CAIT-UTC-060

Research Challenges toward the Implementation of Smart Cities in the United States

Final Report
December 2015

Ruey L. Cheu
Professor

Oscar A. Mondragon
Associate Professor

Soheil Nazarian
Professor

Cesar J. Carrasco
Professor

Ann Q. Gates
Professor

Sergio D. Cabrera
Professor

Natalia Villanueva-Rosales
Assistant Professor

Carlos M. Ferrugut
Professor

Heidi A. Taboada Jimenez
Associate Professor

Esmaeil Balal
Ph.D. Candidate

The University of Texas at El Paso
500 W University Ave, El Paso, TX 79968

External Project Manager
Johanes Makahaube

In cooperation with
Rutgers, The State University of New Jersey
And
The City of El Paso
And
U.S. Department of Transportation
Federal Highway Administration

Disclaimer Statement

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CAIT-UTC-060		
4. Title and Subtitle Research Challenges toward the Implementation of Smart Cities in the United States		5. Report Date December 2015 6. Performing Organization Code CAIT/UTEP
7. Author(s) Ruey L. Cheu, Oscar A. Mondragon, Natalia Villanueva-Rosales, Soheil Nazarian, Cesar J. Carrasco, Sergio D. Cabrera, Carlos M. Ferregut, Ann Q. Gates, Heidi A. Taboada Jimenez, Esmaeil Balal		8. Performing Organization Report No. CAIT-UTC-060
9. Performing Organization, Name and Address The University of Texas at El Paso 500 W University Ave, El Paso, TX 79968		10. Work Unit No. 11. Contract or Grant No. DTRT12-G-UTC16
12. Sponsoring Agency Name and Address Center for Advanced Infrastructure and Transportation Rutgers, The State University of New Jersey 100 Brett Road Piscataway, NJ 08854		13. Type of Report and Period Covered Final Report 9/1/15 - 12/31/2015 14. Sponsoring Agency Code

15. Supplementary Notes
U.S Department of Transportation/Research and Innovative Technology Administration
1200 New Jersey Avenue, SE
Washington, DC 20590-0001

16. Abstract
A smart city is characterized by its ability to integrate people, technology and information to create an efficient, sustainable and resilient infrastructure that provides high quality services while improving the quality of life of its residents. This report focuses on the three infrastructures: smart classroom buildings, smart bridges and smart bus systems, with the aim of making them smarter in the context of smart citires. The objective is to develop Concepts of Operations (ConOps), from user's perspective, for smart buildings, smart bridges and smart bus systems, respectively, for smart cities. A smart classroom building is one which makes used of Information and Communications Technologies (ICT) to link different systems within a building to deliver useful information to different end users so as to improve the quality of teaching, learning and working experiences. A smart bridge has wireless sensors that automatically monitor the structural and geotechnical health, exchanges real-time data with traffic management center and incorporate traffic and emission impacts in the bridge maintenance decision making process. A smart bus system provides passengers a high quality service by implementing several bus rapid transit features and by the use of ICT to integrate and deliver service information to passengers. This report provides a description of each of the infrastructure systems from the system engineering perspective. Several techniques (Stakeholder Influence Diagram, Context Diagram, and Use Case Diagram) are used to identify relevant stakeholders, define the scope of the system and its external entities, and to identify the smart services provided by the smart classroom buildings, smart bridges and smart bus systems. By applying these systems engineering techniques, the challenges and research opportunities of transforming existing classroom buildings, bridges and regular bus systems into smart classroom buildings, smart bridges, and smart bus systems are identified.

17. Key Words		18 Distributional Statement	
Smart cities, smart classroom building, smart bridge, smart bus			
19. Security Classification	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	66	

Form DOT F 1700.7 (8-09)

ACKNOWLEDGMENTS

The authors would like to express appreciation to Office of Research and Sponsored Project (ORSP) at The University of Texas at El Paso (UTEP) which provide the match to co-fund this research through its Interdisciplinary Research (IDR) Program.

The authors also thank Mr. Everett Esparza and Ms. Claudia Garcia from Sun Metro, City of El Paso for providing inputs on smart bus systems.

ABSTRACT

A smart city is characterized by its ability to integrate people, technology and information to create an efficient, sustainable and resilient infrastructure that provides high quality services while improving the quality of life of its residents. This report focuses on the three infrastructures: smart classroom buildings, smart bridges and smart bus systems, with the aim of making them smarter in the context of smart cities. The objective is to develop Concepts of Operations (ConOps), from user's perspective, for smart classroom buildings, smart bridges and smart bus systems, respectively, for smart cities. A smart classroom building is one which makes used of Information and Communications Technologies (ICT) to link different systems within a building to deliver useful information to different end users so as to improve the quality of teaching, learning and working experiences. A smart bridge has wireless sensors that automatically monitor the structural and geotechnical health, exchanges real-time data with traffic management center and incorporate traffic and emission impacts in the bridge maintenance decision making process. A smart bus system provides passengers a high quality service by implementing several bus rapid transit features and by the use of ICT to integrate and deliver service information to passengers. This report provides a description of each of the three infrastructure systems from the system engineering perspective. Several techniques (Stakeholder Influence Diagram, Context Diagram, and Use Case Diagram) are used to identify relevant stakeholders, define the scope of the system and its external entities, and to identify the smart services provided by the smart classroom buildings, smart bridges and smart bus systems. By applying these systems engineering techniques, the challenges and research opportunities of transforming existing classroom buildings, bridges and regular bus systems into smart classroom buildings, smart bridges and smart bus systems are identified.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 Background

Cities are the centers of human's economic, social and cultural activities. Half of the world population is living in cities in 2013, and population in cities is expected to grow from 3.6 billion in 2011 to 6.3 billion by 2050. Urbanization is always accompanied by challenges such as population explosion, high cost of living, (air, water, noise and light) pollution, inadequate infrastructure capacity (e.g., traffic congestion), etc (IEEE 2015). Urban planners, engineers, elected officials, and other decision makers are often faced with the challenge of how to make the services provided by cities operate more efficiently, and how to make the cities more resilient and environmentally sustainable in order to improve the Quality of Life (QoL) for the residents.

Smart cities, or smarter cities, is an emerging concept that has the potential to solve the aforementioned problem faced by cities of all sizes today. The concept of smart cities has emerged from the applications of Information and Communication Technologies (ICT) to enhance the quality and performance of public services, to reduce costs and resource consumption, and to engage more effectively and actively with its residents. Other terms that have been used for the smart cities concept include 'cyberville, 'digital city', 'electronic communities', 'flexi city', 'information city', 'intelligent city', 'knowledge-based city', 'MESH city', 'telicity, 'telecopies', 'ubiquitous city', 'wired city', etc. However, the terms 'smart cities' is the one most commonly used. For the rest of this report, the term smart cities is used throughout.

Although the concept of smart cities is enthusiastically promoted by the ICT industry, it is not simply the implementation of technologies per se. First and foremost, the ultimate objective of smart cities is to improve the QoL of the residents. The meaning of QoL varies from city to city, depending on the size (population), geographical location, natural resources, level of economic development, etc. Second, smart cites involves the participation of many stakeholders, including the political leaders, city management, private industry, university researchers, special interest groups and the residents in the data collection and decision making processes. Third, the information from the various public services in a city needs to be collected and analyzed in an integrated manner, and the decisions communicated to the stakeholders.

From the systems engineering point of view, a smart city is a system of inter-connected infrastructure systems. Proponents of smart cities acknowledge that the sub-systems of a city are no longer operating as isolated, independent systems. Rather, these systems interact with each other in day-to-day operations and during emergency events. Therefore, the data collected from the various infrastructure systems need to be shared and integrated as part of the decision making process so as to optimize the operations of the city.

1.2 Objective and Scope

There are many infrastructure systems owned and operated by a city. Through these infrastructure systems, the city (directly or through its contractors) is providing services to its residents. The infrastructure systems vary from city to city. For example, the following infrastructure systems (in alphabetical order) are managed by the different departments in the City of El Paso:

- Bridges;
- Buildings;
- Emergency services (police, fire, medical);
- Library;
- Mass transit;
- Parks and recreation;
- Solid waste collection, recycling and disposal; and
- Street maintenance.

Although not owned and operated by the City of El Paso, the following infrastructure systems are essential to the functions of the city and the QoL of the residents:

- Electrical network;
- Water supply network;
- Wastewater network; and
- Telecommunications network.

These networks are owned and operated by public or private utility entities.

Due to time and budget constraints, the authors of this report has selected to focus on the three following infrastructures:

- Smart buildings (more specifically smart classroom buildings);
- Smart bridges; and
- Smart mass transit systems (more specifically smart bus systems).

The objective of this research is to develop Concepts of Operations (ConOps) for smart classroom buildings, smart bridges and smart bus systems, respectively, for smart cities. A ConOps is a document describing the characteristics of a proposed (smart) system from the viewpoint of the users. It is used to communicate the quantitative and qualitative system characteristics to all stakeholders. The ConOps is a useful tool for stakeholders to identify the functions or user services of a smart infrastructure system for implementation planning, and to document the associated research issues.

Although an important characteristics of smart cities is data sharing and data integration, this report does not propose a ConOps that integrates the smart classroom buildings, smart bridges and smart bus systems within a city. As the first step, the authors focus on the ConOps of each of the three systems. Each system is analyzed as a collection of several sub-systems, with their own equipment and data. This report identifies stakeholders, and the user services a smart system is expected to provide to the various stakeholders. From there, the report examines data flow, data sharing and data integration between the sub-systems in order to deliver services to users.

1.3 Outline of Report

The outline of this report is as follows:

- Chapter 1 provides the background of smart cities, the objective and scope of this research, and outline of this report.
- Chapter 2 describes the history, definitions, and characteristics of smart cites. The chapter ends by identifying the research issues.
- Chapter 3 presents the development of ConOps for smart classroom buildings.
- Chapter 4 presents the development of ConOps for smart bridges.
- Chapter 5 presents the development of ConOps for smart bus systems.
- Chapter 6 summarizes the findings and identifies research challenges.

CHAPTER 2 CONCEPT OF SMART CITIES

2.1 History of Smart Cities

The term smart cities was first used in the 1990s. At that time, the focus was on the significance of ICT to modernize infrastructures within cities (Albino et al. 2015). IBM started to use the terms smarter cities and smarter planet in 2009 (Harrison and Donnelly 2011). The earliest published documents that used the term smart cities was Washburn and Sindhu (2010) which described that a smart city is a collection of seven smarter city infrastructure and services. In the following year, a white paper entitled "A theory of smart cities" was released by IBM (Harrison and Donnelly 2011) and appears to be the one which generated the momentum for the smart cities movement. The IBM white paper used terms and descriptions such as systems of systems, collaborative, inter-disciplinary, etc., which laid the foundation for the current concept of smart cities.

Realizing this emerging trend, in 2013, a group of large multinational ICT companies formed the Smart City Council to promote the implementation of the smart cities concept (Smart Cities Council n.d.). In the same year, The Institute of Electrical and Electronics Engineers (IEEE) launched its Smart Cities Initiative by forming its IEEE Smart Cities Initiative Working Group. In October 2013, the City of Guadalajara, Mexico, was announced as the IEEE's first smart city pilot site in the world. In the following year, Trento, Italy and Wuxi, China were added as IEEE's smart cities pilot sites. Kansas City, U.S. and Casablanca, Morroco were further added to the list in 2015. The IEEE also held its First International Smart Cities Conference in Guadalajara, Mexico, in October 2015 (IEEE 2015).

2.2 Definitions of Smart Cities

To date, there is no universal definition of smart cities. Many researchers and publications have tried to provide their own definitions, based on their domain expertise and their vision of smart cities. Because there are too many definitions of smart cities, only the definitions used by major industrial associations and standards authorities are discussed in this report.

The IEEE defines a smart city as a city that "*brings together technology, government and society to enable the following characteristics: smart economy, smart mobility, smart environment, smart people, smart living, and smart governance*" (IEEE 2015).

The Smart Cities Council defines a smart city as one where "*digital technology and intelligent design have been harnessed to create smart, sustainable cities with high-quality living and high-quality jobs*" (Smart Cities Council n.d.). It further elaborates that "*a smart city gathers data from smart devices and sensors embedded in its roadways, power grids, buildings and other assets. It shares that data via a smart communications system that is typically a combination of wired and wireless. It then uses smart software to create valuable information and digitally enhanced services*".

The British Standards Institute (BSI) defines a smart city as "*effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens*" (BSI 2014).

The International Standard Organization/International Electrotechnical Commission Joint Technical Committee 1 (ISO/IEC JTC1) describes a smart city as "*a new concept and a new model, which applies the new generation of information technologies, such as the internet of things, cloud computing, big data and space/geographical information integration, to facilitate the planning, construction, management and smart services of cities*" (ISO 2015).

The European Commission states "*smart cities are characterized and defined by a number of factors including sustainability, economic development and a high quality of life. Enhancing these factors can be achieved through infrastructure (physical capital), human capital, social capital and/or ICT infrastructure*" (EC 2015).

Many other definitions of smart cities can be found in Albino et al. (2015).

After reviewing the above definitions, the authors of this report proposed the following definition: "*a smart city is characterized by its ability to integrate people, technology and information to create an efficient, sustainable and resilient infrastructure that provides high quality services while improving the quality of life of its residents*". The important terms in this definition are elaborated as follows. First, a smart city brings people together to provide information (data), technology and make decisions. The term people involves all the stakeholders in the city, which may be individuals or organizations. A smart city also has the ability to use technology (hardware) to collect, process and analyze information (data) across different infrastructure systems. It further includes the integrated processing and analysis of the data, and study the interaction of two or more infrastructure systems. The outcomes are to make the operations of the city and the services they provide more efficient, sustainable and resilient. The term sustainable infrastructure means the infrastructure is more economically, social and environmentally sustainable. Resilient infrastructure means the infrastructure system is able to withstand external stresses and shocks while maintaining a satisfactory level of operations, and has the ability to quickly recover to normal operations. Making the infrastructures more sustainable and resilient are two necessary conditions for a city to provide high quality services to its residents.

2.3 Characteristics of Smart Cities

Smart cities stand out from "conventional" cities by their possession of several characteristics. These characteristics help stakeholders understand what smart cities are about, and what they are capable of. As with the smart cities definitions, different researchers and organizations characterize smart cities in different ways. These characteristics are also referred to as dimensions. Some of the characteristics appear in some of the smart cities definitions.

The IEEE definition of smart cities (IEEE 2015) refers to six characteristics:

- Smart economy;
- Smart mobility;
- Smart environment;
- Smart people;
- Smart living; and
- Smart governance.

The 2014 study "Mapping Smart Cities in the European Union" by the European Parliament's Directorate General for Internal Policies (EP 2014) defined six smart city axes (or dimensions). The list is the same as the characteristics outlined by IEEE (2015).

The European Commission, in its Digital Agenda for Europe (EC 2015), characterizes smart cities by three factors:

- Sustainability;
- Economic development;
- QoL.

The characteristics of smart cities provided by IEEE, European Parliament and European Commission specify the desired outcomes in three to six dimensions without elaborating on how to achieve them. The enablers are only mentioned briefly in the IEEE and European Commission's definitions of smart cities (IEEE 2015; EC 2015).

The IBM's smarter city has three main characteristics (Qin et al. 2010):

- Instrumented;
- Interconnected; and
- Intelligent.

Instrumentation means sourcing of real-time real-world data from both physical and virtual sensors. Such data may be interconnected across multiple processes, systems, organizations, industries, or value chains. The combination of instrumented and interconnected systems effectively connects the physical infrastructure to the virtual world.

The ISO/IEC JTC1 (ISO 2015) outlines the characteristics that are required for smart cities. They are summarized as follows:

- The city will be instrumented;
- The data from different sources will be available to be easily aggregated;
- The data will be easily visualized and accessible;
- Detailed, measureable, real-time knowledge will be available at every level;
- Analytics and decision-making systems will be used;
- The city will be automated;
- The city will have a network of collaborative spaces; and
- The decision making processes are to be much more open and inclusive.

The characteristics described by both IBM and ISO/IEC JTC1 are related to the process of making cities smarter but they do not characterize the outcomes.

The Smart Cities Council (n.d.) does not explicitly list the characteristics of smart cities. However, it provides a list of responsibility areas and a list of enablers. The responsibility areas (which correspond to services provided by the cities to its residents) are:

- Built environment[1];
- Economic development;
- Energy;
- Health and human services;
- Payments (electronic payment of fees);
- Public safety and security;
- Telecommunications;
- Transportation;
- Waste management; and
- Water and wastewater.

The list of enablers (technologies and strategies) are:

- Analytics;
- Citizen engagement;
- Computing resources;
- Connectivity;
- Data management;
- Finance and procurement;
- Instrumentation and control;
- Interoperability;
- Policy and leadership; and
- Security and privacy.

Albino et al. (2015) have summarized the different dimensions of smart cities found in their literature review.

Overall, smart cities have two characteristics that are distinguished from "conventional" cities:

1. The services provided by the cities, the public engagement and decision making are ICT enhanced;
2. The residents of smart cities enjoy better quality of service delivered by their cities.

