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Development of LOS Analysis Procedures and Performance Measurement Systems for Parking

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16. Abstract

• The objectives of this project were: (1) To develop a level of service analysis procedure for off-street parking facilities; (2) To develop a concept of operations for a smart garage performance measurement system; (3) To develop a concept of operations for a smart on-street parking performance measurement system; and (4) To develop equations for on-street parking search time as functions of occupancy ratio.

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Development of LOS Analysis Procedures and Performance Measurement Systems for Parking

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Executive Summary

The objectives of this project were: (1) To develop a level of service analysis procedure for off-street parking facilities; (2) To develop a concept of operations for a smart garage performance measurement system; (3) To develop a concept of operations for a smart on-street parking performance measurement system; and (4) To develop equations for on-street parking search time as functions of occupancy ratio.

For the first objective, the existing level of service criteria using search time as the indicator was adopted. A level of service analysis procedure has been developed for open surface parking lots with one or multiple entrances, and garages with one entrance. The level of service analysis procedure measures individual vehicles' search times and uses the median search time as the level of service indicator. Three methods were proposed to measure individual vehicles' search times: (a) the license plate matching method; (2) the test vehicle method; and (3) the video observation method. The applications of the level of service analysis procedure to the different off-street parking facilities have been demonstrated by three example problems.

For the second objective, the concept of operations for a smart garage has been developed. This concept of operations includes the functionalities, equipment, a level zero diagram, and a use case diagram. The relationships of the U.S. National Intelligent Transportation Systems Architecture and a smart garage's performance measurement system were discussed. User interactions with a smart garage's performance measurement system have also been described. An experiment using the test vehicle method was performed to evaluate the improvements in the search times and level of service after converting a conventional garage into a smart garage.

The third objective is concerned with on-street parking. Six levels of on-street parking performance measurement systems were defined based on the ability of a system to monitor a parking zone's occupancy and payment transactions. The concept of operations of a Level 5 smart on-street parking performance measurement system was described. The level of service analysis procedure for on-street parking using the data from the various levels of performance measurement systems was developed. The proposed procedure was applied to evaluate the level of service of on-street parking at two sites. The first site was in the downtown of Los Angeles, CA, which implemented the Level 4 on-street parking performance measurement system. The occupancy time data at each parking space was used to derive occupancy ratio in order to estimate the average hourly search time in each street block. The second site was in downtown El Paso, TX, which utilized the Level 3 on-street parking performance measurement system. This system only stored anonymous payment data of each metered parking space. The payment data was used to derive occupancy time which led occupancy ratio in order to estimate the average hourly search time in each street block. The search times were converted into the corresponding hourly block level of service.

The fourth objective was to develop equations that estimate on-street parking search time using occupancy ratio as the input. Four models that replicated a square block with on-street parking, combined left turn/right turn and signal/stop control at the intersections were created and have the search time and occupancy data generated by VISSIM. It was found that when the intersections were controlled by signals, the average search time was an exponential function of the occupancy ratio. When the intersections were controlled by stop signs, the average search time was a linear function of the occupancy ratio. The parameter values of the fitted function were different from those reported in the literature.

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1 Introduction

1.1 Project Background

Transportation engineers use the concept of Level of Service (LOS) to communicate the service quality of a transportation facility to peers and the public. The LOS analysis methodologies for many types of transportation facilities have been described in the Highway Capacity Manual (HCM) (TRB, 2010). At present, the current version, simply known as HCM2010, has not included a LOS analysis procedure for parking facilities. The first half of this project partially filled this research gap by developing a LOS analysis procedure for off-street parking facilities.

Owners of some parking facilities, especially garages and on-street parking spaces, are increasingly relying on Intelligent Transportation Systems (ITS) technologies to make the parking facilities "smarter". The ITS-enabled system that monitors a parking facility's performance is called parking Performance Measurement System (PMS). Parking PMSs may be implemented in conventional parking facilities but it is often associated with smart parking facilities. What makes a parking facility "smart"? The second half of this project defines the system components and functions of parking PMSs that will make garages and on-street parking facilities smarter.

