measures the height and weight of freight vehicles for checking overloaded freight vehicles. The system intends to protect the roadway structures and increase traffic safety, and the data collected are used to enforce freight vehicle load violations. The Automatic Traffic Enforcement System (ATES) is a system for detecting speeding, signal BRT line violations, and illegal parking. ATES reduces traffic accidents and inconveniences caused by traffic rule offenders. Advanced Traffic Signal Control Systems (ATSCS) [56] are pre-timed and adaptive traffic signal controls, which are used and integrated into the overall traffic management system.

The National Traffic Information Center (NTIC) serves as a hub for collecting real-time traffic data from Korea Expressway Corporation, local governments highways financed and run by private sectors, and regional administrations. The data are then integrated, processed, and disseminated to the data providers, emergency and intelligence service organizations, and the public.

A vision to achieve zero traffic accidents by 2030 was encapsulated in the Cooperative ITS (C-ITS) Master Plan developed in 2013 [57]. Cooperation between the Ministry of Land, Infrastructure, and Transport (MOLIT) and other organizations initiated a pilot project of C-ITS to promote road accident prevention. The project involved infrastructure development, services, technology verification, system maintenance, and the establishment of standards [21,24]. The services include data collection and information dissemination, toll collection, safe driving support, intersection-traffic safety support, public-transportation safety support, pedestrian care, and accident prevention [6].

The KPMG Autonomous Vehicles Readiness Index (AVRI) 2020 ranked South Korea sixth in the world. The country has reached this level by improving the related infrastructure, provisioning fast broadband, mobile connection speeds, 4G network coverage, and increasing the number of AV testing locations. Korea's national strategy for developing AVs was published in October 2019. The goal of this strategy is for Korea to become a leader in the manufacture of future cars, including hydrogen and electric vehicles, and in AV technology by 2030. This strategy's provisions hope to reduce deaths from accidents by three-quarters by 2030.

The Korean government plans to install supporting infrastructure on major roads and all its toll roads, and V2I and V2X communication systems as part of the strategy's plans for AVs. The country plans to have a legislation and institutions in place such that by 2030, all its 110,000 km of roads can be fully integrated into the three-dimensional mapping.

Moreover, the strategy envisioned that by 2025, nine percent (9%) of new cars to be sold in Korea would be level 3 or level 4 AVs, and it is expected to reach up to fifty-four percent (54%) by 2030, with 12 percent being level 4 AVs. Given the aforementioned strengths, the country lags behind in the usage of AI technology.

3.4.4. Saudi Arabia

The Saudi Vision 2030 encapsulates knowledge sharing, best practices, and innovations in key areas, such as the provision of regional infrastructure, climate change, urban development, evolving social issues, and other initiatives that enhance national integration. National Transformation Programs promote the adoption of new technologies in its operations and support the country's workforce by building their capacities in all aspects of national development. In addition, these programs promote the mainstreaming of new technologies that will help build resilient infrastructure with reduced life cycle costs and more efficient, high-quality services, while reducing environmental and social costs.

The SAHER (watchful) traffic control system, which uses a network of surveillance cameras across the Kingdom, was introduced in 2009 to reduce traffic accidents and ensure smooth traffic flow throughout the Kingdom. SAHER uses up-to-date ITS technologies to improve traffic management, traffic regulation enforcement, and general road safety in the kingdom [27].

Sustainable transportation is one of the focal points of the Saudi Vision 2030, where there are two targeted, sustainable transportation systems. Target 11.2 makes provisions for a safe, cheaper, accessible, and eco-friendly transport system for all. It also promotes and ameliorates the development of public transport that considers vulnerable passengers, such as children, the elderly, and physically challenged individuals. However, Target 3.6 is geared towards reducing road accidents and the resulting death tolls and injuries. It is on the basis of these targets that the Riyadh city authorities have been actively promoting and developing a sustainable transportation system.

The Saudi Kingdom is also actively pursuing policies and legislation that promotes the adoption of electric vehicles in the country. This is evidenced in the announcement by the Ministry of Energy that it has concluded the legislative and technical provisions for effective regulation of the electric vehicle charging market. The Kingdom installed its first electric vehicle charging station in Riyadh in 2019. Since then, many EV chargers have been installed at several petrol stations across the country.