Our first characteristic relates to the enablers and processes, while the second characteristic focuses on the outcomes.

To measure the level of implementation of technologies, and the quality of service, researchers and industrial organizations have developed quantitative indicators for "smartness" of a city which is discussed in the next section.

[1] The Smart City Council defines built environment as buildings, parks and public spaces which may or may not be owned by the city.

2.4 Smart Cities Indicators

After defining smart cities and listing their characteristics, researchers and organizations next develop measures, indicators or metric to evaluate how smart is a city, or how close a city has achieved the smart city status. Another use of measures is to understand the city's performance, discover underlying trends, compare characteristics and identify strength and weaknesses of the city (Vázquez-Castañeda and Estrada-Guzman 2014).

The BSI, in its "Smart Cities – Vocabulary" reports several high level indictors:

- Broadband connectivity, including GPS, Wi-Fi and satellite availability;
- Knowledge workforce;
- Digital inclusion;
- Innovation; and
- Marketing and advocacy.

The ISO/IEC JTC1 (ISO 2015) has developed the ISO 37150 standard that includes global city indicators, green city index series and smart city indicators.

- The global city indicators group city life descriptions into education, health, recreation, safety, transportation, water, finance, etc.
- The green city index series are related to environmental sustainability which cover CO_2, energy, water and transport, etc.
- The ISO researchers are currently working on a new standard that is supposed to measure ICT system performance in smart cities.

The ISO 37120 Sustainable Development of Communities (GCI n.d.) standard has two sets of city metrics: city services and QoL. There are 20 themes which are organized as follows:

City services

- Education;
- Energy;
- Finance;
- Recreation;
- Fire and emergency;
- Response;
- Governance;
- Health;
- Solid waste;
- Transportation;
- Urban planning;
- Wastewater; and
- Water.

QoL

- Civic engagement;
- Culture;
- Economy;
- Environment;
- Shelter;
- Social Equity; and
- Technology and innovation.

The grouping of the themes are similar to the two characteristics the authors of this report have stated in the previous section.

Lombardi et al. (2012) presented 60 indicators grouped into five dimensions:

- Smart economy;
- Smart people;
- Smart governance;
- Smart environment; and
- Smart living.

The most comprehensive set of smart city indicators is perhaps the one used by the Smart City Council (2014) which was provided by Cohen. Cohen's smart city indicators are organized into six dimensions (which is the same as the six characteristics of IEEE and European Parliament's smart cities):

- Environment;
- Mobility;
- Government;
- Economy;
- People; and
- Living.

Each dimension is divided into three working areas. Each working area is further divided into one to four indicators. The dimensions and working areas may be visualized in Figure 2.1. Cohen did not provide any guidance on how to combine the different indicators to arrive at an index.

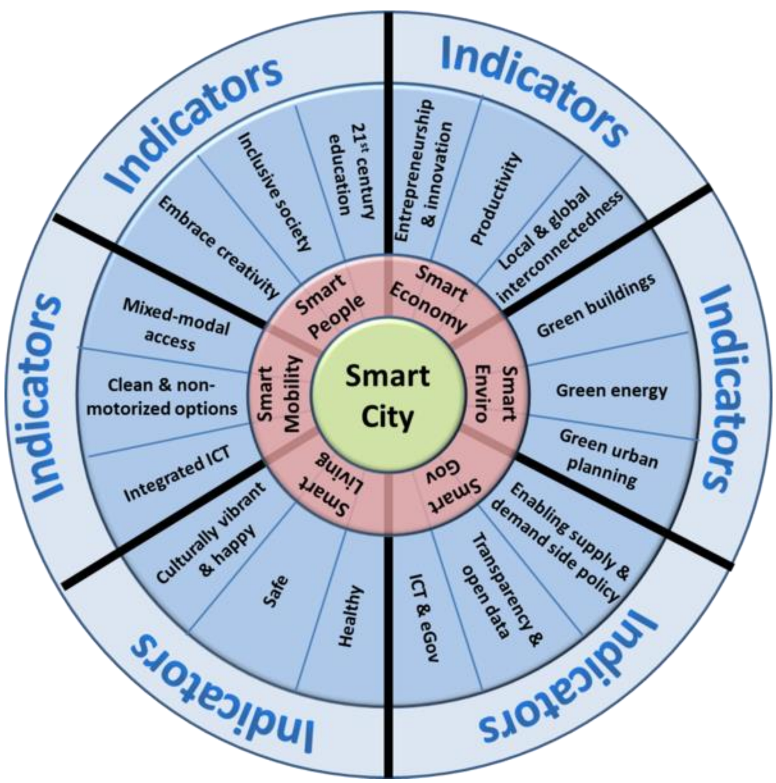

Figure 2.1 Smart city indicator wheel
(from Smart City Council (2014))

As the objective of smart cities is to improve the quality of life of the residents, researchers have also proposed indicators to measure the quality of life.

Mercer (2015) surveyed 440 cities to compile and compare the cities' QoL indices. The indicators consists of 39 factors organized into 10 categories:

- Political and social environment;
- Economic environment;
- Socio-cultural environment;
- Medical and health considerations;
- Schools and education;
- Public services and transport;
- Recreation;
- Consumer goods;
- Housing; and
- Natural environment.

Pribyl and Horak (2015) stated that different individuals have different perceptions of QoL. They conducted a preliminary survey on 41 respondents in Pisek, a city with 30,000 inhabitants in Czech Republic which aspires to be a smart city. The respondents were asked to (i) rank the relative importance of the five pre-defined dimensions of Pisek as a smart city; (ii) answer yes or no for three kinds of transportation information (real-time traffic conditions, public transport connections, parking availability) that need investment to improve service quality. The distribution of the outcomes for each question demonstrated the varied individual preference on what constitutes QoL.

Two issues have been identified by the authors after reviewing the smart cities indicators:

1. The first issue is concerned with the measurement of QoL. The smartness of a city ultimately will be judged by its residents (via their QoL). Therefore, the QoL indicators (the outcomes) are more important than the indicators for the implementation of technologies (the process). Depending on the population, history, geographical location, local resources and economic development, residents of a city may have different priorities related to different QoL indicators. It is therefore difficult to use a set of universal measures to compare cities. It is also necessary for a city to engage its residents (and stakeholders) in deriving a list of characteristics (dimensions) and measurable indicators.
2. As discussed in the above review, a city may have 60 to 100 indicators. The computation of such indicators demands large quantity and up-to-date data. This requires the data to be opened, transparent and shared.

2.5 Research Challenges

This chapter reviews the concept of smart cities by examining the history, definitions, characteristics and indicators. The findings are:

- The concept of smart cities only emerged in 2010. It only gathered momentum in 2013.

- The terms smart city, smart cities and many variants are used by researchers and organizations that refer to the same concept. There is no universally agreed term. The two most popular terms, i.e., smart city, smart cities are being used interchangeably.
- There is no universally agreed definition of smart cities. The definition needs to mention the integration of people, technology and information, and the improvement in services, sustainable and resilient infrastructure systems that lead to improvement of QoL. The authors of this report have proposed a definition that incorporates all of the above.
- A smart city is most frequently characterized by six dimensions: smart economy, smart mobility, smart environment, smart people, smart living, and smart governance. An alternative is to list the characteristics under two groups (i) city services; and (ii) QoL indicators. The authors of this report have provided another alternative description of characteristics in (i) ICT enhanced public services; and (ii) improvement in QoL.
- The smartness of a city may be measured by an index which has the smart cities dimensions as its components. Each dimension consists of several measurable indicators. How the numerical indicators combined to form a dimension's score, and how different dimension scores are aggregated to form an overall index is not clear. The authors caution that the smartness of a city cannot be evaluated by a universal composite measure. The selection of dimensions, and indicators must reflect the resident's preferences, in accordance with the city's development status and other constraints.

A smart city may be designed and built from scratch. However, most, if not all of the cities in United States, as in other parts of the world, are already operating with existing infrastructure systems. It is not practical (at least it is cost prohibitive) to rebuild the entire or even parts of the telecommunication, civil and environmental infrastructures. Doing so may also cause too much disruption to a city's services, which may lead to negative consequences for the smart city initiative. A more realistic approach is to systematically instrument the current infrastructure, and to integrate the information for smart decision making, and then implement the decisions to improve the existing processes. Therefore, it is better for existing cities to be transformed into smart cities by collecting and integrating the information about the operations of the infrastructure systems.

Transforming a city into a smart city requires collaborative efforts between all stakeholders (e.g., government, industry, practitioners, residents and researchers). A common theme is the need for expertise from many disciplines, such as computer science, civil engineering, systems engineering, electrical and computer engineering, to name a few. Bringing together stakeholders with different background to support smart city initiatives will produce several challenges. Some of these challenges involve the differences in expert vocabulary, differences in disciplinary cultures, identification of available and appropriate resources, and integration of heterogeneous data and knowledge.

CHAPTER 3 SMART CLASSROOM BUILDINGS

3.1 Chapter Overview

A building is more than a structure. A modern-day building consists of structural, foundation, security, lighting, temperature control, communications, electricity, water and wastewater systems, etc. These systems are put into operation to serve the users of the building. A building, with the aforementioned mechanical, electrical, civil, and environmental engineering systems, and communication system, is therefore a system of systems. In this regard, a building may be viewed as a microcosm of a city. This purpose of this chapter is to identify the challenges in transforming existing buildings into smart buildings. As there are many types of building to serve different user needs, this chapter focuses on one type of building, namely classroom buildings in an university setting. The rest of this chapter uses classroom buildings in The University of Texas at El Paso (UTEP) as examples in the discussions. However, most of the contents are generic in nature and are applicable to classroom buildings in schools and universities.

3.2 Existing Classroom Buildings

The basic function of a classroom building is to provide spaces for teaching and learning. The most important space of a classroom building is classrooms. The classrooms include lecture hall, seminar rooms and other types of instructional facilities but excluding teaching and research laboratory (which always needs special equipment). A classroom building usually has classrooms of different sizes (seating capacities), furniture, ICT equipment, etc. Other essential physical (and generic) spaces of the classroom building are parking lots, lobby, stairways and hallways, restrooms, staff offices, student work areas, storerooms, and elevator shafts. The daily users of classroom buildings are primarily instructors and students. They are supported by staff and contractors. The existing classroom building has the following standard systems: electrical power, water, wastewater and sewage, solid waste, ventilation, temperature control (heating, air-conditioning), security, communications (telephone, internet) and audio-visual. Figure 3.1 shows two typical classrooms at UTEP.

Figure 3.1 Typical classrooms

In UTEP campus, classroom buildings are owned by the university. The university has a Facility Services department which is responsible for the planning, design, construction and maintenance of all building facilities. Facility Services has gardeners and staff who perform minor electrical, mechanical and civil engineering maintenance works. Each college has a technician who is responsible for making maintenance requests on behalf of the college to Facility Services. The janitors are staff of a private contractor. The ICT services in the classroom buildings are provided by the Information Technology (IT) Department. Some specialized ICT systems are contracted out to technology providers. The Center of Excellence for Teaching and Learning (CETaL) has influence on the instructors' teaching style, and the ICT equipment to be placed in each classroom. Majority of the classroom buildings at UTEP has food and drink vendors.

3.3 Justification for and Nature of Proposed Changes

In Chapter 2, a smart cities has been defined as a city characterized by its ability to integrate people, technology and information to create a sustainable and resilient infrastructure that provides high quality services for its residents. In a similar fashion, a smart classroom building is one which makes used of ICT to link different systems within a building to deliver useful information to different end users so as to improve the quality of teaching, learning and working experiences.

Many existing systems within a classroom building may become smarter by having the, instrumented, or have information stored in a data server and disseminate to users upon requests. Decision makers of the operations of the building can make better informed decisions by having data available from several systems. But building owners or managers often fail to take advantage of those potential capabilities, not realizing that by leveraging on ICT technology, the existing classroom building may be transformed into smart classroom buildings. By linking a classroom building's sub-systems together, additional functions may be implemented to serve the users. The purpose of the smart classroom building is to improve the quality of teaching and learning experiences.

3.4 New Smart Classroom Building

The most important purposes of smart classroom buildings are

i. To provide better classrooms for instructors to deliver high quality teaching; and
ii. To provide better classrooms for students to receive high quality education.

In addition, to improve the QoL of all users, the building should provide the following systems:

- A security system to keep the building from unauthorized users during restricted hours (e.g., weekends, holidays or game days), and records the identifications of authorized users at every classroom at any time.
- An emergency alarm system which includes smoke and carbon monoxide sensors (for fire), and push-buttons (for medical and civil and criminal incidents). The alarm message that is sent to the campus police and fire departments also indicates the exact location (floor, room number) of the incident, and the real-time occupancy of the room.
- An emergency evacuation guidance system that directs the occupants via the most direct paths to the nearest building exits. The evacuation paths are updated in real-time based on the information received from the alarm system, and are disseminated to users via display panels, voice announcements via speakers, text messages and smart phone apps.
- An information display system (via display panels and smart phone apps) which informs the users the floor plan, scheduled classes and events. The information display may be customized by users in their personal devices.
- A smart classroom management system which allows instructors to automatically take attendance, and receive, record and display students' answers to questions, in addition to automatically record each lecture that later on can be reviewed by students.
- A low energy and smart lighting system which can be adjusted by instructors to meet the different teaching-learning modes;
- A system which automatically report gas, water and electricity consumptions periodically to the utility suppliers, and allow the building manager to monitor the utility consumptions in real-time.

It is assumed that a smart building is managed by a Building Manager. This is a Building Manager in every college. The building manager is responsible for the day-to-day operation of all smart buildings in the college. He/she also responsibility for communicating maintenance issues with Facility Services, IT Department, Center for Effective Teaching and Learning (CETaL) and Center for Accommodation and Support Services (CASS).

3.5 Smart Classroom Building Description

This section provides a description of the Smart Classroom Buildings from the systems engineering perspective. Several techniques (stakeholder influence diagram, context diagram, and use case diagram) are used to identify relevant stakeholders, define the scope of the system and its external entities, and to identify the services provided by the Smart Classroom Buildings.

This section identifies and describes the operational scenarios of services that may be provided by a smart classroom building to its users. The process of identification starts with listing possible stakeholders. The stakeholders are then grouped into fewer so-called stakeholder groups. The relationships between the stakeholder groups are then graphically represented in a stakeholder influence diagram. This diagram identifies stakeholders that must be consulted during requirements gathering, project planning, and development processes. The next step is to identify external entities who interact with the smart classroom building in their day-to-day use. The scope of the system can be described with both: a level zero system diagram (also known as the context diagram) and use case diagrams. The high level description on the type of data and materials that flow between each of the external entities and the smart classroom building are illustrated in a level zero system diagram. The knowledge captured in the level zero system diagram identifies all external entities and the data and material being exchanged with the smart classroom building. In addition, the use case diagrams identify all the actors that interact with the smart classroom building and the services requested by these actors. An actor is an external entity, human being, devise or other external system that participate in a service being offered by the system of interest. The use case is a service being offered by the system of interest. Use case description provides the purpose of the service. The services identified in this report do not assume any technical implementation or budget restriction. With a list of multiple services, the building owner has the flexibility to decide what services the smart classroom building should provide, based on the stakeholders' preferences, budget and other constraints.

3.5.1 Stakeholders Influence Diagram

A stakeholder is a group or individual that is affected by or is in some way accountable for the outcome of an undertaking. A Stakeholders Influence Diagram (SID) identifies all stakeholders, groups stakeholders with common interest, and determines the level of influence among the groups. The levels of influence between the stakeholder groups can be used to plan requirements gathering activities and to assign priorities among the requirements to build a smart classroom building.

A smart classroom building has many stakeholders. A classroom in the College of Engineering at UTEP was considered to provide a specific context. The first step is to identify the stakeholders as listed in Figure 3.2. They include stakeholders who are involved in designing a new smart classroom building, and those who help to transform an existing classroom building into a smart classroom building. The list is not meant to be permanent and complete. The stakeholders may be removed, or new stakeholders added to meet the smart classroom building's need and context.

