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Prioritization of the Application of Technologies required for Intelligent Transportation Systems

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16. Abstract

Urban infrastructure with the use of modern technologies, such as Information Communication Technology and the Internet of Things, plays an essential role in enhancing the capability of the city to resolve various urban challenges. Particularly, urban roads supported by advanced systems with modern technologies serve as a principal bedrock to establish a smart city. Witnessing the benefits of intelligent urban roads has promoted city stakeholders to make investment decisions in innovating their road facilities with advanced systems. Therefore, the objective of this project was to present a framework to prioritize advanced systems to innovate urban roads. To achieve the project objective, this project developed a hierarchy table of indicators and measures to assess the current development status of urban roads. The measures at the lowest hierarch level were considered to identify advanced systems that enhance the current development status of urban roads. The prioritization framework uses the cost-effectiveness values of advanced systems that are combined with the weights at the component and indicator levels. The process of the presented prioritization framework was demonstrated by employing a hypothetical example. The contributions of this project include: 1) the development of the hierarchy table of indicators and measures that can dedicate to evaluating the current development status of urban roads and identifying advanced systems for urban road innovation and the advanced system prioritization framework that can increase efficiency in investing city-wide resources in highly needed and valuable advanced systems.

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CHAPTER 1

Introduction

BACKGROUND

Smart cities have emerged as a strategy to maintain the quality of life for citizens living in urban areas that are experiencing a dramatic increase in population (Chourabi et al., 2012). With the evolution of innovative technologies such as Information and Communication Technologies (ICT), the Internet of Things (IoT), and sensing devices, a smart city is a concept of utilizing these modern technologies to enhance the function of city operation. Physical infrastructure with the application of modern, innovative technologies can enhance the capability of a city for economic development, social prosperity, and a sustainable environment (Vasudavan et al., 2019). Specifically, intelligent transportation systems (ITS) apply advanced communication, information, and electronics technology to solve urban transportation issues such as traffic congestion, public safety, transport efficiency, and energy conservation to enhance the performance of modern transportation systems (Figueiredo et al., 2001). Consequently, the ITS is a key component of any smart city concept (Menouar et al., 2017).

Witnessing the benefits of advanced systems in an urban transportation network introduced city officials' need to develop a strategic investment decision on advanced systems. In general, a good investment decision for transportation asset management is achieved through the flow of the right information about current needs for the right strategies at the right time. It has driven the research need for efficient, reliable decision-making for investment by understanding the current development status of urban roads in the context of the requirements specific to individual cities. However, a holistic decision-making approach to ITS investment has been neglected by most of the existing ITS-related research, investigating the applicability of ITS technologies to conventional transportation systems and developing evaluation methods to quantify the risks and benefits of ITS technologies (Zandi and Tavana, 2011, Andersson and Robertsson, 2016). The investment decision-making models of the studies found from the literature review relied on prioritization approaches using subjective inputs. For example, Khademi et al. (2010) analyzed the priorities of user services of ITS by using the analytic network process (ANP) approach. The user services prioritized include traveler information, traffic management, and emergency vehicle management. Krmac and Djordjević (2017) developed indicators to assess railways for ITS. They applied the priorities of the indicators that were determined by the analytic hierarchy process (AHP) approach for the assessment. Curiel-Esparza et al. (2016) analyzed the priorities of urban transport systems, such as pedestrian roads, bicycle networks, bus transport, underground transport (e.g., metro), and parking, to enhance sustainable mobility (e.g., economy, travel quality, and sustainability) in urban areas. They employed the pairwise comparison method (e.g., AHP) with the Delphi technique to identify the relative importance of the transport systems considering multi-criteria such as economy, engineering, environment, social, and risk.

The use of subjective inputs in prioritizing can be viable if well-defined priority evaluation criteria do not exist. However, prioritization approaches based on empirical data can generally provide more exquisite priorities, not distorting priority results due to subjectivity (Jahedi and Méndez, 2014). Also, the prioritization approaches based on subjective inputs usually undergo additional analyses (e.g., sensitivity analysis) to enhance priority results' quality, making prioritization processes more complicated (Siksnelyte-Butkiene et al., 2020).

OBJECTIVES

The objective of this project was to develop a framework to prioritize advanced systems for transportation systems using a hierarchy table of indicators and measures in the context of a smart city. The scope of this project focused on the development of a hierarchy table and prioritization framework for urban roads in a city transitioning into a smart city. The hierarchy table was designed to assess the current development status of urban roads. The urban roads in this project represent roadway facilities, such as roads, bridges, tunnels, and over/underpasses, and roadside facilities such as traffic signals and signs, parking facilities, guardrails, streetlights, crosswalks, and sidewalks, within a city boundary. This project defines advanced systems as integrating modern, innovative technologies and materials such as ICT, IoT, sensing technologies, Cloud computing, optical fibers, and piezoelectric devices into urban roads.