Public transport in Saudi Arabia is receiving special attention from the Ministry of Transport. The ministry has commissioned several studies to find the best and state-of-the-art public transportation system that will address the country's mobility needs. In line with this, public transport projects in Riyadh, Makkah, and Madinah are being implemented. Moreover, the Public Transport Authority was established to oversee the development and implementation of the public transport plan in the Kingdom. Presently, a comprehensive public transport plan has been prepared for Madinah, Jeddah, Dammam, Buraidah, Jazan, and Taif, while Hail, Abha, and Hofuf are in the pipeline.

The Saudi Public Transport Company "SAPTCO", established in 1979, provides intracity and intercity public transport services, international transport services, "VIP EXPRESS" premium services, and specialized services and digital services. In addition, SAPTCO established another company to construct, supply, operate, manage, and maintain metro buses in Riyadh contained in King Abdul Aziz public transport projects in Riyadh [58].

In terms of the rail system, Saudi Arabia has 2939 km of railway tracks according to the International Union of Railways in 2018. The first line established in Saudi Arabia is the eastern line, with a track network of approximately 1775 km. The line extends from Dammam to Riyadh, while connecting many towns in between. The Haramain line is located in western Saudi Arabia, and the Haramain High-Speed Railway connects Makkah and Medina, the holy cities of Islam. The train is scheduled to stop at Makkah, Jeddah, King Abdullah Economic City, and Medina. It is the latest and fastest train in the Middle East.

Another important aspect of the transportation system that received attention is the parking system. The Kingdom of Saudi Arabia provides a complete range of parking solutions and automated parking systems that solve all sorts of parking issues in the country, especially in major cities where congestions often occur. Although these initiatives are geared towards establishing a resilient and vibrant transportation system, there is much to be done, especially in the areas of smart mobility. The country needs to learn from countries that have successfully implemented smart solutions in their transportation systems, such as Korea, Singapore, and Japan.

4. Results

The benchmarking results of the development of smart mobility systems in the four countries as a whole, as well as the smart mobility eco-system, private, public, and emergency transport services, are shown in Figure 2. The results showed that Korea was only slightly smarter (Smart Mobility Index, SMI = 92%) than Singapore (SMI = 91%) and Japan (SMI = 89%). However, Saudi Arabia (SMI = 61%) is way behind all three countries in terms of smart mobility development.

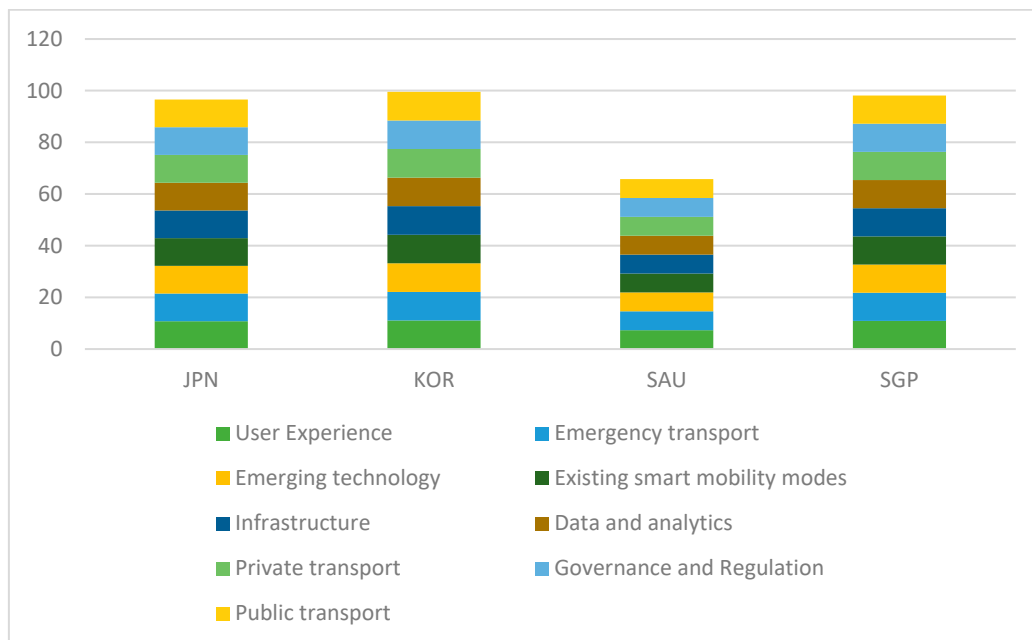


Figure 2. Smart mobility index ranking for Japan, Korea, Singapore, and Saudi Arabia.