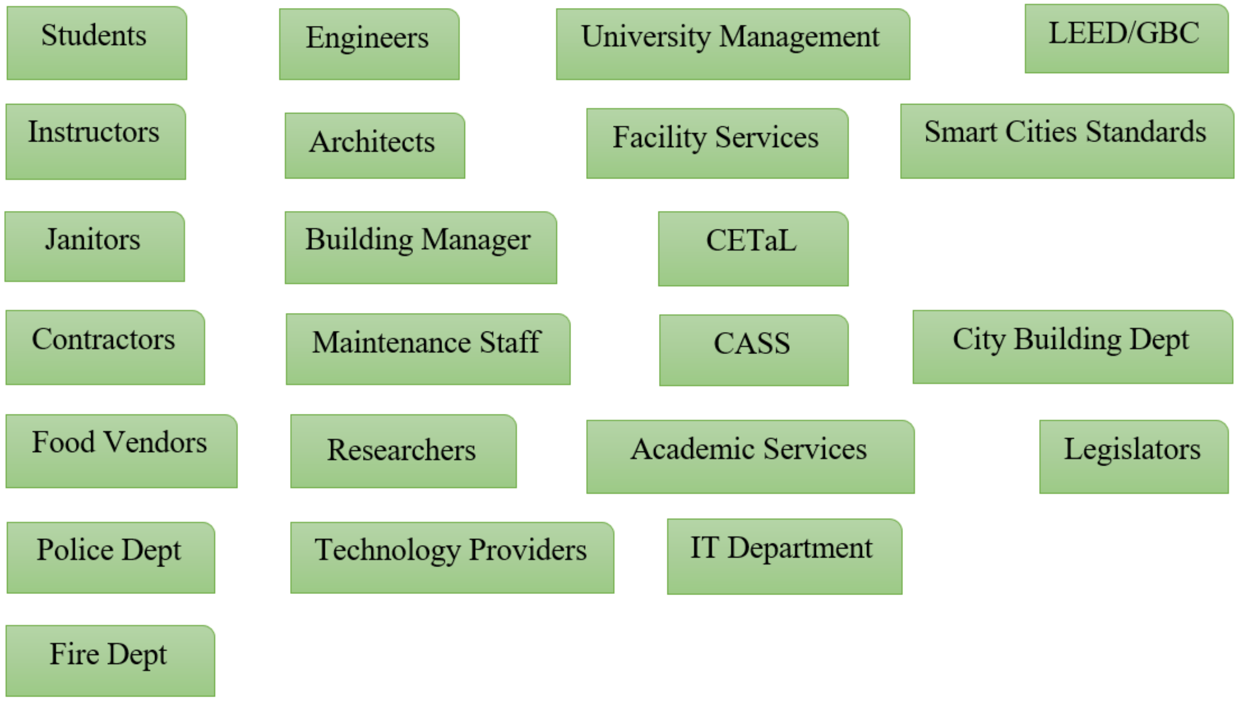

Figure 3.2 Stakeholder diagram for smart classroom buildings

The roles and responsibilities of the identified stakeholders are as follows:

- Students: attend classes in the classrooms.
- Instructors: teach classes in the classrooms.
- Janitors (companies): clean all parts of the building, including the exterior.
- Contractors (companies): perform civil, electrical and mechanical works.
- Food Vendors (companies): sell food and drinks in the building.
- Police Department (university police): patrols the building and responses to incidents.
- Fire Department (university department): responds to fire alarms and medical emergencies.
- Engineers (companies): design the civil, electrical and mechanical systems of the building.
- Architects (companies): design the building.
- Building Manager (university staff): manages the day-to-day operations of the building.
- Researchers (university staff): analyze operational data of the building.
- Maintenance Staff (university staff): maintain mechanical, electrical and civil engineering systems in the building.
- Technology Providers (companies): provide ICT services.
- Utility Suppliers (companies): provide gas, electric and water.
- University Management: makes decisions on the design and use of the building.
- Facility Services (university department): maintains university facilities.
- CETaL (university department): promotes effective teaching and learning.
- CASS (university department): takes care of special needs of the users.
- Academic Services (university department): schedules classes and assigns classrooms.
- IT Department (university department): provides ICT services.

- Leadership in Energy & Environmental Design (LEED) by Green Building Council (GBC): provides norms for sustainable building.
- Smart Cities Standards: provides norms for smart cities.
- City Building Department (local authority): issues building permits, inspects and certifies the building for occupation.
- Legislators (state authority): passes laws that control building codes and funding to the university.

The second step, is to group the stakeholders that have common or similar interests. Grouping the stakeholders offers the opportunity to reduce the effort in eliciting and capturing the levels of influence and requirements. The stakeholders identified for the smart classroom buildings (in Figure 3.2) have been organized into the following groups:

- Users (customers): demand services from the building.
- Facility Managers: manage the building.
- Facility Owners: own the building.
- Authorities: give authorizations from the government.
- Design Authorities: provide design, operations or maintenance standards of the building.
- Service Providers: provide services to the building or its users.

A stakeholder may belong to more than one group. For example, the IT Department belongs to Design Authorities as well as Service Providers. The above six groups may further be aggregated into three major groups: government, industry and people. After grouping, the stakeholders are shown in Figure 3.3.

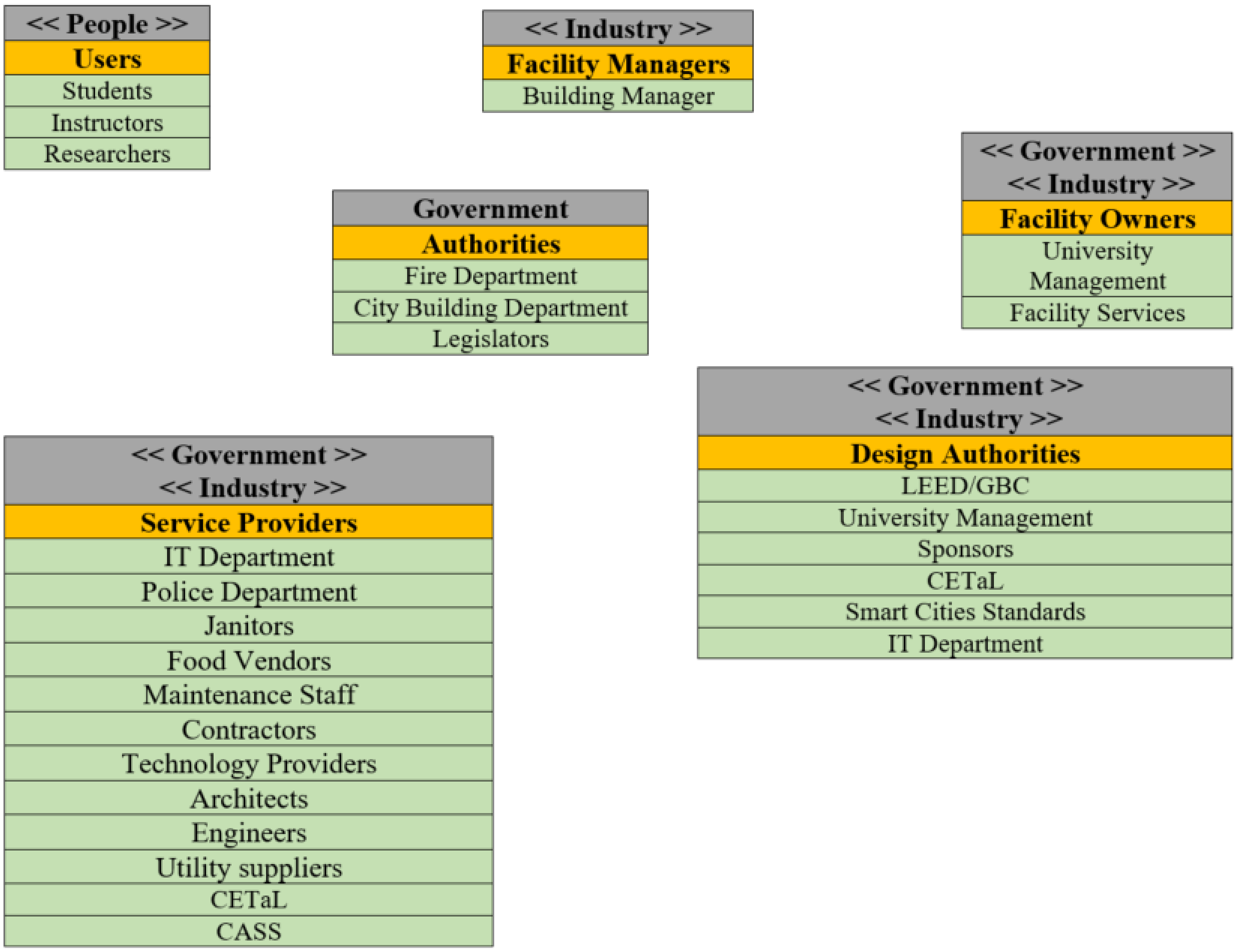

Figure 3.3 Stakeholder group diagram for smart classroom buildings

The arrangement shown in the above diagram is only one of the many alternatives. The assignments of stakeholders to the groups depends on the university's organization structure and business practice. Stakeholders may be added to a group or removed from a group based on a given context.

The third step is to build a stakeholder influence diagram as shown in Figure 3.4. A stakeholder influence diagram identifies, organizes and documents the interactions between the stakeholder groups.

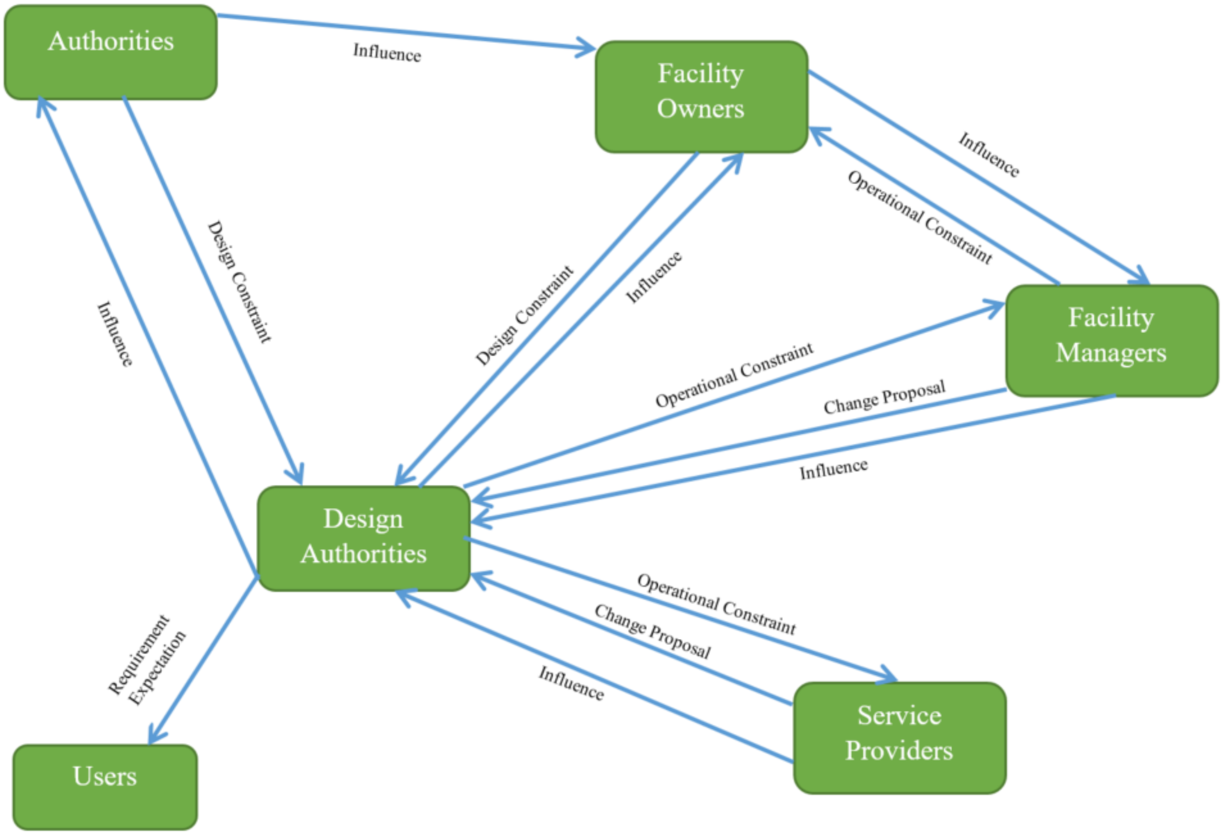

Figure 3.4 Stakeholder influence diagram for smart classroom buildings

Five types of interactions are identified between the six groups of stakeholders:

- Influence - Authorities have influence on Facility Owners.
- Change proposal - Service Provider can request Design Authorities to change the design of certain system components or request changes to the requirements.
- Design constraint - Authorities can impose design constraint on Design Authorities.
- Operational constraint - Design Authorities can impose operational constraints on Service Providers.
- Requirement expectation - Design Authorities have certain expectation or requirement for the users.

3.5.2 Level Zero System Diagram

The level zero system diagram depicts the scope of the system identifying all the external entities. It is also known as the data and material flow diagram or the context diagram. This step is to identify all the external entities who/which interact with the smart classroom building in their day-to-day use, as shown in Figure 3.5. There are no functionality identified at this level zero system diagram. The diagram depicts the smart classroom building at the center, surrounded by all the external entities that interact with it. Moreover, the arrows indicate the directional data or material flow between the smart classroom building and the external entities. In Figure 3.5, Utility Suppliers are divided into more specific organizations: Gas Supplier, Water Supplier, and Electricity Supplier. Parking Service and Garden Services are taken out of Facility Services as they perform specific functions.

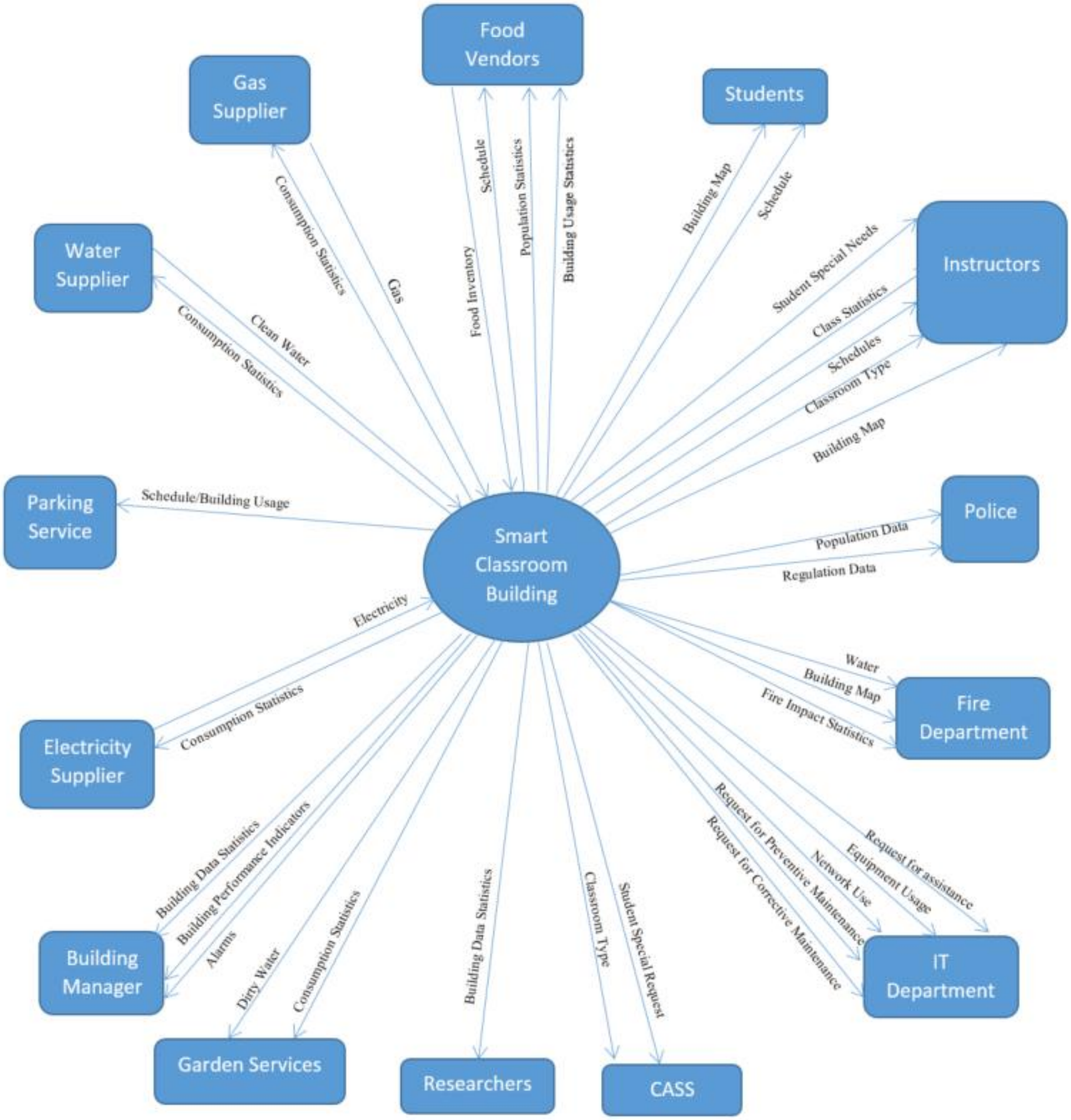

Figure 3.5 Level zero system diagram for smart classroom buildings

The data or material flow between the smart classroom building and the external entities are:

- Students request the building layout and class schedule of each classroom.
- Instructors request the building layout, class schedule of each classroom, classroom type (furniture and equipment), student with special needs, and student statistics (e.g., enrollment, attendance).
- Police Department requests real-time occupant data on the number of users in each room during emergency events, and the list of users who are authorized in each room at any time.
- Fire Department requests water hosts in the building, building layout, and the temperature map of each floor within the building.
- IT Department receives requests to assist users in a particular classroom to make preventive and corrective maintenance of IT equipment in the building, and monitors the equipment usage and network statistics.
- Food Vendor requests building schedules and historical usage so as to cater the food and drinks to sell to the building users.
- CASS receives requests from users on special needs, and requests classroom type (furniture and equipment) to accommodate students with special needs.
- Researchers receive building usage data for analysis.
- Garden Services requests recycled water for irrigation, and water consumption.
- Building Manager receives fire, smoke and security alarm events, requests building usage data (by users), and energy and water consumption statistics.
- Electricity Supplier provides electricity to the building and receives consumption statistics.
- Parking Service requests scheduled events and real-time usage to control traffic.
- Water Supplier provides clean water to the building and receives consumption statistics.
- Gas Supplier provides gas to the building for heating and receives consumption statistics.