DATA AND DATA STRUCTURES

The raw data collected for this project were main sentences extracted from the ITS-related documents through a literature review. The main sentences describe the benefits of urban roads for smart cities. The main sentences were then fragmented into keywords in words and/or phrases to develop the indicators and measures of the hierarchy table through text mining. Another data type was pseudo data used to demonstrate the prioritization framework presented by this project. The pseudo data consist of advanced systems along with their costs and effectivenesses. These data were processed to normalized costs and effectivenesses for weighted cost-effectiveness results.

CHAPTER 2

Methodology

INTRODUCTION

This section describes the methodology used to develop a hierarchy table and prioritization framework. The procedures for a hierarchy table were composed of three phases: data preparation, data analysis, and a hierarchy table. Then, the hierarchy table was applied for the prioritization framework phase consisting of two modules: input for advanced systems information and advanced systems prioritization. Figure 1 shows the overall methodology used for this study.

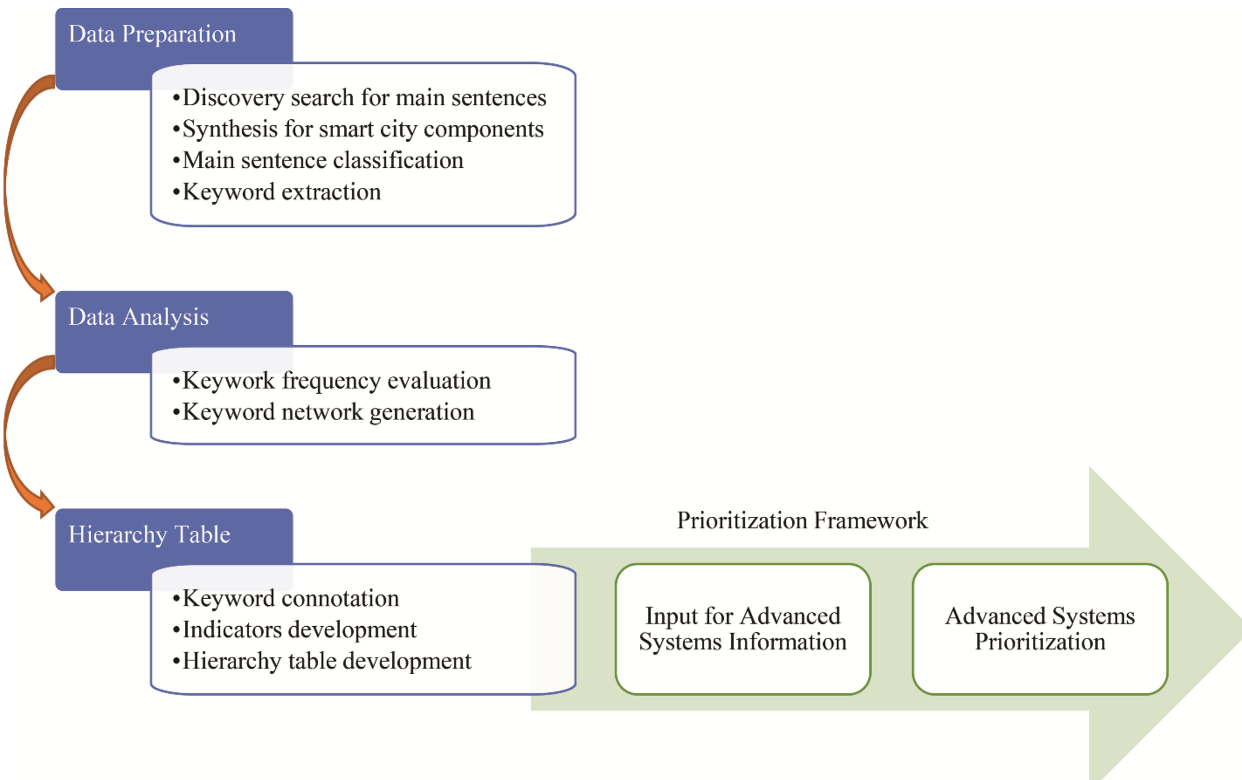

Figure 1. Overall Methodology

PHASES FOR HIERARCHY TABLE AND PRIORITIZATION FRAMEWORK

Phase-1: Data Preparation

The data preparation phase first derived smart city components encompassing all service areas required for a smart city. Smart city components are placed at the first level of a hierarchy table, subordinating indicators and measures at lower levels. The approach used to derive smart city components was based on synthesizing existing smart city indexes identified through the comprehensive discovery search. A total of 37 components were identified from the discovery search, as listed in Table 1. Some of the components of similar properties were listed together. The synthesis process finalized the selection of the smart city components for the *environment*, *mobility*, *governance*, *economy*, and *living*.