1.2 Objectives

The objectives of this project were:

1. To develop a LOS analysis procedure for the following off-street parking facilities:
    a. Open surface parking lots with one entrance.
    b. Open surface parking lots with multiple entrances.
    c. Garages with one entrance.

   This objective included three example problems to illustrate the applications of the proposed LOS analysis procedure to the above off-street parking facilities.
2. To develop a Concept of Operations (ConOps) for a smart garage PMS. This objective included a study to estimate the benefits, in terms of search time and LOS, by converting a conventional garage into a smart garage.
3. To develop a ConOps for a Smart On-Street Parking (SOSP) PMS. This objective included methodologies to estimate the parking occupancy ratio and use it to estimate the average search time.
4. To develop equations that estimate the average search time for on-street parking as functions of occupancy ratio.

1.3 Outline of Report

This report consists of six sections:

1. Section 1 introduces the project, defines the objectives, and outlines the sections in this report.
2. Section 2 reviews the literature and existing practices that are related to the research objectives. The topics reviewed included LOS for parking, PMSs for parking, ITS technologies for parking, and performance-based parking management.
3. Section 3 introduces a new LOS analysis procedure for off-street parking facilities. The first half of this section describes this LOS analysis procedure which includes three methods of measuring search times. The second half of this section presents three example problems. Each example problem applied the LOS analysis procedure in combination with a search time measurement method to one off-street parking facility.
4. Section 4 describes the ConOps for a smart garage PMS. This section also includes a study to estimate the average saving in parking search times if a conventional garage is converted into a smart garage.
5. Section 5 describes the ConOps for an SOSP PMS. Two case studies, using data from on-street parking PMSs in Los Angeles, California, and El Paso, Texas, illustrated the use of occupancy or payment transaction data, respectively, to estimate the parking search times.
6. Section 6 reports an experiment that used VISSIM to generate search time and occupancy data and used the data to fit several functions of average search time in terms of occupancy ratio.
7. Section 7 concludes the work performed, summarizes the outputs, outcomes, and impacts of this research, highlights the limitations, and suggests future research directions.

2 Review of Literature and Existing Practices

2.1 Level of Service for Parking

The 2020 Edition of Highway Capacity Manual or HCM2010 (TRB, 2010) prescribes the standard procedures to evaluate the service quality of different transportation facilities. The HCM2010 uses Level of Service (LOS) to represent the performance of a transportation facility from the user's perspective, with LOS A being the best and LOS F being the worst. The LOS A to F is determined by comparing the output value of a LOS analysis procedure against the LOS criteria. The LOS analysis procedure analyzes the interaction between transportation demand against infrastructure supply. It outputs a numerical value as a LOS indicator. This LOS indicator is then compared with the LOS criteria (a table or a chart) to assign a letter grade A to F for the LOS. Since the LOS concept was introduced in 1965, the Highway Capacity Manual has been revised several times. Each revision added new LOS analysis procedures and LOS criteria for transportation facilities not covered in the past versions. The manual has yet to prescribe a LOS analysis procedure and LOS criteria for a parking facility.

The handbook A Policy on Geometric Design of Highways and the Streets (AASHTO, 2018) is the only existing national level guidebook that provides LOS criteria for parking. AASHTO (2018) awards LOS A to F for a parking facility based on criteria that use the layout and physical dimensions of the parking spaces as the LOS indicators. Similarly, Chrest et al. (2012) used the physical dimensions of parking spaces as the LOS indicators in his LOS criteria that defined four LOS grades for parking garages. The physical dimensions of a parking space indicate the accessibility of the parking space for the users: the ease for a vehicle to be moved in and out of the parking space, and the ease for vehicle occupants to alight from and board the vehicle. These LOS criteria and indicators do not include search time for an empty parking space. Search time is the cause of frustration when drivers look for a space to park. Search time for parking is similar to control delay at intersections. Being the most direct indicator of a user's experience, search time should be used as a LOS indicator for parking.