3.5.3 Use Case Diagrams

A use case is a methodology used in system analysis to identify, clarify, and organize the services provided by the system of interest. A use case diagram depicts the scope of a system by identifying both actors that interact with the smart classroom building and services requested by these actors. An actor is an external entity. An actor can be a human being, devise or other external system that participates in a service being offered by the system of interest. The use case is a service being offered by the system of interest. Use cases description provides the purpose of the service. Use cases can be further decomposed in scenarios that provide a step by step description of the interaction between the actor and the system of interest (smart classroom building) to fulfill a given service.

The services identified in this section for the smart classroom building do not assume any technical implementation or budget restriction. With a list of multiple services, the building owner can then decide what services the smart classroom building should provide, based on the stakeholders' preferences, budget and other constraints.

A list of actors and a list of services have been identified for smart classroom buildings in order to draw the use case diagrams. The actors consists of but are not limited to:

- Students: attend classes in the classrooms.

- Instructors: teach classes in the classrooms.
- Visitors: visit the building or attend an event in the building.
- Janitors: clean all parts of the building, including the exterior.
- Food Vendors: sell beverage and food in the building.
- Building Manager: manages the day-to-day operations of the building.
- IT Department: provides ICT services to the building.
- Maintenance staff: maintain mechanical, electrical and civil engineering systems in the building.
- Academic Services: schedules classes and assigns classrooms.
- CASS: takes care of special needs of the users.
- Technology Providers: provide hardware and software services to the building.
- Researchers: analyze operational data of the building.
- Police Department: enforces laws and patrol the building.
- Fire Department: responds to fire alarms and medical emergencies.

These actors interact with the smart classroom building frequent enough to be included in the list. The Visitors are not included in the earlier stakeholder list. Visitors are added in this step because they are more in need of certain services than regular users.

The following are some of the services which should be provided in a smart classroom building. In some services, the term "room" is used instead of "classroom" because there are other types of room in the building that also require the services.

- Display structural condition: displays hot-spots in the structural components that need attention.
- Display schedule: displays the schedule of all classrooms which could include three different attributes: class name, event name and classroom assigned.
- Record attendance: provides a name list of persons who are present in each classroom, and for each of them the time of arrival at the classroom and departure from the classroom.
- Record student participation: records and displays each student's answers to instructor's question in the class.
- Display classroom type: provides the list of classrooms and their capacity, sitting arrangement, furniture, equipment and accessibility.
- Display building map: provides the floor plan of the building.
- Display real-time occupant statistics: during emergency provides in real-time the number of people in each room to police department, fire department and building manager.
- Display usage statistics: provides the number of occupants per hour per room to indicate the spatiotemporal usage of the building.
- Display evacuation route: during emergency provides in real-time the escape routes from each room to the nearest and safe building exit.
- Display room temperature: provides in real-time the temperature of each room.
- Display unauthorized users: provides in real-time the number of unauthorized persons in each room.
- Display special needs resources: provides the list and type of all resources in each classroom for students with special needs.
- Display utility consumption statistics: provides the amount of usage of utilities such as gas, water and electricity for the entire building.

- Display parking statistics: Provides the number of all types of parking stalls (e.g., cars, buses, motorcycles, and handicap) and the occupied and available ones.

Finally, the actors, services, and their relationship are shown in use case diagrams. Figure 3.6 shows the use case diagrams for a smart classroom building.

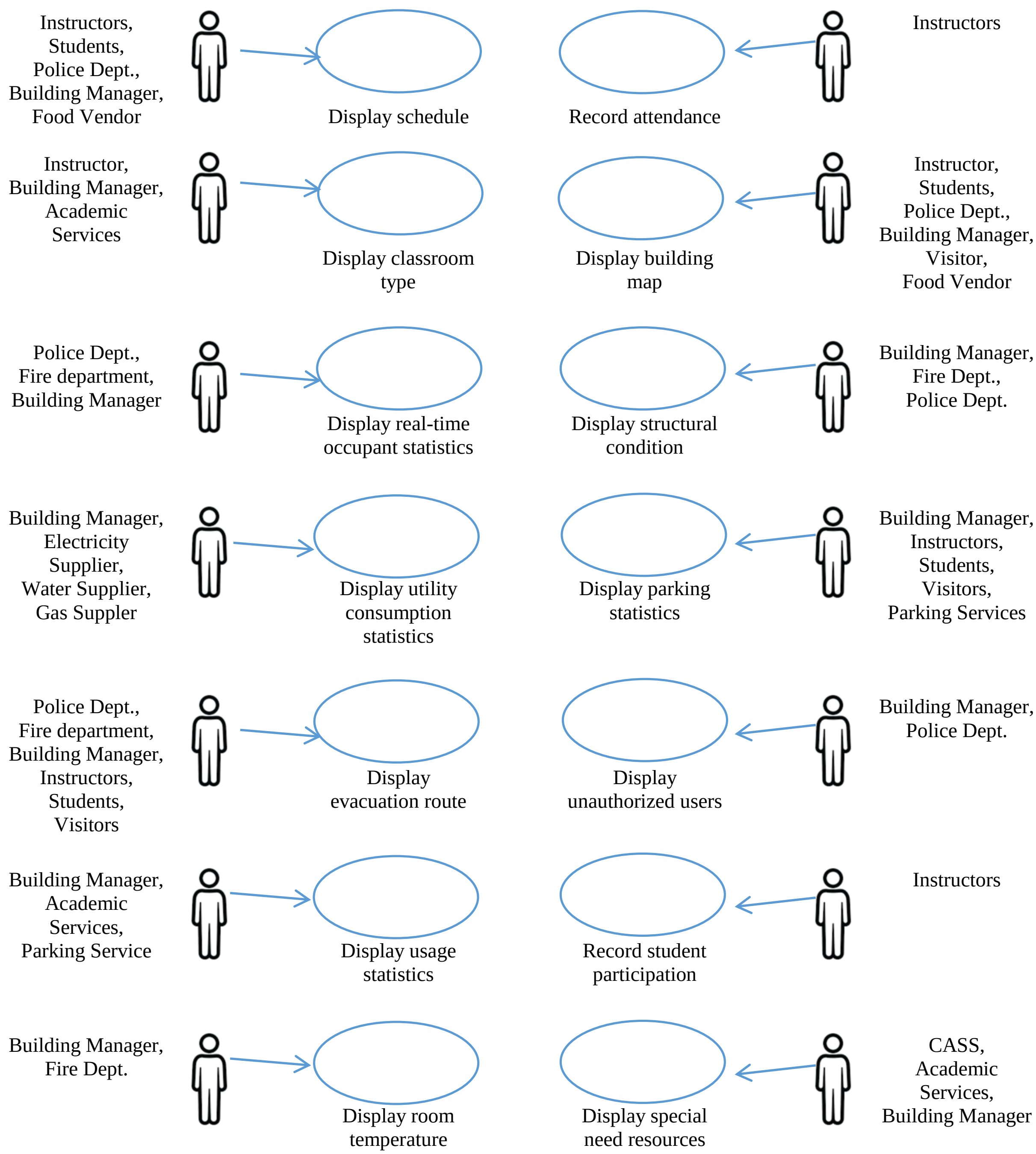

Figure 3.6 Use case diagrams for smart classroom buildings

3.6 Research Challenges

The first challenge in smart classroom buildings research and implementation is the definition of smart classroom buildings. Smart classroom buildings should be defined and characterized in such a way that the outcome is to improve the QoL of the users (who are primarily students and instructors). The end result is similar to that of smart cities.

The second challenge is that a smart classroom has many stakeholders, each come to the building with different needs, resources, influence, standards and constraints. When analyzing or designing a smart classroom building, the analyst needs to limit the number of stakeholders (i.e., draw the system's boundary). In Section 3.5, only users who/which have frequent interactions with the smart classroom building are considered in the level zero system diagram and use case diagrams.

The third, and probably most challenging topic of research is closing the loop of user services. In the use case diagrams, each case represents a service provided by the building to its users. The building's operation, and quality of service, may further be improved by taking advantage of the ICT technology by closing the loop. That is, data on user behavior and feedback may be collect at the same time from two sources: (1) the database of the building's management center; (2) smart phones (when the users are using the apps) and other sensors. Data from these two sources need to be collected, integrated and analyzed together. The results are provided to the relevant users so that they are able to make better decisions. Understanding the user's behavior and needs is a big research gap that needs to be filled.

CHAPTER 4 SMART BRIDGES

4.1 Chapter Overview

Highway bridges are parts of the road infrastructure that provides the physical links between cities, and within cities. Over two hundred million trips are taken daily across deficient bridges in the nation's 102 largest metropolitan regions (ASCE 2013). Yet, they are one of the most vulnerable components of the highway transportation infrastructure system. The collapse of a highway bridge always lead to catastrophic consequences: loss of life, traffic congestions and economic loss. This chapter focuses on bridges in the interstate highway and national highway systems, on the user services that enable new and existing bridges to be transformed into smart bridges. The interstate and national highway systems form the major highway transportation networks between cities in the U.S. They also carry relatively higher traffic volume in the urban areas. The interstate and national highway systems, and their bridges, are owned, operated and maintained by the respective state Department of Transportation (DOT). For example, the bridges along Interstate 10 Freeway and U.S. Highway 54 in El Paso, TX are owned, operated and maintained by the Texas Department of Transportation (TxDOT). Although the discussions are based on the bridges in the interstate highway and national highway systems, majority of the discussions are also applicable to bridges in urban streets and rural highways, which are often owned by the county or municipality.

4.2 Existing Bridges

In 2014, the U.S. has 31,496 bridges in its interstate highway systems and another 20,821 in the national highway system. Among the 31,496 bridges in the interstate highway systems, 1,235 are structurally deficient and 7,267 are functionally obsolete (FHWA 2015). These figures have yet to include problematic bridges in the state, urban and rural highways.

The 2013 American Society of Civil Engineers (ASCE) Infrastructure Report Card gave the nation's bridges a C+ grade. The average age of the nation's bridges was 42 years in 2013. More than 30% of the existing bridges have exceeded their 50-year design life (ASCE 2013). Replacing deficient bridges with new ones requires time and budget. Therefore, these old bridges will still need to be in service, maintained, repaired, and rehabilitated until new bridges are constructed. An interim solution is to make these bridges smarter.

As highway bridges are public infrastructure, they are owned, operated and maintained by a single government agency. For the interstate highway and national highway systems, the bridges are owned, operated and maintained by the respective state DOT. Bridges in city streets are usually under the jurisdiction of the county or city's transportation department. Figure 4.1 shows two highway bridges along the Interstate 10 Freeway in El Paso, TX.

(a) Thorn Ave overpass at Interstate 10 Freeway

(b) Yarbrough Dr. underpass at Interstate 10 Freeway

Figure 4.1 Typical bridges in El Paso, TX

Most of the agencies (owners) use a Bridge Management Systems (BMS) such as AASHTOWare BrM (AASHTO 2015) as a decision support tool. AASHTOWare BrM, the industry's standard tool developed by the American Association of State Highway Transportation Officials (AASHTO), is a software tool that stores, organizes and analyzes bridge inspection and inventory data. It also allows the bridge owner to track preservation and maintenance history, perform deterioration modeling, and guide the owner toward selecting the most cost-effective alternatives for bridge preservation, rehabilitation and replacement.

Highway bridges are designed to carry traffic loads. The structural behavior of a bridge may be viewed as the outcome of demand and supply interaction. The demand are traffic load (traffic volume and vehicle weight). The supply is the structure strength. Structurally deficient bridges already have their structure strength deteriorated over time. The demand for bridges has increased over the year due to the growth of traffic volume, especially the increase in truck volume, which also comes with heavier load. Additional risk may be imposed on the bridge by earthquake (seismic risk) and foundation or embankment failure (geotechnical risk) (FHWA 2015). Extreme weather, due to climate change phenomena, may subject the bridge to higher wind load, flooding and extreme temperature.

The assessment of the long-term structural and geotechnical performance of a bridge requires a variety of data. These data include construction records, inspection and maintenance history, service environment, and post-construction monitoring data (FHWA 2013a, 2013b). The traditional methods of bridge structural health evaluation rely on human inspection and manual data logging, for example, using a licensed inspector carrying a tablet computer installed with the ScanPrint software (FHWA 2010). The Federal Highway Administration (FHWA) has a Long-Term Bridge Performance Program (LTBP). This program has developed improved data collection methods, such as a robotic system for bridge deck condition assessment (FHWA 2013b) and new nanosensors (FHWA 2013c). Different health indicators may be measured by a variety of tools and approaches, such as impact echo, ground penetrating radar, half-cell corrosion potential, and resistivity measurements. These data collection methods are at most semi-automated.

4.3 Justification for and Nature of Proposed Changes

The existing practice of bridge management has several shortcomings. These shortcomings have been identified and described below. When addressed, can make the bridges (and their management decisions) smarter:

- The 2013 ASCE Infrastructure Report Card stated that majority of the bridges are not inspected at the mandated intervals because of insufficient qualified inspectors and budget (ASCE 2013). A smart bridge should have the capability of monitoring the structure and geotechnical performance of the bridge itself and warn the owner and users on the impending issues with the bridge. The owner may then respond by selecting an appropriate method of repair.
- Although AASHTOWare BrM is a powerful tool in bridge management, it is designed and operated as a standalone system. Its input and output data may be exchange with other external transportation management systems to drive greater benefits to the users of the transportation system. For example, the AASHTOWare BrM, or its equivalent, can function more effectively and efficiently if it is linked to real-time data collected by the Traffic Management Center (TMC).
- Bridge management field activities affect bridge users. These activities impact traffic to various degrees. For example, closing one lane of a bridge for minor deck repair reduces the traffic capacity by more than one lane which may cause congestion, delay, increase emission, accident, etc. Some vehicles may detour to different routes (or use a different

bridge) thus increase the level congestion at nearly facilities. Such area wide impact on users and non-users of the bridge in question should be considered as a factor in making bridge management decisions.

4.4 New Smart Bridges

The proposed smart bridges use ICT to enable functions that better serve its users and stakeholders. The authors have identified three major areas in which ICT will have significant impacts in bridge management:

- A smart bridge has a variety of sensors to monitor its structural and geotechnical health status. These sensors may be instrumented in critical structural components to detect cracks, excessive strain, deformation or deflection, corrosion, etc and transmit the sensor data by wireless means to the BMS.
- The BMC and TMC should share their data with each other in real-time. Many TMCs are already sharing data with the police departments and the media (radio and television stations). TMCs, through their traffic sensors and video cameras, are able to quickly detect incidents in and around the bridges. The real-time traffic conditions TMC provides is critical in helping the owner in understanding the traffic demand and traffic load on the bridge.
- The input and output data of BMS (such as AASHTOWare BrM) should be linked with a network level traffic simulation software (such as DynusT) and/or emission estimation software (such as MOVES), so that traffic and/or emission impacts may be considered as part of the bridge management decision making process. When developing the traffic simulation model, traffic operation data collected by the sensors on the bridge (volume, speed) may be used for model calibration.

As can be seen from the above discussion, a smart bridge benefits both the owners as well as the public users. With real-time wireless sensor data, and with consideration of traffic impacts, the owner is able to make smarter maintenance and lane closure decisions. The benefits are the reductions in congestion, delay and emission, although these may not be apparent to the drivers, pedestrians and cyclists. With more traffic sensors at the bridge deck and the surrounding highways, the users will receive higher quality real-time traffic information. This benefit will be obvious when an incident has occurred at the bridge.

4.5 Smart Bridge Description

It has been mentioned that smart bridges uses ICT to enable functions that deliver better quality of service to stakeholders. This section provides a description of smart bridges from the systems engineering perspective. Several techniques (stakeholder influence diagram, context diagram, and use case diagram) are used to identify relevant stakeholders, define the scope of the smart bridges and its external entities, and to identify the services provided by the smart bridges.

4.5.1 Stakeholders Influence Diagram

A smart bridge has many stakeholders. The stakeholders who are associated with the design, operations, maintenance and use of a bridge in a TxDOT highway have been identified in Figure 4.2.