Table 1. Smart city components retrieved from the existing smart city indexes.

Component	Count
Environment/Planet/Energy/Sustainability	9
Mobility/Transportation	8
Governance	7
Economy	6
Living/Culture/Society/Housing	6
People/Citizen/Human	5
Health/Safety	5
Education/Opportunity	4
Technology/Telecommunication	4
Plan/Strategy	3
Infrastructure/Buildings	2
Coordination/City partners	2
Policy/Legal framework	2
International outreach	1
Data	1
Budget	1
Propagation	1
Activity	1
Stakeholders	1
Waste	1
Water	1

The discovery search also collected the documents related to intelligent urban roads and extracted the main sentences describing the benefits of urban roads for smart cities. Then, the primary benefits of the main sentences were classified by the smart city components. A total of 527 documents were collected, which generated 510 main sentences. Figure 2 shows the classification result of the main sentences.

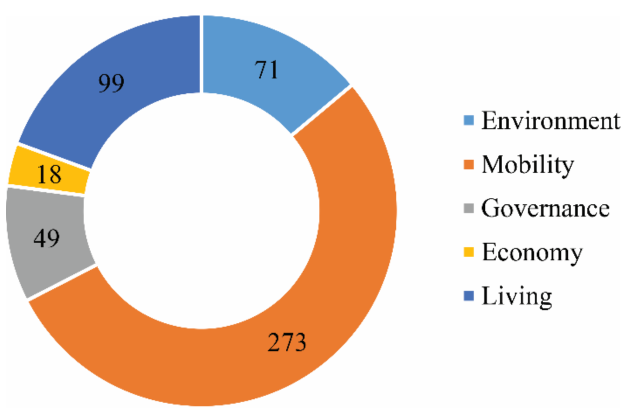

Figure 2. Main sentences classified by smart city components

Lastly, the main sentences were processed to separate keywords through a keyword extraction process, taking the steps as follows :

- Fragment the main sentences into words and/or phrases containing meaningful information such as benefits, subjects, and objects
- Creat keywords by processing the fragmented words/phrases from each main sentence
- Evaluate the keywords at each smart city component to combine synonymous keywords, which was essential for reliable data analysis.

Phase-2: Data Analysis

The data analysis phase was conducted for the keyword frequency evaluation and keyword network generation. The keyword frequency evaluation aimed to evaluate the integrity of the main sentence classification resulting from the data preparation, which was essential to develop indicators and measures well-suited to the relevant smart city components. The approach used for the keyword frequency evaluation was the comparison of top-ten frequent keywords at each smart city component with the central words/phrases representing the attribute of the smart city component. The goodness of the main sentence classification performance was made by verifying the similarity of high-frequent keywords to the central words/phrases of their smart city component while showing the dissimilarity with any other components. The failure in this evaluation required moving back to the main sentence classification for reclassification, which was not the case in this research.

Table 2. Top-ten keywords for each smart city component

Smart City Components	Central Words/Phrases	Top-ten Keywords
Environment	Pollution problems Resource management Environment protection Energy consumption	Fuel consumption; Road; Road lighting; Electricity generation; Eco-signal operation; Emission; Energy-saving; Design; Electricity; Traffic signal
Mobility	Traffic congestion/traffic flow/vehicle speed Transport efficiency Convenient movement Accessibility	Travel time; Road; Delay; Traffic congestion; Incident; Vehicle speed; Vehicle; Intersection; Transit signal priority; Bus
Governance	Planning Strategies Asset/disaster management Decision-making Communication	Monitoring; Structural health monitoring; Maintenance; Sensor; Road pavement; Traffic violation; Automatic license plate recognition; Management; Road; Vehicle detection
Economy	Economic development Labor productivity Trade markets City revenues	Cost savings; Bridge; Operation; Inspection; Drone; Toll revenue; Maintenance; Revenue; Streetlight; Toll transponder
Living	Quality of life Convenience Safety/Security/Healthcare Social welfare	Driver; Accident; Warning system; Safety; Intersection; Accident prevention; Vehicle; Vehicle speed; Animal detection system; Injury

Table 2 shows the central words/phrases that describe the smart city components and the ten keywords in high frequencies for the smart city components. As the keywords of single words had the wide connectivity to make information with other keywords, some keywords of single words, such as road, vehicle, intersection, and maintenance, were included in more than one component. As the keywords of phrases were supposed to deliver specific information together, these phrase-keywords of a component were listed as high-frequent keywords matching well with the central words/phrases of the component in Table 2. For example, the environment component clearly shows the well-matching keywords, such as fuel consumption, road lighting, electricity generation, eco-signal operation, and energy-saving, with the central words/phrases. The traffic signal keyword in the environment component seemed more relevant to the mobility component. However, the keyword also matched with the central word, pollution problems, by reducing vehicle fuel consumption through efficient traffic signal control.