Although not yet included in the national manuals, researchers have proposed and used search time as the LOS indicator for parking. He et al. (2012) defined a LOS analysis procedure for parking facilities in Beijing, China. Their LOS criteria consisted of four indicators: peak demand/capacity ratio, average occupancy, parking cost, and circulation time. The last indicator was the search time. Das and Ahmed (2018) defined three selection criteria for user's choice of on-street parking locations in downtown: parking operations; safety and geometric design. The parking operations criterion was evaluated by five indicators: volume to capacity ratio, parking utilization rate, parking fee, ease time, and turnover rate. Ease time was related to search time. Gurbuz and Cheu (2020) conducted a survey with 1,022 drivers to develop LOS criteria for parking based on parking search time as the LOS indicator. The participants were asked to state their thresholds of search time for LOS A to F. The LOS criteria developed from this survey are listed in Table 1. The survey did not specify the type of parking facility and therefore Table 1 may be applied to surface parking lots, garages, and on-street parking.

	Parking search time	Comment
LOS A	0-2 minutes	Can find an empty parking stall immediately
LOS B	>2-4 minutes	Can find an empty parking stall after a short time
LOS C	>4-7 minutes	Can find an empty parking stall after some time
LOS D	>7-10 minutes	Can find an empty parking stall after a while
LOS E	>10-15 minutes	Can only find an empty parking stall after a long time
LOS F	>15 minutes	Unacceptable

Data source: Gurbuz and Cheu (2020).

Table 1: Level of Service Criteria for Parking

For off-street parking, a vehicle's search time may be measured from the time this vehicle enters the parking facility until it occupies a parking space. For on-street parking, it is difficult to determine when a driver begins his/her search for a parking space. Axhausen et al. (1994) introduced an empirical model to estimate the average parking search time, T, as a function of parking occupancy ratio, Ω (in decimal, dimensionless) of the zone of interest, with α as a parameter equivalent to the minimum search time:

$$T = \frac{\alpha}{1-\Omega}, \quad \Omega<1 \tag{1}$$

Belloche (2015) surveyed the search time of 923 drivers who were given addresses to park along downtown streets in Lyon, France, and found that α=26.1 seconds in Equation (1). Belloche (2015) further proposed:

$$T = \gamma e^{\beta\Omega} \tag{2}$$

with β as a dimensionless parameter. Using the on-street parking data collected in downtown Lyon, the calibrated parameter values were γ=0.307 seconds, β=7.407. Caicedo (2009) introduced a search time function for parking garages in the form of:

$$T = \eta\left(1 + \rho\Omega^{\theta}\right) \tag{3}$$

The calibrated values of η=0.1, ρ=3.2 and θ=1.0 for level 1 of a garage which may be used for street parking. Caicedo (2009) did not specify the unit of T. Based on the estimated magnitude, it appeared that T in Equation (3) is in minute.

Smith and Butcher (2008) outlined different LOS criteria based on how far a user must walk from their parked car to his/her destination. They classified parking facilities into five types. For each type of parking facility, they used walking distance as the LOS indicator to assign LOS A to D. Walking distance is difficult to measure without knowing the final destinations of every parker, especially for on-street parking.

After reviewing the available literature concerning the LOS for parking, the research team concluded that search time was the most commonly used indicator. Several researchers have proposed a multi-criteria approach to evaluate the LOS for a parking facility. Given that (1) HCM2010 uses one indicator to determine the LOS for most of the transportation facilities; and (2) for practical purposes in data collection, the research team selected search time as the LOS indicator for the remaining tasks in this project.