Figure 4.2 Stakeholder diagram for smart bridges

The roles and responsibilities of the stakeholders that are listed in Figure 4.2 are:

- Drivers, Pedestrians, Cyclists: use the bridge.
- Bridge Manager (DOT staff): makes bridge maintenance decisions.
- Bridge Inspector (consutant): inspects the structural and geotechnical health of the bridge at regular intervals and reports to the Bridge Manager.
- TMC Manager (DOT staff): monitors traffic on the bridge and the surrounding highways.
- Maintenance Staff (DOT staff): perform routine bridge maintenance works such as cleaning, painting.
- Contractors (companies): repair, construct, rehabilitate or retrofit the bridge or part of the bridge.
- Technology Providers (companies): provide the technologies, equipment and services.
- Engineers (DOT staff or consultants): design the structural or geotechnical aspect of the bridge.
- Utility Suppliers (companies): supply gas, electricity and water to the bridge and use the right-of-way to bring gas, electricity and water across the bridge.
- Owner (DOT): owns the bridge (including the right-of-way) and is responsible for the maintenance of the bridge.
- Police Department (county or city department): enforces laws and performs accident investigation.
- Fire Department (county or city department): performs emergency medical assistance and put off fire.

- FHWA (federal agency): sets the standards for bridge inspection, condition reporting and maintenance.
- AASHTO (professional association): sets the standard of geometric design and develops bridge management software.
- Metropolitan Planning Organization (MPO, regional agency): approves transportation projects and performs network modeling to access traffic impacts of bridge maintenance or construction.
- Department of Public Safety (DPS, state agency): enforces the vehicle weight limits, especially commercial vehicles.
- American Concrete Institute (ACI, professional association): sets the standard for reinforced concrete design.
- American Institute of Steel Construction (AISC, professional association): sets the standard for streel structure design.
- Researchers (university staff): analyze bridge data.

The next step is to group the stakeholders that have common or similar interests. The stakeholders identified for the smart bridges have been organized into the following groups:

- Users: use the bridge.
- Facility Managers: manage the bridge.
- Facility Owners: own the bridge.
- Authorities: who give authorizations from the government.
- Design Authorities: provide design, operations or maintenance standards.
- Service Providers: provide all services to the bridge, its owner or users.

A stakeholder may belong to more than one group. The above groups may further be aggregated into three major groups: government, industry and people. After grouping, the stakeholders are arranged as in Figure 4.3. The stakeholders that belong to multiple groups are:

- Owner: the owner (DOT) has authority over its bridges, and it also has design standards.
- FHWA: reviews and approved designs, and sets the bridge condition reporting standards.
- Utility Suppliers: use the bridge's right-of-way to supply gas, electricity and water across the bridge and also provide electricity to light up to the bridge and water to clean the bridge.

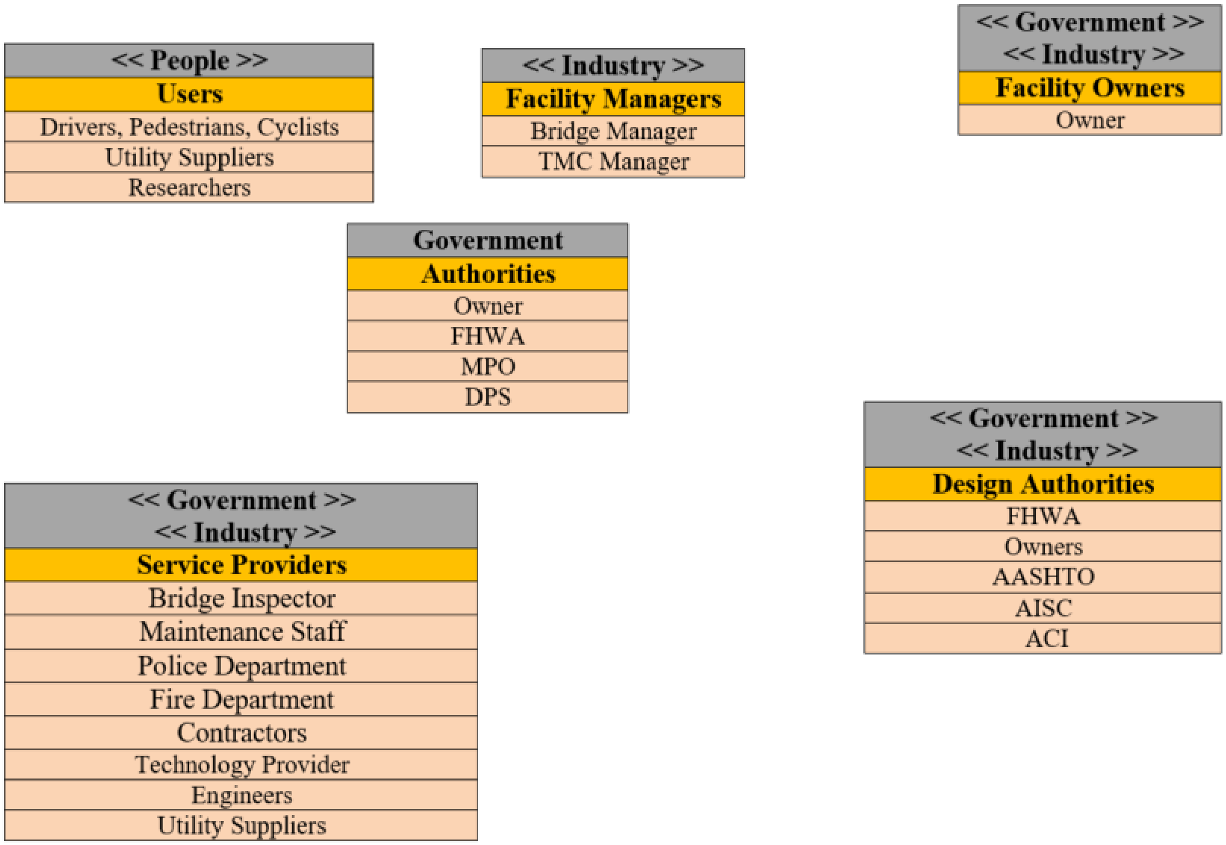

Figure 4.3 Stakeholder group diagram for smart bridges

The third step is to construct a stakeholder influence diagram (as shown in Figure 4.4) that identifies, organizes and documents the interactions between the stakeholder groups.

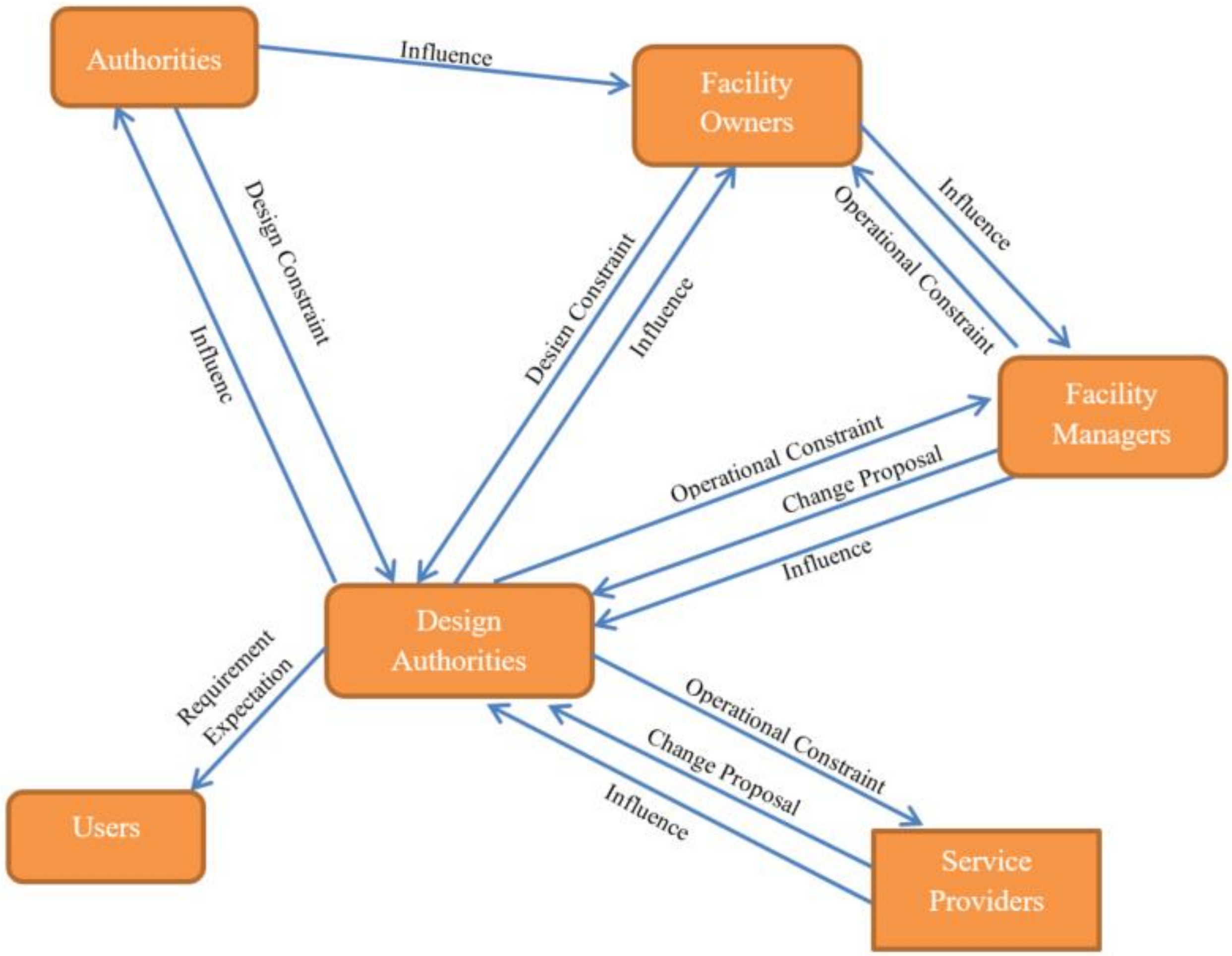

Figure 4.4 Stakeholder influence diagram for smart bridge

4.5.2 Level Zero System Diagram

The level zero system diagram (also called data and material flow diagram) depicts the scope of the system and identifying all the external entities. The data and material flow between the smart bridge and the external entities are:

- Drivers, Pedestrians, Cyclists triggers traffic sensors on the bridge and requests real-time traffic condition in the area around the bridge, bridge closure information and detour plan.
- Bridge Manager requests real-time the traffic conditions, bridge integrity data (through the inspection report, sensor data), provides emergency response and maintenance decisions.
- Bridge Inspector requests sensor data and other observational data to write Bridge Inspection Reports at regular intervals.
- TMC Manager uses sensor and video data to monitor traffic on the bridge, detect incidents and disseminates real-time traffic information.

- Maintenance Staff perform bridge maintenance works according to the schedule provided by the Bridge Manager.
- Technology Providers install sensors, read, transmit and process sensor data.
- Engineers use the sensor data and standards to design the structural or geotechnical aspects of the bridge improvement at the request of the Bridge Manager.
- Contractors receive maintenance schedule and/or design instructions to carried out work;
- Utility Suppliers request electricity and water consumption data, request maintain schedule of the bridge to plan for service disruption.
- Owner receives bridge inspection reports.
- Police Department receives emergency requests and controls/reroutes traffic.
- Fire Department receives emergency requests and controls/reroutes traffic.
- FHWA sets the standards for bridge inspection, receives bridge inspection reports from the owner, and approves engineering designs submitted by the owner.
- AASHTO sets the standard of geometric design and provides bridge management software.
- MPO requests sensor data (traffic demand) and maintenance schedule (lane or bridge closure) as inputs into the regional transportation planning model and emission estimation model, and provides predicted network level impacts.
- ACI sets the standard for reinforced concrete design.
- AISC sets the standard for streel structure design.
- Researchers request sensor data, conduct research to improve bridge maintenance practice, and provide feedbacks to the Bridge Manager.

Note that:

- DPS is not included in this list because it has no data or material flow with the smart bridge.
- Maintenance schedule include the nature and task, time and scope of work, lane and bridge closure information.
- Sensors include traffic, structural, geotechnical and hydraulic sensors.
- Sensor data include the data recorded by all kinds of sensors. They could be historical data or real-time data.
- Real-time traffic information includes the operating speed, incidents, and lane or road closures.

Figure 4.5 Level zero system diagram for smart bridges

4.5.3 Use Case Diagrams

A use case is made up of a set of possible sequences of interactions between systems (smart bridges) and users (actors, external entities).

A list of actors and a list of services have been identified for smart bridges so as to draw the use case diagrams. The actors consist of but are not limited to:

- Drivers, Pedestrians, Cyclists: use the bridge.

- Bridge Manager: makes bridge maintenance decisions.
- Bridge Inspector: inspects the bridge at regular intervals and reports to the Bridge Manager.
- TMC Manager: monitors traffic on the bridge and the surrounding highways.
- Maintenance Staff: performs routine bridge maintenance works.
- Contractors: repair, construct, rehabilitate or retrofit the bridge or part of the bridge.
- Technology Providers: provide the technologies, equipment and services.
- Engineers: design the structural or geotechnical aspect of the bridge.
- Utility Suppliers: supply gas, electricity and water to the bridge and use the right-of-way to bring gas, electricity and water across the bridge.
- Owner: owns the bridge (including the right-of-way) and is responsible for the maintenance of the bridge.
- Police Department: enforces laws and performs accident investigation.
- Fire Department: performs emergency medical assistance and put off fire.
- FHWA: sets the standards for bridge inspection, condition reporting and maintenance.
- AASHTO: sets the standard of geometric design and develops bridge management software.
- MPO: approves transportation projects and performs network modeling to access the traffic impact of bridge maintenance or construction.
- DPS, state agency: enforces the vehicle weight limits, especially commercial vehicles.
- ACI: sets the standard for reinforced concrete design.
- AISC: sets the standard for streel structure design.
- Researchers: analyze the bridge data.

The following are some of the services which should be provided in smart bridges:

- Display real-time traffic information: displays speed map, lane, road and bridge closure information in the area around the bridge.
- Upload/download inspection report: allows authorized users to upload or download bridge inspection reports.
- Request emergency assistance: notifies the Police Department and/or Fire Department for emergency assistance at the bridge.
- Display detour route: displays detour routes during a road or bridge closure.
- Upload/Download maintenance schedule: allows authorized users to upload or download bridge maintenance schedule.
- Display sensor data: allows authorized users to see certain sensor data.
- Display sensor locations: displays in map all the sensor locations and type.
- Display consumption statistics: shows electrical, water and gas consumptions at the bridge per month.
- Request maintenance: requests certain items in the bridge to be repaired.
- Display structural hot spots: warn the Bridge Manager the detection of certain structure elements that has lost structural strength.
- Display geotechniccal hot spots: notofies the Bridge Manager the detection of certain foundation/geotechnical elements that has lost strength.
- Display weather forecast: displays the weather forecast and warn users of any severe weather condition.

- Display maintenance schedule: allows authorized Maintenance Staff, Contractors and Technology Providers to receive maintenance schedule.

Finally, the actors and services are linked via use case diagrams. Figure 4.6 shows some of the use case diagrams for smart bridges.