The keyword network generation required a correlation analysis to investigate any connections between the keywords extracted. Then, the correlated keywords were used to make up indicators and measures in the succeeding hierarchy table development procedure. While various methods were applicable to keyword correlation analysis, including Jaccard similarity, cosine similarity, and Pearson correlation coefficient, the cosine similarity method was applied. The higher correlation values indicate a stronger connection between the two keywords being used together to provide information. However, interpreting correlation values in this research were made deliberately, considering the two possibilities. First, correlation values are unreliable for smaller sample sizes due to the higher chances of sampling errors (Knudson and Lindsey, 2014). Second, correlation values are higher for smaller sample sizes that are likely to have less variability of samples (Bujang and Baharum, 2016; Winter et al., 2016). The discovery search in the data preparation identified different sample numbers (i.e., numbers of main sentences) across the smart city components, depending on the influential extent of intelligent urban roads in a smart city. Therefore, the minimum threshold of correlation values for each smart city component was employed to limit the keywords in network generation, as listed in Table 3, which helped to enhance the reliability of the keyword connotation in the hierarch table phase.

Table 3. Minimum similarity threshold values applied to create keyword networks

Smart City Component	Minimum Similarity Threshold Value
Environment	0.211
Mobility	0.113
Governance	0.335
Economy	0.360
Living	0.193

Phase-3: Hierarchy Table

The hierarchy table phase took the three tasks: 1) keyword connotation, 2) indicator development, and 3) hierarchy table development. The keyword connotation task was to create measures through a semantic approach that captured information by combining and refining the words correlated. Thus, the keyword networks generated in Phase 2 were the sources to make up measures for each smart city component. Then, the measures were post-processed to evaluate their commonality and conveyance based on the knowledge obtained from a measure-oriented discovery search, which resulted in complete measures. The complete measures in each smart city component were grouped to develop indicators. The development of the indicators for each smart city component took into account the processes as follows: 1) group the measures from the same clusters, 2) compare the grouped measures across the different clusters to merge when necessary, and 3) create indicators that encompass the grouped measures. Phrasing indicators also considered the indicators in the existing smart city indexes and other available sources (e.g., public transportation documents and websites) for possible alignment with the indexes. Finally, the indicators and measures were organized into a hierarchy table, associating them to matching smart city components.

Phase-4: Prioritization Framework

Module-1: Inputs for Advanced Systems Information

The input for the advanced systems information module was composed of three tasks: 1) advanced systems identification, 2) advanced systems matching to measures, and 3) advanced systems information investigation. The advanced systems identification task generated a list of advanced systems required to innovate the performance of urban roads for measures. An extensive discovery search was a primary approach required to identify various advanced systems. Upon completing the discovery search, the advanced systems identified were matched with each measure in the hierarchy table. The matching task considered the usages (e.g., purposes or benefits) designed for an individual advanced system. As a result, matching the advanced systems with the measures produced the three cases as follows:

- An advanced system was dropped out due to no existence of matching measures.
- An advanced system was matched with more than one measure due to the multi-usages of the system.
- A measure had more than one advanced system, resulting from market demands and the maturity of source technologies to develop various advanced systems for the measure.

The task for advanced systems information investigation sought the cost and effectiveness information of the matched advanced systems. The cost of an advanced system was a lifetime cost that included initial installation and operation/maintenance costs. On the other hand, the effectiveness of an advanced system was the estimation of its performance to the matching measure(s). The system's effectiveness was investigated by various methods, depending on the attributes of measures; for example, performance inspection or observation for quantitative measures and public surveys or expert interviews for qualitative measures. The cost and effectiveness information of advanced systems were estimated for the same range (e.g., a whole city or a section of a city) for equal comparisons. The cost and effectiveness information of the advanced systems matching measures were the output from Module 1, which became the inputs for the advanced systems prioritization in Module 2.