The study has identified several smart technologies being implemented for the smarter management of transport systems in Korea, Singapore, and Japan. All three countries have deployed a wide range of smart technologies in their transportation systems. For example, considering the smart mobility ecosystem, the experience of the transportation system users can be a good measure of the smartness of the system. Therefore, these countries have advanced information and communication technology and the Internet of things (IoT), which make it possible to provide solutions to the usual unpleasant experiences of an inefficient transportation system. The use of smartphones and mobile apps for ride-sourcing, demand-responsive bus services, smart parking, and mobility-as-a-service (MaaS) is revolutionizing people's mobility in these countries. The countries provide eco-friendly rides within their urban environment using the existing smart mobility modes, such as shared bikes and scooters, car-sharing and ride-sharing services, connected vehicles, electric vehicles, and autonomous mass transit.

There are several emerging technologies, such as automated vehicles, robots, drones, and hyperloop tunnels, cropping into the mobility systems in these countries. This set of technologies is the future of transportation and logistics. A large amount of data are

being generated by the existing transportation modes and, more especially, through smart mobility initiatives. Therefore, artificial intelligence and predictive analytics are used to create systems that collect, process, analyze, and share through intuitive visualization tools to manage transportation systems more effectively. This is the backbone of smart mobility systems in these countries; although there is a lot to be done in this respect. Infrastructure is an important component of smart mobility. Therefore, in these countries, transport infrastructures are being designed and/or upgraded such that sensing and 5G technologies are accommodated, making the infrastructure somewhat intelligent.

An intelligent infrastructure collects information and communicates both with vehicles and the management centers. The major factor behind the success of these countries in the implementation of smart mobility solutions is legislative actions that ensure coordination between various institutions to create new and equitable smart mobility solutions and business models that are easily accessible and sustainable. Furthermore, the set of regulations to support smart mobility are mostly flexible, inclusive, and responsive. Policies and smart mobility agendas are being developed at all levels of governance to ensure standards, easier license regimes, cybersecurity, data privacy, and physical security. This approach provides confidence in the private sector and has encouraged them to engage in the smart mobility revolution in these countries fully.

Moreover, looking at the smart mobility system technologies in these countries, one would discover that all buses and trains are equipped with Automatic Vehicle Location Systems (AVLS). This gives passengers real-time information on the arrival and departure timings at most bus/train stops and through mobile applications and online channels. Furthermore, taxi services can be booked in real-time in these countries. The integrated, intermodal, and contactless electronic fare collection system was found to be operating fully in these countries. Bus rapid transit systems, self-driving transit systems, lane enforcement, and traffic signal priority systems for buses and emergency vehicles are some of the key characteristics of the smart mobility systems in these three countries. The smart private transport services in the countries include a network coordinated traffic signal system, variable message system, and ramp metering (except in Singapore).

These countries' automated and smart parking systems provide parking information through roadside message panels, mobile apps, and web portals. The countries also have ANPR systems for detecting red-light violations and other traffic incidents. However, most of these services are either at the planning stage, trial phases, partial coverage, or nonexistent in Saudi Arabia, as indicated by the lower rank in the benchmarking exercise. The smart services identified in these countries increase accessibility, reduce travel delays, increase the efficiency of transit operations, and cause public transport to be preferred over private and personal transport.

The availability of sophisticated smart solutions, such as prediction, healing, and prevention, is not well-advanced in these countries. Therefore, there is a strong need to study machine learning and artificial intelligence in predicting real-time demands to provide a responsive supply. More research in smart mobility systems is needed to encourage the implementation of sophisticated technologies in advanced smart countries. This would provide learning opportunities for countries that are not well advanced in smart technologies to become smart through the adoption of these technologies.