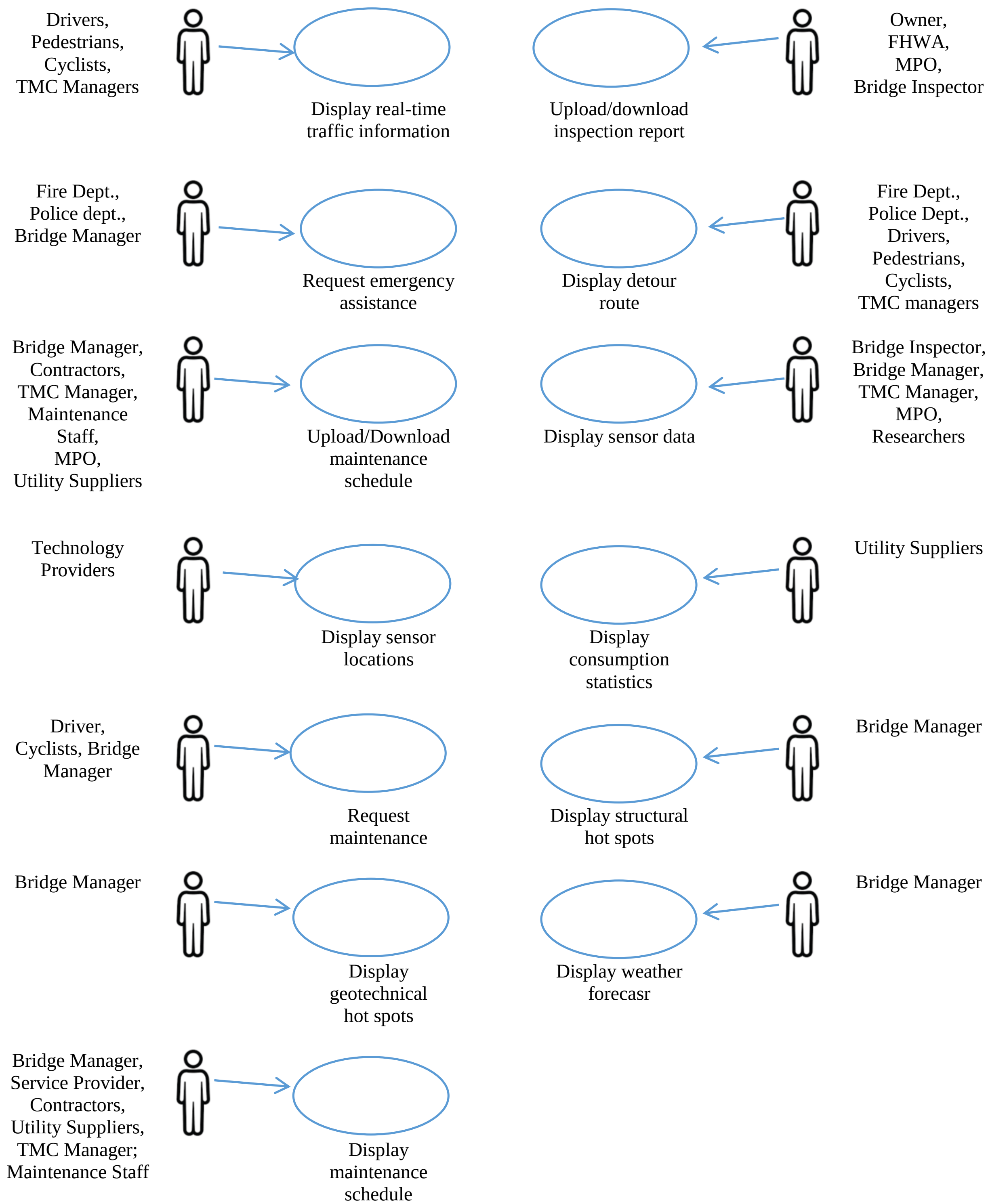

Figure 4.6 Use case diagrams for smart bridges

4.6 Research Challenges

The first challenge in the design of a new smart bridge, or transforming an existing aging bridge into a smart bridge, is sensor instrumentation. The structural and geotechnical engineers need to make decisions on what to measure, the types of sensor, the quantity and locations of placement. To do so, it is necessary for the engineer to predict the extreme loading patterns, the failure mode, and warning signs. He/she must also design the communication system to transmit sensor data in real-time to the BMC.

The second challenge in the design of a new smart bridge, or transforming an existing bridge into a smart bridge, is to design for partial failure. This means that, when a likely failure mode has been identified, the bridge structure or foundation may be designed to fail in parts, leaving the minimal service capacity that gives users enough time to evacuate. Existing bridges may be retrofitted to partially fail in a specific mode to serve the same purpose.

The third challenge is the design of data exchange between the BMC and TMC. Traditionally, the BMC and TMC are designed as independent, standalone systems operated by different departments in the DOT. The Bridge Manager will have a better idea on the traffic operations on the bridges if he/she has the real-time traffic volume and speed on the ridges, and the video feeds. The data collected by the TMC's intelligent transportation systems may be combined with data collected from sensors instrumented in the bridge to derive the traffic demand pattern. This is related to the forth challenge which is to incorporate area wide traffic impacts in making bridge closure and detour decisions. In the problem of pavement maintenance scheduling involving lane and link closures, the approach to find the solution that minimizes network traffic impact have been demonstrated by Ma et al. (2004) and Cheu et al. (2004). The challenge here is to collect time-dependent traffic demand pattern, user behavior in response to bridge closure information, for input into the simulation model and for model calibration. Once the maintenance schedule has been decided, the TMC can makes use of its sensors and equipment to monitoring the work progress and traffic operations.

CHAPTER 5 SMART BUS SYSTEMS

5.1 Chapter Overview

Public transportation is one of the essential services provided by cities to its residents and visitors. Public transportation may be defined as "systems that are available for use by all persons who pay the established fare" (Vuchic, n.d.). Public transportation is also known as public transit. Public transportation modes, which usually operate on fixed routes and with fixed schedules, include bus, light rail transit, metro, regional rail and several other systems (Vuchic, n.d., 2005). The U.S. Federal Transit Administration (FTA) lists the following modes as public transportation: buses, subways, light rail, commuter rail, monorail, passenger ferry boats, trolleys, inclined railways, and people movers (FTA, 2015). However, according to the first (and broader) definition by Vuchic, public transportation also includes modes that operate without a fixed route, such as taxi, dial-a-ride, carsharing, vanpool, etc, as long as they provide transportation service to the public for a fee.

The American Public Transportation Association (APTA, 2015) includes bus, paratransit, light rail, commuter rail, subways, waterborne passenger services, and high-speed rail as public transportation systems of interest. APTA members also include large and small companies who plan, design, construct, finance, supply, and operate bus and rail services. Government agencies, MPOs, state DOTs, academic institutions, and trade associations are also part of APTA's membership.

As can be seen from the above discussions, public transportation covers many modes and involves many stakeholders. A smart city should have a variety of public transportation modes to serve its residents of different travel needs. Residents should have the flexibility to choose the modes depending on their trip purpose, origin, destination, day of week, time of day, time budget, cost, etc. To limit the scope, this chapter focuses on one mode of public transportation: fixed route bus system, or simply bus system. The bus system discussed here is limited to buses operating on fixed routes (and stops) and fixed schedule in a city. The bus system discussed here does not include the terminal building, financing, design, construction and intermodal connections with metro rail, light rail, intercity rail, etc. The discussions in this chapter primarily uses Sun Metro (Sun Metro, 2015), the public bus system in the City of El Paso, TX, as the example.

5.2 Existing Bus Systems

Fixed route bus service in a city may be classified as: (1) Regular Bus Service (RBS); (2) Bus Rapid Transit (BRT); or a combination of both (such as expressed bus service). RBS typically uses conventional buses with seating capacity of 40 to 55 passengers that run along the streets in mixed traffic (sharing lane with other types of vehicle), serving bus stops at approximately 400 m apart. BRT may be viewed as an upgraded version of RBS. BRT incorporates a set of distinctive features that include exclusive bus lanes, street design improvements, traffic signal prioritization, better stations and/or bus shelters, fewer stops (800 m to 1.5 km apart), faster running speed, cleaner, quieter, and more attractive vehicles (GAO, 2001). However, not all the BRT systems are the same. Galicia et al. (2009) describes three stages of BRT system implementation: limited, moderate and aggressive, each designed with increasing passenger capacity, budget and amenities. Cities may decide the stages of BRT they want to implement depending on the resident's preference, ridership estimate, project budget, right of way, etc.

The City of El Paso owns and operates its public bus system named Sun Metro (Sun Metro, 2015). Sun Metro aims to provide safe, reliable, professional, and courteous customer service to El Paso residents and visitors. It has a fleet of 231 vehicles. It operates 60 RBS routes, one BRT route and two special service (Project Aminstad) routes. Its infrastructure network consists of seven transfer hubs (called transfer centers) plus 2827 bus stops. The transfer center has the additional free Wi-Fi service, restrooms and televisions. The entire bus system carries 51,016 passengers/weekday in 2015. Sun Metro routes and locations of the transfer centers are show in Figure 5.1. For RBS, the bus stops either has no shelter, a simple outdoor garden bench or a simple shelter with seats. Fare collection is performed onboard. In-vehicle fare box next to the driver accepts cash, pre-paid tickets or season cards. Depending on the route, day of week and time of day, RBS headways range from 15 minutes to one hour.

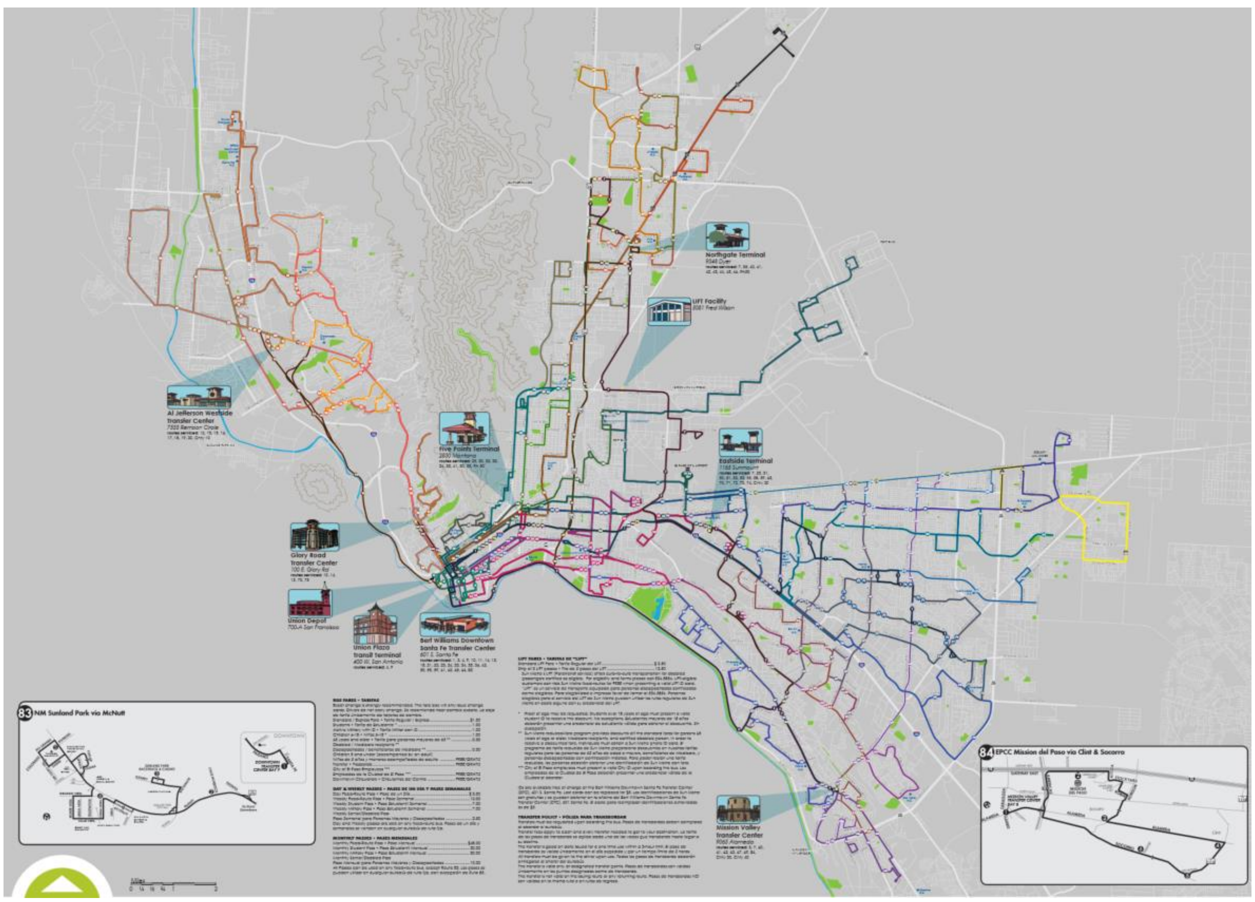

Figure 5.1 Route map of Sun Metro
(source: Sun Metro (2015))

The BRT service operated by Sun Metro is called BRIO. The only existing BRIO route is 8.6-mile (14 km) long (one-way) and has 11 stops along the Oregon St. and Mesa St. corridor. Several segments of the route have exclusive lane for BRT buses. Transit signal priority is provided at major intersections. BRIO stops have bigger shelters, more comfortable seats, ticketing machines, real-time bus arrival time displays, route and service information, and even vending machines. The BRT buses are low floor, 60-ft articulated vehicles which can accommodate 48 sitting and 24 standing passengers. The service headways are 10 minutes during peak hours and 15 minutes during off-peak hours. Sun Metro charges the same fare for RBS and BRIO, at $1.50 per ride for adults including one free tranfer. The city plans to add three additional BRT routes between 2016 and 2019. Figure 5.2 shows a typical bus, bus shelter and ticketing machine of BRIO.

(a) Typical bus

(b) shelter

(c) ticketing machine

Figure 5.2 Typical bus, shelter and ticketing machine for BRIO

Sun Metro has a modern depot which was just put into operations in 2015. The depot has a bus maintenance workshop, driver training facility, and a fleet control center. The fleet control center monitors all the bus locations in real-time, and is able to communicate directly with drivers, dispatch roadside maintenance crews and empty buses to the spots where buses have broken down. All the Sun Metro buses are instrumented with GPS-based automated vehicle location system and in-vehicle security cameras. The vehicle locations are transmitted to the fleet control center every few seconds. However the video recordings are stored in a hard drive inside the bus and are only copied into a data warehouse at the end of a shift, when the bus returns to the depot.

5.3 Justification for and Nature of Proposed Changes

Many elected officials, policy makers, urban planners, transportation engineers and residents agree that public transportation is more environmentally sustainable than private cars. However, very few of them are attracted to use public transportation. Public transportation modes are perceived to be less comfortable, less safe, less accessible, takes longer travel time, inconvenient and less flexible in schedule. Weather may also play a factor in mode choice. One way of attracting more riders from the private car mode to the bus mode is to make the bus system "smarter".

The RBS provided by Sun Metro is typical in many U.S. cities. BRT may be viewed as the smarter version of RBS. However, not every city has the resources to upgrade its RBS to BRT, or passenger volume to justify the investment. However, RBS may be made smarter by selectively implement several user services.

5.4 New Smart Bus Systems

A smart bus system provides passengers a high quality transportation service via a safer, more comfortable, more reliable rides with better value for money. This is achieved by implementing several BRT features and by the use of ICT to integrate and deliver service information to passengers. To Sun Metro, a smart bus system is one that has all the aggressive stage of BRT features and the ability to monitor ridership data for regular route and service schedule revisions.

While it may be impractical for a city to implement all the aggressive BRT features, a smart bus system should incorporate a few of them. The full list of BRT features may be divided into infrastructure and operational features (Galicia et al. 2009). Depending on passenger preference, budget and the level of technology implementation, the designer of a smart bus system may select a few features, bundle them to transform the existing RBS into a smart bus system.

Infrastructure features

- Guideway and bus lane
    - Exclusive lane, includes contraflow lane
    - Queue jumper
- Station
    - Enhanced shelter with seats and lighting
    - Enclosed shelter with air condition and heating
    - Bus floor level boarding platform
    - Improved pedestrian and ADA access
    - Display of maps, routes, schedule and real-time arrival information
    - Ticketing machine

    - Vending machine
    - Bus and passenger counters
    - Wi-Fi service
    - Video for security monitoring
    - Emergency phone
- Intermodal connections
    - Bicycle parking
    - Taxi stand
    - Park-and-ride lot
- Surrounding land use
    - Improved sidewalk
    - Mixed land use near station
    - Lighting
- Vehicles
    - Low emission or zero emission vehicle
    - Low platform vehicle
    - High capacity vehicle
    - Multiple entrances and exits
    - Comfortable and ergonomic seats
    - Wi-Fi in vehicle
    - Next stops and arrival times information
    - Video security monitoring
    - Emergency phone

Operational Features

- Fare collection
    - Smart card payment (on board or at station)
    - Multiple payment options (on board or at station, cash and credit)
- Intelligent transportation systems
    - Transit signal priority
    - Automated vehicle location
    - Passenger boarding-alighting location recording
    - Precision docking
    - Collision warning
- Service and operation
    - Increased service coverage area
    - Reduced number of stops or further station spacing
    - Smaller service headway
    - Longer service hour
    - Higher operating speed

5.5 Smart Bus System Description

5.5.1 Stakeholders Influence Diagram

A smart bus system, being a public transportation system provided by a city, inevitably has many stakeholders. The stakeholders of a smart bus system, in the context of Sun Metro in El Paso, TX, are listed in Figure 5.3:

Figure 5.3 Stakeholder diagram for smart bus systems

The above stakeholder list is not meant to be permanent and complete. The stakeholders may be removed, or new stakeholders added to meet the smart bus system's need. The roles and responsibilities of the stakeholders identified in Figure 5.3 are described below:

- Drivers (city employees): drive the buses.
- Passengers: pay to ride the buses.
- Janitors (city employees): clean the buses and bus stops.
- Maintenance Staff (city employees): maintain or service the buses.
- Advertisers (companies): rent space in the buses or shelters to put advertisements.
- Vendors (contractors): sell newspapers, magazines, food and drinks at the bus stops (in kiosks or via vending machines).
- Technology Providers (contractors): provide equipment or services such as Wi-Fi, security cameras and fare collection system in the buses or at the stations.
- Researchers (university staff): analyze data.
- County/Municipality: provides local fund, owns the bus system, right-of-way of bus routes (streets), bus stops, and provides emergency services such as police, firemen and ambulances during accidents.
- Bus Operator (city department): operates the bus system, including staff who make decisions, who plan and monitor the routes and schedule.
- Police Department (city department): performs law enforcement and re-direct traffic (detour).