Module-2: Advanced Systems Prioritization

The priorities of advanced systems to apply for urban roads were determined based on their weighted cost-effectiveness values. The weights of smart city components and indicators were multiplied by the cost-effectiveness values of advanced systems, as shown in Eq. 1.

$$CE'_{m/i/c}(s) = CE_{m/i/c}(s) \times w_{i/c} \times w_c \qquad \text{Eq. 1}$$

where, w_c is the weight of smart city component c; $w_{i/c}$ is the weight of indicator i nested in smart city component c; $CE_{m/i/c}(s)$ is the cost-effectiveness of an advanced system s for measure m of indicator i and smart city component c; and $CE'_{m/i/c}(s)$ is a weighted $CE_{m/i/c}(s)$. The weights of smart city components and indicators were estimated by taking the steps as follows:

- Set a target (T), baseline (BL), and current development status (CDS) for each measure.
- Calculate percent current achievement ($\%CA$), using Eq. 2.

$$\%CA = \frac{Abs(CDS - BL)}{Abs(T - BL)} \times 100(\%) \qquad \text{Eq. 2}$$

- Get an average *%CA* of the measure(s) at each indicator.
- Subtract the average *%CA* (*avg. %CA*) from 100% for an average percent demand (*Avg. %D*), as seen in Eq. 3, for each indicator.

$$Avg.\%D = 100\% - Avg.\%CA \qquad \text{Eq. 3}$$

- Normalize the *Avg. %D* values of the indicators at each smart city component for indicator weights, as seen in Eq. 4.

$$w_{i/c} = \frac{Avg.\%D_{i/c}}{\sum_{i=1}^{n} Avg.\%D_{i/c}} \qquad \text{Eq. 4}$$

- Get an average of the *Avg. %D* values of the indicators at each smart city component, using Eq. 5, and normalize the component average percent demands for component weights, as seen in Eq. 6.

$$Avg.\%D_c = \frac{\sum_{i=1}^{n} Avg.\%D_{i/c}}{n} \qquad \text{Eq. 5}$$

$$w_c = \frac{Avg.\%D_c}{\sum_{c=1}^{m} Avg.\%D_c} \qquad \text{Eq. 6}$$

The effectiveness of an advanced system is estimated in terms of its matching measure. It implies that the units and scales of the system effectiveness could vary according to measures. Thus, the standardization of system effectiveness values was required, using Eq. 7 and Eq. 8 for the measure targets pursuing higher and lower values, respectively.

$$CR = \frac{Effectiveness}{Abs(T - BL)} \qquad \text{Eq. 7}$$

$$CR = 1 - \frac{Effectiveness}{Abs(T - CDS)} \qquad \text{Eq. 8}$$

As the actual effectiveness values of advanced systems were transformed into contribution ratios ranging from 0 to 1, system lifetime costs also needed a normalization to make distinctive comparisons. For any advanced systems contributing to more than one measure, all the weighted cost-effectiveness values of the systems across the measures were combined for ranking.

CHAPTER 3

Findings

HIERARCHY TABLE

Table 4 shows the hierarchy table, including 53 measures in 14 indicators for the smart city components.

Table 4. Hierarchy table of indicators and measures

Component	Indicator	Measure
Environment	Sustainable Resource Management	Number of reduced road lights by using intelligent road markings
		Reduced electricity consumption of road lights through energy-efficient controls
		Reduced electricity consumption of road lights by using energy-efficient parts
		Energy savings in road tunnels and bridge lighting systems
	Renewable energy utilization	Per-vehicle use of renewable energy generated by roadways
		Use of renewable energy generated from roadways for road facilities
		Self-use percentage of renewable energy for roadside facilities
	Pollution controls	Reduced fuel consumption per vehicle at traffic signals
Mobility	Traffic operational performance	Reduced waiting time at traffic signals
		Reduced response time of emergency vehicles
		Reduced travel time of self-driving vehicles at autonomous lanes
		Reduced traffic delays at toll plazas
		Reduced clearance time at the roads of integrated corridor management
		Increased ratio of average vehicle speed to speed limit at work zones
		Increased throughput time at bottlenecks (e.g., ramps and temporarily closed lanes)
		Volume-to-capacity ratio at work zones
		Delayed travel time on roads in hazardous driving conditions
	Traffic operational performance – Efficient transport and multi-modal access	Reduced travel time at HOV lanes
		Increased throughput time on HOT lanes
	Efficient transport and multi-modal access	Increased rates of using shared bike areas at peak hours
		Increased rates of using park and ride facilities
		Public transportation dwell time at traffic signals
		Reduced travel time of commuters through integrated corridor management

Table 4. Hierarchy table of indicators and measures (continued)