The smart countries could serve as the training grounds for cities such as Saudi Arabia wishing to implement similar smart mobility initiatives as indicated in its Vision 2030. Therefore, this study could help Saudi Arabia and other cities to identify gaps in their deployment of smart mobility technologies by comparing their initiatives against those of the three countries used in this study. The prospective smart cities could also learn from these smart countries' success/failure stories. These three countries generally have similar supportive factors to the development of smart mobility systems. Public, private, and research institutes cooperate excellently to initiate and promote smart mobility systems. The most common practices among these countries include policy, pilot projects, standard and

regulatory frameworks, and collaboration between stakeholders, including government agencies, private organizations, and research and development (R&D) institutions.

Comparing Saudi Arabia and the three Asia-Pacific countries could reveal that all the countries have clear policies and have created pilot projects being implemented. The support and cooperation from all the stakeholders and the research communities in these countries are a clear means of ensuring success in the development of smart mobility systems. However, Saudi Arabia has all the basic ITS systems in its plans, but the general platform for the implementation of the smart mobility system is not well grounded. Although some advanced technologies are being introduced independently in some of the cities in the Kingdom, such as Riyadh and Dammam, an integrated and holistic approach needs to be put in place. There is a need for a smart mobility master plan for the whole country for the smooth implementation of smart mobility initiatives in a well-coordinated manner such that the progress can be effectively appraised.

The national policy in Saudi Arabia should focus on encouraging relevant government agencies to use advanced smart technologies to enhance the smartness of their transportation systems. Although the research institutions in the country are increasingly focusing on applications of advanced technology in transport and traffic management, there is a need for information sharing through workshops and conferences to allow the coordination and implementation of these ideas by the practitioners. The private sectors need to be encouraged more by providing an enabling environment in terms of policies, regulations, and standards for them to operate seamlessly. Emerging technologies, such as CAVs, robots, drones, and hyperloop tunnels, are featured in almost all the smart mobility plans and strategies of the three countries in preparation for future mobility. Although, the plans are not explicit in their strategy to incorporate emerging technologies in their systems, probably because there are many potential technologies for the future. Thus, the KSA's future mobility plans need to be highly flexible, resilient, and adaptive.

5. Conclusions

Smart mobility is an integral part of smart cities, which significantly impacts the cities' sustainability. Therefore, aspiring smart cities or countries need to learn from the successes and pitfalls of smarter cities worldwide. This study highlights the major components of smart mobility systems and simultaneously explores the development of these systems in case-study countries with a view to providing a clear path for Saudi Arabia and other aspiring countries to follow suit. Consequently, Saudi Arabia can join these smarter countries through similar smart mobility strategies. The country needs to adopt inclusive development, standardization, and policy-driven strategies with clear commitments to public, private, and research collaborations. Moreover, cybersecurity must be taken seriously because most of the smart mobility systems use wireless and IoT technologies, which may be vulnerable to hacking, and thus impact system safety. In addition, the smart mobility system should consist of a monitoring and evaluation system comprising the number of accidents, usage of public transportation, and traffic congestion levels.

Benchmarking studies, such as this study, are used to evaluate the strategies of the smart mobility systems in those countries to help future smart countries evolve. In this context, a robust framework for evaluating smart mobility systems in three Asia-Pacific countries and Saudi Arabia was developed based on the indicators derived from the smart mobility ecosystem and three major types of transport services (private, public, and emergency). Sixty indicators of smart mobility systems were identified through a rigorous search of the literature and other secondary sources. Emerging technologies, such as IoT, 5G, robots, drones, hyperloop tunnels, and self-driving technologies, are used as part of the indicators of smart mobility systems in those countries.

Although the indicators and variables used are equally weighted due to a lack of enough information on the extent of application of these technologies, the study reveals that the three Asia-Pacific countries are moving head-to-head in terms of smart mobility

development. The indicators data used in this study were collected in 2022, which is likely to change in the near future considering the rapid developments in the countries. Therefore, care should be taken when using the results for comparison purposes in the future. Furthermore, future studies should involve conducting surveys among candidate cities, weighting the indicators with different weighting methods, and evaluating their uncertainties.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su15043158/s1>, Table S1: Indicators Data; Table S2: The set of indicators used for this study.

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