- Fire Department (city department): performs roadside medical assistance and re-direct traffic (detour).
- FTA (federal agency): provides funds for transit projects.
- State DOT (state agency): owns the right-of-way of bus routes (streets), bus stops, provide state funds for transit projects and provides standards in highway design.
- MPO (regional agency): models the city/region's transportation conditions and approves all transportation projects.
- Transit Capacity and Quality of Service Manual (TCQSM) (TRB, 2004): the national manual for determining the quality of transit services.

The grouping of stakeholders is based on stakeholders that have common or similar requirements. The following groups have been created for smart bus systems:

- Users (customers): demand services from the bus system.
- Facility Managers: manages the bus system.
- Facility Owners: owns the bus system.
- Authorities: gives authorizations from the government.
- Design Authorities: provide design, operations or maintenance standards of the bus system.
- Service providers: provide services to the bus system, facility manager or its users.

The stakeholder group diagram is presented in Figure 5.4. Venders, which sells newspapers, magazines, food and beverages at the bus stops are both Users and Service Providers. Police Department and Fire Department are Authorities and Service Providers. They enforce laws as well as provide assistants to the users during emergencies.

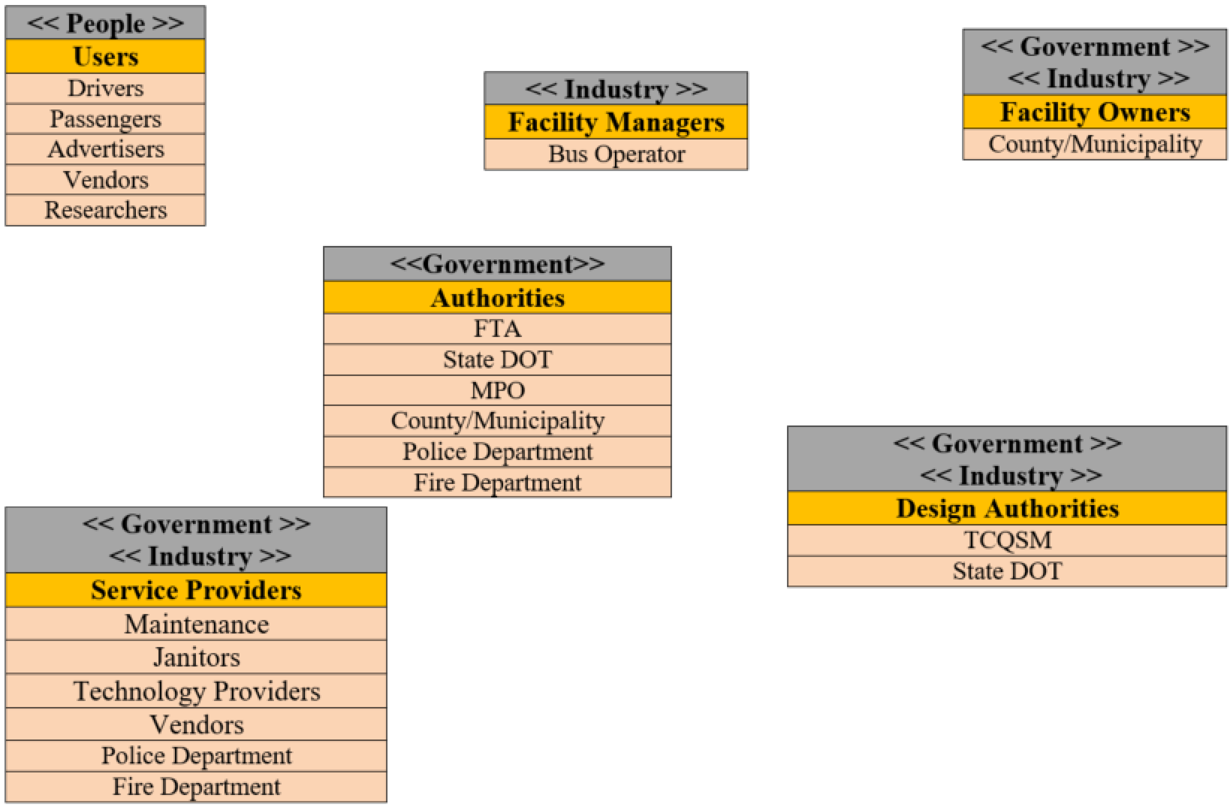

Figure 5.4 Stakeholder group diagram for smart bus systems

The arrangement shown in the above figure is only one of many alternatives. The assignments of stakeholders to the groups depend on the city's organization structure and business practice. Stakeholders may be added to a group or removed from a group based on a given context.

The relationships between the stakeholder groups identified in Figure 5.4 are graphically depicted in Figure 5.5. These relationships are the same as in Figure 3.4.

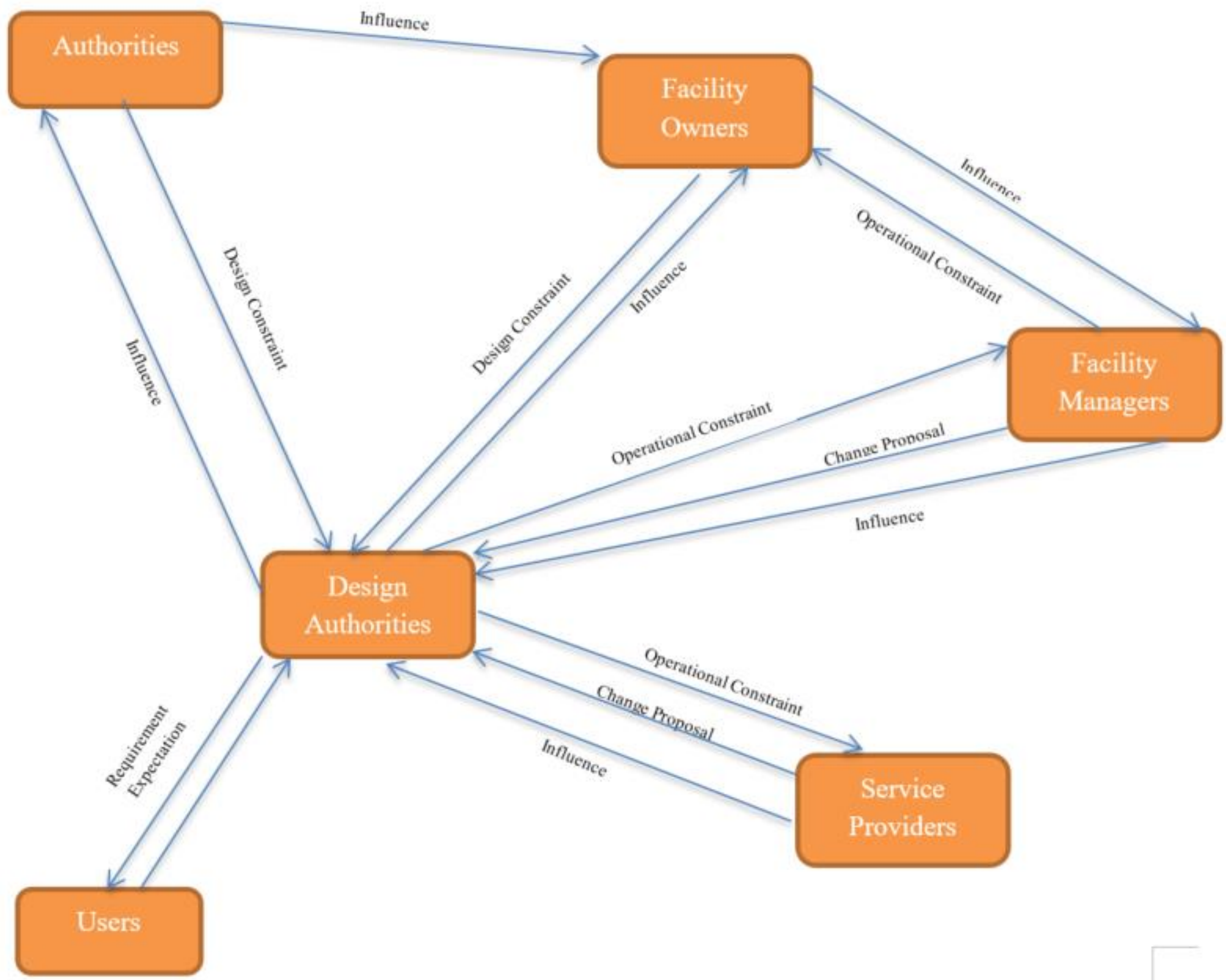

Figure 5.5 Stakeholder influence diagram for smart bus systems

5.5.2 Level Zero System Diagram

The next step is to construct the level zero system diagram, also known as the data and material flow diagram, for the smart bus system. For the smart bus system there is no material flow. The level zero system diagram is shown in Figure 5.6. It does not include the data flow between the smart bus system, state DOT and FTA as these two agencies do not interact with the system on daily basis. The smart bus system at the center of the diagram represents the data and communication hub of the fleet control center.

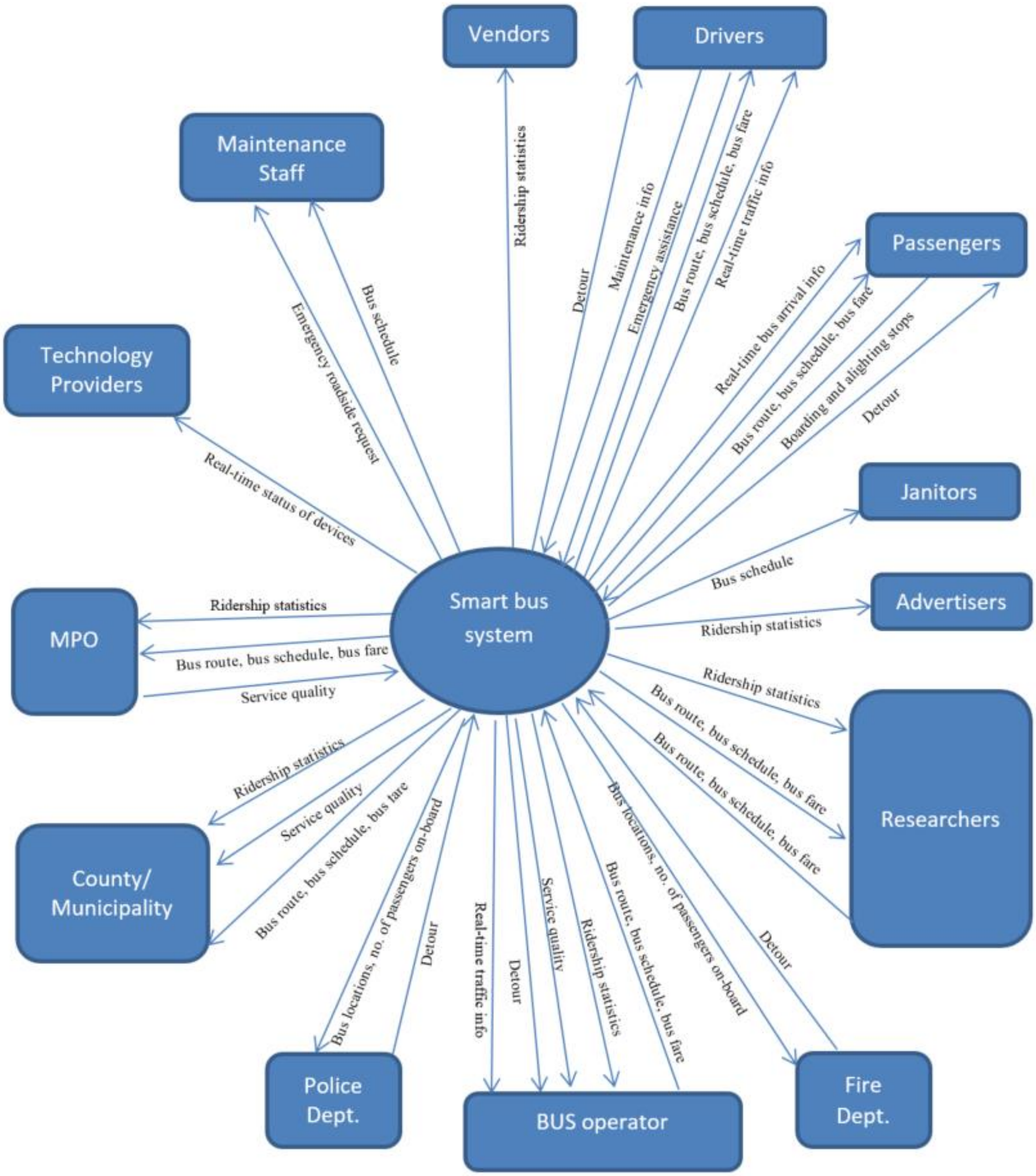

Figure 5.6 Level zero system diagram for smart bus systems

The data flow between the smart bus system and the external entities are:

- Drivers request information on bus route, bus schedule, bus fare, real-time traffic conditions along the route, and detour route during emergency, report maintenance issues to the Maintenance Staff and request the Police Department and Fire Department for emergency roadside assistance.

- Passengers request information on bus route, bus schedule, bus fare, real-time bus arrival times (at the stops and on-board), let the on-board readers capture their boarding and alighting stops, and perform fare transactions.
- Janitors request bus service schedule so as to know when to clean the buses at the depot.
- Maintenance Staff request the bus schedule so as to set time for maintenance and the location of the buses when providing emergency roadside assistance.
- Vendors request ridership statistics at every stop so as to cater for newspapers, magazines, food and drinks at the stops.
- Advertisers request ridership statistics at every stop for placing advertisements at the stops, and route ridership statistics for placing advertisements on-board of the buses.
- Technology Providers request real-time operating status of their field equipment.
- Bus Operator (staff) provides planned bus routes and schedule, requests operational and ridership statistics, and communicates between departments through the system during emergency events.
- Researchers request ridership data, bus schedule, bus routes and bus fare, and recommend adjustments to the routes, schedule and/or fare.
- County/Municipality: requests bus schedule, ridership statistics and service quality to see how the bus system is serving the residents;
- Police Department communicates with Drivers, Passengers and the Bus Operators during emergency, and re-direct traffic (detour).
- Fire Department performs roadside medical assistance and communicate with the Drivers, Passengers and Bus Operators during emergency, and re-direct traffic (detour);
- FTA specifies planning and operational standards, and provides funds to subsidize transit infrastructure and operations;
- State DOT provides standards on highway and bus stop designs, disburse funds on behalf of FTA for transit projects that are approved by MPO.
- MPO requests transit ridership statistics and service information to perform modeling, and provides feedback on service quality.
- TCQSM provides the standards in evaluating transit service quality.

5.5.3 Use Case Diagrams

A use case is made up of a set of possible sequences of interactions between smart bus systems and users (actors, external to the smart bus system).

A list of actors and a list of user services have been identified for the smart bus system. The actors consist of but are not limited to:

- Drivers: drive the buses.
- Passengers: pays to ride the buses.
- Janitors: clean the buses and bus stops.
- Maintenance Staff: maintain or service the buses.
- Advertisers: rent space in the bus or shelters to put advertisements.
- Vendors: sell newspapers, magazines, food and drinks at the bus stops.

- Technology Providers: provide equipment or services such as Wi-Fi, security cameras and fare collection system in the buses or at the stations.
- Researchers: analyze data.
- Bus Operator: operates the bus system, plan and monitor the routes and schedule.
- Police Department: performs law enforcement and re-direct traffic (detour).
- Fire Department: performs roadside medical assistance and re-direct traffic (detour).
- County/Municipality: provides local fund, right-of-way of bus routes (streets), bus stops, and provide emergency services such as police, firemen and ambulances during accidents.
- MPO: models the city/region's transportation conditions and approves all transportation projects.

The following are some of the services which should be provided in smart bus system:

- Display bus schedule: displays the days and hours when bus service is available for each route.
- Display bus route, bus fare: displays for each route the streets, bus stops and bus fares.
- Display ridership statistics: for each route, provides the origin-destination matrix per day and passenger volume per route segment (between two adjacent stops).
- Display service quality: reports performance indictors to users who make the request.
- Display detour: displays, for a route, at the bus stops and in the buses, in graphical and in text formats, the detour route and delay during an emergency event.
- Display real-time status of devices: displays the real-time operating status of ticketing machines, fare card readers, Wi-Fi routers, and etc.
- Request emergency assistance: informs the Bus Operator when the Driver or a Passenger press an emergency button in the bus or at a bus stop.
- Display real-time traffic information: displays, for a route, at the bus stops and in the buses, in graphical and in text formats, the traffic conditions along a bus route, the location of the bus and the estimated bus arrival times at upcoming stops.
- Read boarding and alighting stops: for every passenger, record the stop he/she boards the bus and the stop he/she leaves the bus.
- Display real-time bus arrival time: displays at the bus stops the waiting time until the arrival of next bus and the route number.
- Request maintenance: informs the Maintenance Staff about a mechanical issue with the bus.
- Display bus locations and number of passengers on-board: displays in real-time at the Bus Operator's fleet control center, in graphical format, the locations of the buses and the number of passengers on board.

Finally, the actors and services are linked via use case diagrams. Figure 5.6 shows some of the use case diagrams for smart bus systems. The list of actors, list of services and the use case scenarios are not exhaustive. For example, the use case diagram for Researchers is not shown. Designers and decision makers of the smart bus system may modify the user services and add new user services.