Component	Indicator	Measure
Governance	Facility management planning	Percentage of using road weather information for winter maintenance decision-making
		Percentage of using advanced technologies to improve road inspection data quality
		Percentage of using advanced technologies to improve bridge inspection data quality
		Efficiency of bureaucracy adopting advanced technologies/materials for pavements
		Efficiency of bureaucracy adopting advanced technologies/materials for bridges
		Managerial efficiency for road facilities security
	Emergency operations plan	Efficiency of evacuation planning to respond to disasters
		Efficiency of road resilience planning to respond to disasters
		Extent of integrated controls of services for emergency response
	Public and social services	Adoption rate of advanced technologies for smart parking operation
		Administrative efficiency for law enforcement
		Administrative efficiency for law-abiding
Economy	Productivity	Operation cost savings for toll charge/collection services
		Operation cost savings for parking fee charge/collection services
		Cost savings for roadside facilities operations
	Efficiency	Cost savings for winter inspection/maintenance
		Cost savings for pavement inspection
		Cost savings for bridge inspection
		Cost savings from road control and maintenance (e.g., rehabilitation and repair)
Living	Accessibility	Satisfaction with access to public parking
	Emergency service	Satisfaction with the road operation in accident situations
	Safety for road users	Satisfaction with accident controls at crossing points (e.g., overpass and underpass)
		Satisfaction with incident management to prevent secondary accidents
		Percentage of reduced accidents in hazardous road surface conditions
		Percentage of reduced accidents at traffic signals
		Percentage of reduced accidents by enhancing road visibility conditions
		Comfort level of road users in high-visibility conditions
		Reduced number of motorized user casualties at accident-prone areas (e.g., curve and wrong-way)
		Reduced number of non-motorized user casualties at accident-prone areas (e.g., school zone and crosswalk)

Table 5. Advanced systems for the prioritization framework application

Component	Indicator	Measure	System	Cost ($)	Effectiveness
Environment (A)	Sustainable resource management (A1)	Number of reduced road lights by using intelligent road markings (M1)	Intelligent road marking (S1)	1,128	5 (EA)
		Energy savings in road tunnels and bridge lighting systems (M2)	Automated street lighting system (S1)	151,800	361 (kWh/year)
			Intelligent road markings (S2)	71,280	78 (kWh/year)
			LED lighting system (S3)	42,560	119 (kWh/year)
	Renewable energy utilization (A2)	Self-use percentage of renewable energy for roadside facilities (M1)	Wind-powered street lighting system (S1)	36,590	40 (%)
			Solar-powered street lighting system (S2)	92,530	92 (%)
			Solar-powered traffic signs and signals (S3)	23,120	100 (%)
	Pollution controls (A3)	Reduced fuel consumption per vehicle at traffic signals (M1)	Adaptive signal control system (S1)	710,500	165 (gallons)
			Eco-traffic signal timing (S2)	954,000	150 (gallons)
			Transit signal priority (S3)	435,000	130 (gallons)
Mobility (B)	Traffic operational performance (B1)	Reduced waiting time at traffic signals (M1)	Adaptive signal control system (S1)	710,500	26 (sec)
			Eco-traffic signal timing (S2)	954,000	22 (sec)
			Transit signal priority (S3)	435,000	18 (sec)
		Increased ratio of average vehicle speed to speed limit at work zones (M2)	Variable speed limit system (S1)	259,200	0.3
			Automated work zone information system (S2)	343,500	0.2
		Increased throughput time at bottlenecks (e.g., ramps and temporarily closed lanes) (M3)	Variable speed limit system (S1)	259,200	21 (sec)
			Ramp metering (S2)	119,200	12 (sec)
		Delayed travel time on roads in hazardous driving conditions (M4)	Variable speed limit system (S1)	259,200	25 (sec)
			Snowmelt system (S2)	3,215,300	5 (sec)
	Efficient transport and multi-modal access (B2)	Increased rates of using park and ride facilities (M1)	Bike-sharing system (S1)	6,520	12 (%)
			Smart parking meter system (S2)	5,640	4 (%)
		Public transportation dwell time at traffic signals (M2)	Transit signal priority (S1)	435,000	30 (sec)

PRIORITIZATION FRAMEWORK APPLICATION RESULTS

Table 5 shows the advanced systems for the selected components (e.g., environment and mobility), indicators, and measures in the hierarchy table and their costs and effectiveness within a city boundary. Some advanced systems found more than one measure matching due to their versatilities; for example, intelligent road marking for A1-M1 and A1-M2 and adaptive traffic signal control system for A3-M1 and B1-M1. As there was a limitation to finding exact lifetime costs and effectiveness values for all the advanced systems from open sources, pseudo-data were used for the advanced systems whose lifetime costs and/or effectiveness values were not available. As estimating the weights of the smart city components and indicators required setting three input variables, such as the target (*T*), baseline (*BL*), and current development status (*CDS*) for each measure, their actual values were assumed in Table 6. The *T*, *BL*, and *CDS* values of the advanced systems were processed to the percentages of current achievement *%CAs* for the measures and the average percent demands *Avg. %D* for the indicators using Eq. 2 and Eq. 3. Then, the processed values were estimated to the weights for the selected smart city components and indicators, using Eq. 4 and Eq. 6. Table 7 shows the result of all the processed values.