2.2 Performance Measurement Systems for Parking

Performance measurement is the use of statistical evidence to determine progress toward specifically defined objectives (FHWA, 2020). A Performance Measurement System (PMS) collects, integrates, analyzes data, and determines quantitative and qualitative measures. The search time and LOS described in Subsection 2.1 are quantitative and qualitative performance measures, respectively, for a parking facility. The search time of a parking facility may be measured by the facility's PMS. However, search time and LOS measure the performance from the user's perspective. A parking facility's PMS should serve more than the users, and measure more than the search time.

Several researchers have proposed alternative ways to measure the performance of parking facilities. Table 2 summarizes the proposed performance measures into a metric. The metric consists of dimensions, criteria, indicators, and quantitative/qualitative measures. This metric has two dimensions: user and owner. Each dimension evaluates the parking facility's performance using static and dynamic criteria. Each criterion has at least one indicator, and each indicator is measured by a quantitative value or a qualitative descriptor. This metric applies to short-term users of a parking facility because they represent the attractiveness of a facility to this type of user. Long-term users (season pass holders) typically do not select between parking locations (facilities) from day to day.

Dimension	Criterion	Indicator	Measure (unit)	Reference
User	Static	Walking distance	Distance (ft or m)	Smith and Butcher (2008)
		Weather protection	Sheltered walkway (%)	Smith and Butcher (2008)
		Geometric design	LOS A to F	AASHTO (2004)
		Geometric design	LOS excellent, good, acceptable	Kimberly Horn (2016)
		Signage and wayfinding	*Proposed: no. of signs/space*	Kimberly Horn (2016)
		Safety and security	*Proposed: No. of incidents/space/time-period*	Kimberly Horn (2016)
		Parking fee	Rate ($/hour)	He et al. (2015)
	Dynamic	Utilization	Rate (%) converted to excellent, good, fair, poor	He et al. (2015)
		Search time	Time (minutes) converted to LOS A to F	Gurbuz and Cheu (2020)
		Circulation time	Time (minutes) converted to excellent, good, fair, poor	He et al. (2015)
Owner	Static	none	none	none
	Dynamic	Occupancy	Occupancy (%)	Revenue Hub (2020)
		Revenue	Average revenue/time-period	Revenue Hub (2020)
		Revenue per transaction	Average revenue/ transaction	Revenue Hub (2020)
		Revenue per space	Average revenue/space/ time period	Revenue Hub (2020)

Table 2: Performance Metric for Parking Facilities

2.3 Intelligent Transportation Systems Technologies for Parking

This subsection reviews the ITS technologies that make a parking facility "smart". They also enable the implementation of a PMS for parking.

2.3.1 Sensors

Sensors detect vehicles in a parking facility. There are many makes and models of vehicle sensors on the market. Instead of referring to specific products, this section reviews the two most commonly used sensor technologies in parking: ultrasonic, geomagnetic and image processing.

Ultrasonic sensors have been installed in vehicle bumpers as parking sensors. Ultrasonic sensors emit ultrasonic waves (of frequency >20 kHz) that are projected to a cone shape detection zone programmed with a specific range of several feet or meters. A vehicle is detected when the ultrasonic waves are reflected off the vehicle body and are received by the sensor. Ultrasonic sensors can be mounted on the ceiling of each parking space in a garage to detect if the space is occupied. This type of sensor usually comes with LED lights of red and green colors to indicate to the drivers the parking space is occupied or available. Ultrasonic detectors can also be mounted on the ceiling of a garage's entrance and exit to make vehicle counts.

Geomagnetic sensors are wireless in-ground, low-power sensors. Each sensor is approximately 100 mm in diameter and 50 mm in height, powered by a lithium-ion battery. The sensor uses the change in magnetic field caused by motions of vehicles to detect the presence of a vehicle in a parking space. This type of sensors may be installed into the pavement surface of open parking lots or on-street parking stalls.