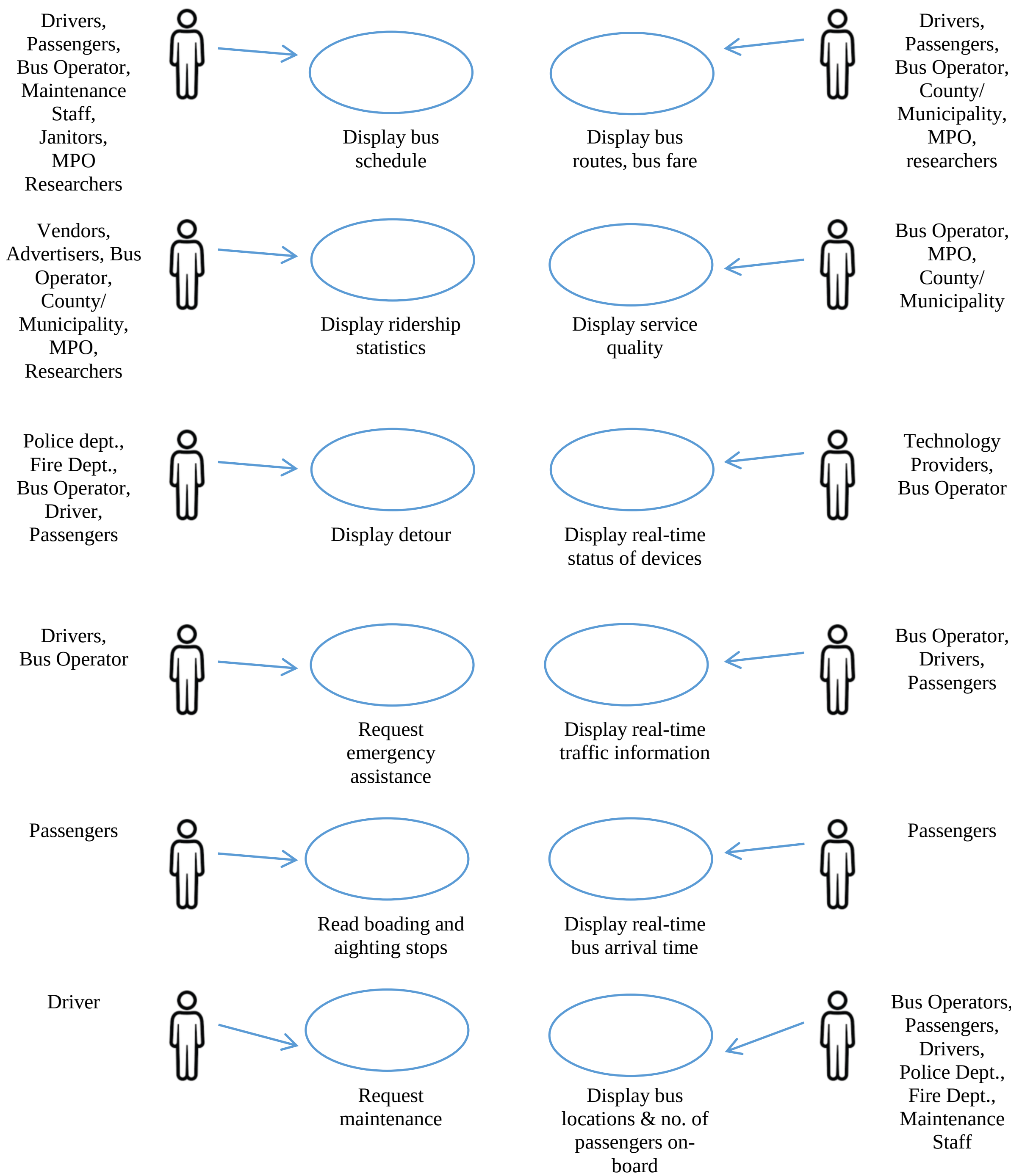

Figure 5.6 Use case diagrams for smart bus systems

5.6 Research Challenges

The research team has identified two challenges in implementing smart bus systems, or transforming existing regular bus systems into a smart bus systems.

First and most importantly, the designer of a smart bus system must make the “smart” system distinct from the RBS and BRT. A smart bus system links the data flows between the users and the systems through ICT. By linking data from several sources, a smart bus system has the capability to offer users services not found in today’s RBS and BRT systems. During normal operation, services such as display real-time traffic information, display bus locations, display bus arrival times may be offered to smart bus passengers for free. However, such services may already been offer by bus operators of the RBS and BRT systems, or through third party smart phone apps. Passengers may also have difficulty in distinguishing a smart bus system from a BRT system. During normal operations, smart bus systems and BRT systems share many infrastructure and operational features. The distinctions will be clear during incidents when there are road closures and buses are rerouted by the Police Department or Fire Department. Smart bus systems, because of using ICT to collect, store, process, analyze data collected from different sources and share data with different users, has the capability to response faster, in a relatively coordinated, organized and informed manner. Such data analysis and processing usually take place in the background in the bus operator’s fleet control center. Only during emergency the benefits become clear to the passengers. How to brand and market smart bus systems is one of the most important research topics. This is because the projected ridership statistics affects the economic feasibility of a smart bus project.

A smart bus system has the capability to automatically collect every passenger’s trip data, such as boarding stop, alighting stop, boarding time, alighting time, in-vehicle time, route transfer and etc. Such information may be recorded by fare card readers on-board (assuming all passengers use the so-called “smart” fare cards). Such origin-destination data is valuable for route, service hours, and service schedule revisions. The second research challenge is to develop image processing software that uses video captured by cameras on-board, combined with GPS locations to identify the same passenger’s boarding and alighting stops.

CHAPTER 6 SUMMARY

6.1 Definition and Characteristics of Smart Cities

A smart city is characterized by its ability to integrate people, technology and information to create a sustainable and resilient infrastructure that provides high quality services while improving the QoL of its residents". A smart city brings people (stakeholders) together to provide information (data), technology and make decisions. A smart city also has the ability to use technology (hardware) to collect, process and analyze information (data) across different infrastructure systems. This process further includes the integrated processing and analysis of the data, and study the interaction of two or more infrastructure systems. The outcomes are to make the operations of the city and the services they provide more sustainable and resilient. Making the infrastructures more sustainable and resilient are two necessary conditions for a city to provide high quality service to its residents.

To quantify and evaluate the smartness of cities, researchers have proposed several sets of indicators. The most comprehensive set of smart city indicators is the one used by Smart City Council (2014). The smartness of a city are viewed in six dimensions: environment, mobility, government, economy, people and living. Each dimension is divided into three working areas. Each working area is evaluated by one to four indicators. Two issues have been identified by the authors after reviewing the smart cities indicators. The first issue concerns with the measurement of QoL. The smartness of a city ultimately will be judged by its residents. Therefore, the QoL indicators (the outcomes) are more important than the indicators for the implementation of technologies (the process). Residents of different cities may have different priorities on different QoL indicators. It is therefore difficult to use a set of universal measures to compare cities. It is also necessary for a city to engage its residents (and stakeholders) to derive a list of characteristics (dimensions) and measurable indicators that are important to them. The computation of such indicators demands large quantity and up-to-date data. This requires the data to be opened, transparent and shared. The authors caution that the smartness of a city cannot be evaluated by a universal composite measure. The selection of dimensions, and indicators must reflect the resident's preferences, in view of a city's development status and constraints. How the numerical indicators combined to form a dimension's score, and how different dimension scores are aggregated to form an overall index is a topic of smart cities research.

In the U.S., It is not practical (at least cost prohibitive) to rebuild the entire or even parts of the infrastructures. A more realistic approach is to systematically instrument the current infrastructure, and to integrate the information for smart decision making, and then implement the decisions to improve the existing process. Therefore, it is better for existing cities to be transformed into smart cities by collecting and integrating the information about the operations of the infrastructure systems.

Transforming a city into a smart city requires collaborative efforts between all stakeholders. A common theme is the need for expertise from many disciplines, such as computer science, civil engineering, systems engineering, electrical and computer engineering, to name a few. Bringing together stakeholders with different background to support smart city initiatives will produces several challenges. Some of these challenges involve the differences in expert vocabulary, differences in disciplinary cultures, identification of available and appropriate resources, and integration of heterogeneous data and knowledge.

6.2 Research Challenges for Smart Classroom Buildings

Smart classroom buildings are designed to take advantage of ICT for instructors to deliver high quality teaching and for students to receive high quality education. By linking a classroom building's sub-systems together, additional "smarter" functions may be implemented to serve the users (primarily students and instructors). A smart classroom building may be characterized by its use of ICT to deliver user services to improve the quality of teaching and learning. In Chapter 3, 14 user services have been identified which, when some of these services are implemented, the classroom building will be smarter.

In smart classroom buildings research and implementation, the first challenge is the definition of smart classroom buildings. Smart classroom buildings should be defined and characterized in such a way that the outcome is to improve the QoL of the users. The second challenge is that a smart classroom has many stakeholders, each come to the building with different needs, materials, influence, standards and constraints. When analyzing or designing a smart classroom building, the analyst needs to limit the number of stakeholders. The third research challenge is closing the loop of user services. That is, data on user behavior and feedback may be collect at the same time while providing the user services Understanding the user's behavior and needs is a big research gap that needs to be filled.

6.3 Research Challenges for Smart Bridges

Smart bridges uses ICT to enable functions that better serve its stakeholders or users. A smart bridge has a variety of sensors to monitoring its structural and geotechnical health status and provide timely warning to the Bridge Manager. The BMC and TMC are linked digitally by sharing real-time operational data. The bridge management software is linked to a network level traffic simulation software so that traffic impact assessment be considered as part of the bridge management decision making process. The research team has identified 13 potential user services that could be implemented in bridges to make them smart bridges.

The first challenge in the design of a new smart bridge, or transforming an existing bridge into a smart bridge, is sensor instrumentation. The structural and geotechnical engineers need to make decisions on what types of sensor, the quantity and location of placement. He/she must also design the communication system to transmit sensor data in real-time to the BMC. The second challenge is to design for partial failure of the bridge, leaving the minimal service capacity that gives users enough time to evacuate. Existing bridges may be retrofitted to partially fail in a specific mode to serve the same purpose. The third challenge is the exchange of data between BMC and TMC. The data collected by TMC’s intelligent transportation systems may be combined with data collected from sensors instrumented in the bridge to derive the traffic demand pattern. This is related to the forth challenge which is to implement a practical framework to solve for the optimal bridge maintenance schedule that minimizes the traffic impacts in the area around the bridge. The challenge here is to collect traffic demand pattern as a function of time, and user behavior in response to bridge closure information, for input into the simulation model and for model calibration.

6.4 Research Challenges for Smart Bus Systems

A smart bus system provides passengers a high quality bus service via safe, comfortable, reliable rides with value for money. This is achieved by implementing several BRT features and by the use of ICT to integrate and deliver service information to passengers. A smart bus system also constantly monitors ridership data for the bus operator to make regular route and service schedule revisions. In Chapter 5 of this report, a set of 12 user services have been identified for a smart bus system.

The authors have identified two challenges in implementing smart bus systems, or transforming existing regular bus systems into smart bus systems. First and most importantly, the designer of a smart bus system must make the system “smart” by making it distinct from RBS and BRT. Smart bus systems, because of using ICT to collect, store, process, analyze, and share data from different sub-systems, has the capability to response faster, in a relatively coordinated, organized and informed manner. Only during emergency these benefits become clear to the passengers. However, these benefits may not be apparent during normal operations. How to brand and market smart bus systems is the most important research topic. This is because projected ridership statistics affect the economic feasibility of a smart bus project. To the bus operator, a smart bus system automatically collects every passenger’s trip data for periodic route, service hours, and service schedule revisions. Another research challenge is to develop image processing software that uses video captured by cameras on-board, combined with GPS locations to identify the same passenger’s boarding and alighting stops.

REFERENCES

AASHTO (2012). AASHTOWare Bridge. American Association of State Highway and Transportation Officials. http://www.aashtoware.org/Bridge/Pages/default.aspx.

Albino, V., Berardi, U. and Dangelico, R. M. (2015). "Smart cities: definitions, dimensions, performance, and initiatives." Journal of Urban Technology, 22(1), 3-21.

APTA (2015). American Public Transportation Association. http://www.apta.com. Accessed 19 December, 2015.

ASCE (2013). 2013 Report Card for American Infrastructure. American Society of Civil Engineers. http://www.infrastructurereportcard.org.

BSI (2014). Smart Cities – Vocabulary. BSI Standard Publication PAS 180:2014. British Standard Institute. http://www.bsigroup.com/en-GB/smart-cities

Cheu, R. L., Wang, Y., Fwa, T. F. (2004). "Hybrid genetic algorithm-simulation methodology for pavement maintenance scheduling." Computer-Aided Civil & Infrastructure Engineering, 19, 446-455.

EC (2015). Defining Smart Cities. Digital Agenda for Europe. https://ec.europa.eu/digital-agenda/en/content/defining-smart-cities.

EP (2014). Mapping Smart Cities in the EU. European Parliament, Directorate General for Internal Policies, Brussels. http://www.europarl.europa.eu/RegData/etudes/etudes/join/2014/507480/IPOLITRE_ET(2014)507480_EN.pdf

FHWA (2010). LTBP News. Vol. 1, Issue 1, Summer 2010, Long-Term Bridge Performance Program, Federal Highway Administration.

FHWA (2013a). FHWA LTBP Workshop to Identify Bridge Substructure Performance Issues, March 4-6, 2010, Orlando FL. Pub. No. FHWA-HRT-11-037, Federal Highway Administration.

FHWA (2013b). LTBP Bridge Performance Primer. Contract DTFH61-07-R-00136, Federal Highway Administration.

FHWA (2013d). Real-Time Bridge Monitoring – Developing Wireless Nanosenors to Monitor Structural Integrity. Exploratory Research Program, Pub. No. FHWA-HRT-13-057, Federal Highway Administration.

FHWA (2013c). Robotic System for Condition Assessment of Concrete Bridge Decks. Pub. No. FHWA-HRT-13-035, Federal Highway Administration.

FHWA (2015). Long-Term Bridge Performance (LTBP). Office of Research, Development, and Technology, Federal Highway Administration. http://www.fhwa.dot.gov/research/tfhrc/programs/infrastructure/structures/ltbp.

FTA (2015). U.S. Department of Transportation, Federal Transit Administration. http:// http://www.fta.dot.gov/about/13886_9546.html. Accessed 19 December, 2015.

GAO (2001). Mass Transit: Bus Rapid Transit Shows Promise. GAO-01-984, United States General Accounting Office.

GCI (n.d.). ISO 37120 Sustainable Development of Communities: Indicators for City Services and Quality of Life. Global City Institute. www.cityindicators.org.

Harrison, C. and Donnelly, I. A. (2011). "A theory of smart cities." White Paper, IBM.

IEEE (2015). http://smartcities.ieee.org/

ISO (2015). Smart Cities Preliminary Report 2014. ISO/IEC JTC 1 Information Technology. International Standard Organization. http://www.iso.org/iso/catalogue_detail?csnumber=62436

Lombardi, S. G., Farouh, H. and Yousef, W. (2012). "Modelling the smart city performance." The European Journal of Social Science Research, 25(2), 137–149.

Ma, W., Cheu, R. L. and Lee, D-H. (2004). "Scheduling of lane closures using genetic algorithms with traffic assignments and distributed simulations." Journal of Transportation Engineering, 130(3), 322-329.

Mercer (2015). Location Evaluation and Quality of Living Reports. Mercer LLC.

Pribyl, O. and Horak, T. (2015). "Individual perception of smart city strategies." Proceedings of the 1st IEEE Smart Cities Conference, Guadalajara, October 25-28, 2015.

Qin, H., Li, H., Zhao, X. (2010). "Development status of domestic and foreign smart city." IEEE Xplore, vol. 2010, no.9, pp.50-52.

Smart City Council (n.d.). http://smartcitiescouncil.com/

Smart City Council (2014). Smart City Index Master Indicators Survey. http://smartcitiescouncil.com/

Sun Metro (2015). Sun Metro, City of El Paso. http://www.sunmetro.net. Accessed 19 December, 2015.

TRB (2004). Transit Capacity and Quality of Service Manual, 2nd edition, Transportation Research Board, Washington, D.C.

Washburn, D. and Sindhu, U. (2010). Helping CIOs Understand “Smart City” Initiatives. Forrester Research Inc.

Vázquez-Castañeda, C. and Estrada-Guzman, E. (2014). “Towards the preparation of the Guadalajara’s Smart City Metrics Structure.” IEEE-GDL CCD Smart Cities White Paper.

Vuchic, V. R. (2005). Urban Transit: Operations, Planning and Economics, John Wiley.

Vuchic, V. R. (n.d.). Urban Public Transportation Systems. In Encyclopedia of Life Support Systems (EOLSS), Vol. I, Eolss Publishers, Paris, France.