Table 6. Hypothetically produced T, BL, and CDS values

Component	Indicator	Measure	Unit	*T*	*BL*	*CDS*
A	A1	M1	EA	10	0	2
		M2	kWh	2,000	1,000	1,200
	A2	M1	%	100	10	40
	A3	M1	Gallon	400	0	200
B	B1	M1	Sec	60	0	20
		M2	-	0.5	0	0.125
		M3	Sec	30	0	5
		M4	Sec	0	60	40
	B2	M1	%	30	0	5
		M2	Sec	80	180	130

Table 7. Weights at the smart city component and indicator levels.

Component (Weight)	Indicator (Weight)	Measure	*%CA*	*Avg. $\%CA_{i/c}$*	*Avg. $\%D_{i/c}$*	*Avg. $\%D_c$*
A (0.48)	A1 (0.41)	M1	20.0%	20.0%	80.0%	65.6%
		M2	20.0%			
	A2 (0.34)	M1	33.3%	33.3%	66.7%	
	A3 (0.25)	M1	50.0%	50.0%	50.0%	
B (0.52)	B1 (0.52)	M1	33.3%	27.1%	72.9%	69.8%
		M2	25.0%			
		M3	16.7%			
		M4	33.3%			
	B2 (0.48)	M1	16.7%	33.3%	66.7%	
		M2	50.0%			

All the effectiveness values of the advanced systems in different units and scales (see Table 5) were normalized and then converted into the contribution ratios, applying Eq. 7 and Eq. 8. The effectiveness values in the contribution ratios of 0 to 1 needed the lifetime costs to scale down for distinctive comparison. Once both raw effectiveness values and lifetime costs were standardized, the cost-effectiveness was calculated by dividing the contribution ratios by the normalized lifetime costs. Then, the weights of the smart city components and indicators were multiplied by the weighted CEs. For example, the cost-effectiveness (*CE*) of the advanced system, A1-M1-S1, was estimated by Eq. **9**.

$$CE = \frac{CR}{NC} = \frac{0.63}{3.052} = 0.205 \qquad \text{Eq. 9}$$

By applying the weights of the component (= 0.48) and indicator (i.e., 0.48 and 0.41, respectively; see Table 7), where this advanced system is included, the weighted CE was estimated using Eq. 1. Table 8 shows the CE and weighted CE values of the advanced systems. However, the weighted CE values in Table 8 did not represent some advanced systems, such as variable speed limit system, transit signal priority, adaptive signal control system, intelligent road marking, and eco-traffic signal timing, contributing to more than one measure. Therefore, the weighted CE values for those were summed so that the priorities of the advanced systems were finalized, as shown in Table 9. In this hypothetical example, the prioritization framework recognized the variable speed limit system as the most cost-effective advanced system for investment.

Table 8. CE and weighted CE Results.

System Label	E	CR	Cost	NC	CE	Weighted CE
A1-M1-S1	5	0.63	1,128	3.052	0.205	0.040
A1-M2-S1	361	0.45	151,800	5.181	0.087	0.017
A1-M2-S2	78	0.10	71,280	4.853	0.020	0.004
A1-M2-S3	119	0.15	42,560	4.629	0.032	0.006
A2-M1-S1	40	0.67	36,590	4.563	0.146	0.024
A2-M1-S2	92	1.00	92,530	4.966	0.201	0.033
A2-M1-S3	100	1.00	23,120	4.364	0.229	0.037
A3-M1-S1	165	0.83	710,500	5.852	0.141	0.017
A3-M1-S2	150	0.75	954,000	5.980	0.125	0.015
A3-M1-S3	130	0.65	435,000	5.638	0.115	0.014
B1-M1-S1	26	0.65	710,500	5.852	0.111	0.030
B1-M1-S2	22	0.55	954,000	5.980	0.092	0.025
B1-M1-S3	18	0.45	435,000	5.638	0.080	0.022
B1-M2-S1	0.3	0.80	259,200	5.414	0.148	0.040
B1-M2-S2	0.2	0.53	343,500	5.536	0.096	0.026
B1-M3-S1	21	0.84	259,200	5.414	0.155	0.042
B1-M3-S2	12	0.48	119,200	5.076	0.095	0.026
B1-M4-S1	25	0.38	259,200	5.414	0.069	0.019
B1-M4-S2	5	0.88	3,215,300	6.507	0.134	0.036
B2-M1-S1	12	0.48	6,250	3.796	0.126	0.032
B2-M1-S2	4	0.16	5,640	3.751	0.043	0.011
B2-M2-S1	30	0.4	435,000	5.638	0.071	0.018

E: Effectiveness, CR: Contribution, NC: Normalized Cost, CE: Cost-Effectiveness

Table 9. Prioritization result of advanced systems.