Video-based detection is an established technology used by many cities and state transportation agencies to measure the volume and speed of vehicles on highways, and volumes at signalized intersections. It works by analyzing the colors and brightness of pixels in digital images to identify vehicles from the background. For applications in parking lots and garages, a video camera is usually mounted to a pole on the ceiling or columns with a field of view of several parking spaces. The primary function of a video-based detection system is to detect parked vehicles. Its software may also have the capability to identify license plates for access control, security enforcement and/or automated payment. The video-based detection system may also be installed at the entrance and exit of a parking lot or a garage.

2.3.2 Dynamic Message Signs

Dynamic Message Signs (DMSs) are electronic signs on the highway that provide drivers with real-time traffic information. Each DMS used on freeways consists of an array of LED lights that form up to three rows of 20 characters. The characters are displayed in amber color but multiple colors may also be used. When used in a parking PMS, DMSs can only communicate messages one way, from the PMS to the drivers. DMS may be applied to attract drivers and to guide drivers to parking spaces in various ways as shown in Table 3.

2.3.3 Communications

A smart parking PMS must communicate the parking facility's usage (e.g., number and locations of empty spaces) and guide drivers to available parking spaces. The communication of information may be via smartphone or DMS.

Smartphones are the personal devices of drivers. The communication between the smartphone and the PMS may be two-way. The information may be displayed in text or graphical format on the smartphone screen. Some vehicle models have dashboard displays that can be connected to smartphones by Bluetooth and duplicate the displays on the smartphone screen.

Location	Purpose	Example
On-street, approach to a garage	To display the number of available parking spaces in the garage	Airport short-term parking: 67
On-street, approach to multiple garages	To display the number of available parking spaces in the various facilities	Sun Bowl parking North garage: 125 South garage: 66 East garage: Full West garage: Closed
At garage entrance	To display the number of available parking spaces at each level	Space Level 4: 89 Level 3: 34 Level 2: 5 Level 1: 2
At garage entrance	To display the assigned/reserved space for a particular vehicle (by license plate)	BMT216A Proceed to level M Space no. 007
Inside the garage, on-ramps leading to every floor	To display the number of available parking spaces at each level	Spaces Level 4: 89
Along an aisle	To display the number of available parking spaces ahead	Spaces 12 ← → 19
Along an aisle	To guide a particular vehicle to its assigned/reserved space	BMT216A Space no. 007 →

Table 3: Potential uses of Dynamic Message Signs in Parking Facilities

2.3.4 Mobile applications

Many mobile applications on the market help users to locate parking spaces/lots, navigate to parking spaces/lots, and pay for parking. They also give owners the choice of extending the paid time without going to a meter or pay station (Volkswagen, 2020). Certain applications even give drivers the option to reserve a parking space up to two weeks in advance (ParkMobile, 2020). Similarly, many applications partner with trip generators/attractors so that drivers can save time by reserving a spot in advance and paying directly through mobile applications (SpotHero, 2020). This relieves the drivers from having to search for a parking space when attending a major event.

2.4 Performance-Based Parking Management

This subsection reviews the performance-based parking management that is made possible by parking PMSs.

Many cities have implemented performance-based parking pricing as a tool to manage parking in downtown areas. With the help of ITS technologies, a performance-based parking PMS adjusts the price of parking based on the zone's or garage's occupancy. San Francisco, Los Angeles, and Seattle are some cities that have taken advantage of the parking PMS.

San Francisco uses a parking PMS called SFPark to adjust/distribute the on-street parking demand in the city (SFPark, 2020). Sensors are embedded into the pavement of parking spaces to detect occupancy. Depending on the occupancy ratio in a zone, the parking price of the zone is adjusted accordingly to bring the occupancy ratio towards 0.85.

The City of Los Angeles uses the LA Express Park as its parking PMS (LA Express Park, 2020). The system uses smartphones and DMSs to direct drivers to vacant spaces. The LA Express Park uses performance-based pricing to control a parking zone's occupancy.

Since 2010, the Seattle Department of Transportation has been using the performance-based parking system on over 12,000 parking spaces throughout the city. The city keeps the parking space occupancy ratio between 0.75 and 0.85. This PMS collects and analyzes the parking space usage data annually, and if a zone's occupancy ratio exceeds 0.85, the parking price may be increased by as much as $0.50/hour. On the other hand, if a parking zone is underutilized (occupancy ratio <0.75), the hourly parking fee will be reduced to encourage more usage (SDOT, 2019).

3 Level of Service Analysis Procedures for Off-Street Parking

3.1 Section Introduction

This section describes a LOS analysis procedure that is applicable for three types of off-street parking facilities: an open surface parking lot with one entrance; an open surface parking lot with multiple entrances; and a parking garage with one entrance. The subsections are arranged to follow the outline of a typical chapter in HCM2010 (TRB, 2010).

3.1.1 Analysis Boundaries and Travel Modes

The analysis boundaries define the areas of LOS analysis. The key question an analyst should ask is "where do drivers start to look for a parking space?" For parking at off-street facilities, it is reasonable to assume that drivers start to search for a parking space when they have entered the parking facility. For an open surface parking lot with one entrance, the analysis boundary is the area of the parking lot, after vehicles have passed the access control equipment. For a multistory garage with a single entrance, the analysis boundary is treated in the same way as the open surface parking lot with one entrance. For an open surface lot with multiple entrances, the area of analysis is bounded by the access control points at the different entrances.

3.1.2 Level of Service Criteria

The LOS criteria for off-street parking facilities are based on parking search time. Parking search time is defined as the time when a vehicle enters the parking facility until the vehicle first enters a marked space. The search time includes time driving between the aisles, delays caused by pedestrians, delays caused by other vehicles entering and exiting parking spaces, and the time it takes for the driver to move the subject vehicle into the parking space for the first time. It does not include the re-positioning of the vehicle to the center of the parking space.

Table 1 shows the criteria for LOS A to F using search time as the LOS indicator (Gurbuz and Cheu, 2020). This LOS criterion may be applied to measure the LOS for a single vehicle or multiple vehicles. When assigning LOS for multiple vehicles, the vehicles are sampled over a period (called the "analysis period") before the median value is identified and applied to Table 1. It is recommended that the LOS be determined based on the median value of all the measured search times observed in 15 minutes.

3.1.3 Required Input Data

The required input data is the individual vehicle search time as defined above.

3.1.4 Scope of the Methodology

The methodology applies to off-street open surface parking lots with one or multiple entrances, and garages with one entrance.

3.1.5 Limitations of the Methodology

The methodology can only be applied to off-street parking facilities which are in operation.

3.2 Methodology

This subsection describes the methods of measuring search times within a 15-minute analysis period. Three methods have been proposed:

- License plate matching method.
- Test vehicle method.
- Video observation method.

3.2.1 License plates matching method

The license plate matching method may be applied to measure the search times for an open surface parking lot with one or multiple entrances. It can also be applied to a garage if there are enough observers.

For a parking lot or garage with one entrance, the following steps are recommended:

1. Divide the lot or garage into n_o parking modules. Each module consists of an aisle and parking spaces on both sides of the aisle. The size of the parking module should be such that one observer can read the license plates when vehicles are parked.
2. The required number of observers in the team is $n_o + 1$. Position the n_o observers, one at each parking module. The additional observer is positioned at the entrance.
3. Each observer carries a stopwatch, a pen, and a clip board with papers for notetaking. The clock times of all the $n_o + 1$ observers are synchronized.
4. Start the observations at the beginning of the 15-minute analysis period.
5. When a vehicle arrives at the entrance of the parking lot or garage within the analysis period, the observer at the entrance writes down the last four digits of the entering vehicle's license plate number and the time stamp.
6. When a vehicle pulls into a parking space, the observer who has been assigned to that parking module writes down the last four digits of the vehicle's license plate number and the time stamp.
7. Repeat steps 5 and 6 for all the entering vehicles until the 15-minute analysis period has expired. Note that, vehicles may enter the parking lot or garage towards the end of the analysis period. The observers should wait until all these vehicles are parked even if the parked time extends beyond 15-minute the analysis period.