Priority	Advanced system	Label	Total Weighted CE
1	Variable speed limit system	B1-M2-S1 B1-M3-S1 B1-M4-S1	0.101
2	Transit signal priority	A3-M1-S3 B1-M1-S3 B2-M2-S1	0.053
3	Adaptive signal control system	A3-M1-S1 B1-M1-S1	0.047
4	Intelligent road marking	A1-M1-S1 A1-M2-S2	0.044
5	Eco-traffic signal timing	A3-M1-S2 B1-M1-S2	0.040
6	Solar-powered traffic signs and signals	A2-M1-S3	0.037
7	Snowmelt system	B1-M4-S2	0.036
8	Solar-powered street lighting system	A2-M1-S2	0.033
9	Bike sharing system	B2-M1-S1	0.032
10	Automated work zone information system	B1-M2-S2	0.026
11	Ramp metering	B1-M3-S2	0.026
12	Wind-powered street lighting system	A2-M1-S1	0.024
13	Automated street lighting system	A1-M2-S1	0.017
14	Smart parking meter system	B2-M1-S2	0.011
15	LED lighting system	A1-M2-S3	0.006

CHAPTER 4

Conclusions and Recommendations

CONCLUSIONS

A smart city enhances its functionality to solve various urban challenges and address the different needs of citizens. Urban infrastructure development by applying innovative technologies has been vital for a city to be smart. The urban road network is one of the critical infrastructures to sustain a city in operation. An efficient decision-making tool helps city officials evaluate the current status of urban roads, identify advanced systems to improve the current status and prioritize the advanced systems, which collectively leads to efficient investment.

This project developed a hierarchy table of indicators and measures connected to smart city components to assess the current development status of urban roads in a smart city and identify the investment priority of advanced systems. This project also presented a new method to determine the weights of smart city components and indicators for the prioritization framework. Thus, the priority of the advanced systems was determined by the weighted cost-effectiveness values of advanced systems. All the steps in the modules of the prioritization framework were demonstrated using the data obtained from a discovery search and produced hypothetically. With these deliverables, the contributions of this project are:

- A new hierarchy table of indicators and measures specific to urban roads enhances the knowledge deficit. As another knowledge-based contribution, the procedures used to develop the indicators and measures in this project can be developmentally applied to other individual service areas of a smart city.
- The practical use of the hierarchy table is its capability as a platform on which city planners can customize the indicators and measures considering the sizes (e.g., small, medium, and large cities) of and demands specially requested for their cities.
- The presence of the hierarchy table has the potential to encourage city officials to develop a prospective decision-making practice in innovating urban roads. In general, a decision-making process to establish investment strategies begins by gathering information about current needs. The accuracy of the information is paramount for good policy-making for an investment decision. Thus, the presence of the hierarchy table has a partial contribution to developing a prospective decision-making practice in innovating urban roads.
- As prioritizing different options is core for a practical decision-making tool for investment, the presented framework can improve the ability of city officials to make proper investment decisions on advanced systems for urban roads.
- The weight estimation method conceived in this project can broaden an understanding of determining weights in performance-based decision-making problems. Thus, the presented prioritization framework is applicable for urban infrastructures such as drinking and wastewaters, electricity, hospitals, and schools.

RECOMMENDATIONS

To expand the applicability of the hierarchy table and prioritization framework in this project, some future works should be considered as follows :

- The indicators and measures in a hierarchy table require continuous updates with more availability of documents related to urban roads innovation for a smart city.
- As the framework involves various mathematical functions in its procedures, developing a computing tool can benefit city officials in systematically implementing their smart city program.
- While this project employed a measure-specific approach that considered the effectiveness of an advanced system pertaining to its matching measure only, other supplemental benefits from a system application can come into play for cost-effectiveness analysis. For example, city officials might consider the locality of an advanced system for a city-wide economy in its effectiveness evaluation along with the measure-specific benefit.
- Although the prioritization framework was successfully demonstrated to verify its procedures working together to generate a priority list of advanced systems, the application of the framework for a test city can provide an opportunity to evaluate its applicability in actual city-wide practice.

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