8. At the end of the session, enter all the data into a worksheet. By matching the license plates, the individual vehicle's search time can be calculated.

The measurement of search time for an open surface lot with multiple entrances is more challenging. This is because parking lots with multiple entrances are usually bigger, requiring more observers. The search time measurement at a parking lot with multiple entrances follows the eight steps as discussed above. Instead of $n_o + 1$ observers, there should be $n_o + n_{en}$ observers where n_{en} is the number of entrances.

During data collection, two special cases may occur. The cases and how the data should be handled are:

- Special case 1: Pick-up or drop-off. A vehicle that enters the parking lot or garage to pick up or drop off a passenger will have its arrival time and license plate recorded by the observer at the entrance. Since this vehicle does not pull into a marked space, there is no record by any observer at the parking modules. Therefore, the license plate matching method will not be able to calculate a search time.
- Special case 2: Full occupancy. A vehicle arriving at a fully occupied parking lot or garage has three possible outcomes:
    1. The vehicle parks illegally. In this case, the vehicle does not park in a marked space. There will be no record of the time it pulls into a marked space.
    2. The vehicle waits in the aisle or continues circulating beyond the 15-minute analysis period until it finds a parking space. In this case, the observer should still record the time this vehicle enters a marked space (even if this is after the 15-minute period).
    3. The vehicle waits for several minutes, aborts the search, and leaves. This vehicle may park at a subsequent lot or garage. Since it does not complete a parking maneuver, no search time is recorded. The inability of this method to capture the search times of these vehicles can potentially underestimate the median search time. To rectify this bias, the recorded search time was taken as the time this vehicle entered the parking lot until the first vehicle (after the space seeking vehicle has left) pulled out of a parked space and left the exit. This pseudo search time was used in the determination of LOS.

3.2.2 Test vehicle method

This test vehicle method essentially uses a test vehicle to measure search times. This method may be applied to any off-street parking facilities, including a parking facility that has been completed but yet to open to traffic, or when the occupancy is high and the license plate method has difficulty handling too many special cases.

The test vehicle method is as follows:

1. Divide the parking lot or garage into m parking modules.
2. For each parking module, randomly select one space. Mark on the floor the selected space number ($s = 1, 2, 3, \dots, m$) with chalk.
3. Use a test vehicle to simulate an average driver driving from the entrance to a marked parking space. The driver does not know the exact locations of the marked spaces ($s = 1, 2, 3, \dots, m$).

The driver is to repeat the search m times, starting from the entrance. Before each trip, the driver is told to search and park at the space marked with a particular randomly selected number.

4. For each trip, the driver positions the test vehicle at the garage entrance. He/she starts to measure the trip time using a stopwatch and proceeds with his/her drive to search for the targeted marked space. He/she stops the stopwatch after the vehicle has been pulled into the marked space. The observed trip time from the entrance to the marked spaces s is recorded as t_s which is the search time.

The main advantage of this test vehicle method is that it requires one driver and another person who marks the spaces with chalk to tell the driver the space number to search for and park. This method also avoids the special cases of pick-up, drop-off, illegal parking, and abortion. This method is designed for the test vehicle to cover all the parking modules once. It assumes that the supply of empty spaces to park is randomly spread in the parking lot or garage, such that a driver has the same probability of finding a parking space in every module. However, a test vehicle may not be able to complete the m parking modules with the 15-minute analysis period. In this case, multiple test vehicles are necessary.

3.2.3 Video Observation Method

The video observation method, as its name suggests, is to have an observer watch the video recording of parking activities and extract the search times. This method is more suitable for small off-street open surface parking lots (with one or multiple entrances) because of the feasibility of recording the video from a vantage point or from an unmanned aerial vehicle that covers the entire parking lot.

For this method to work, the recorded video should be of high quality. A high definition of 720p at a frame rate of 30 fps is preferred. The video should be played back in the normal or at a slower speed in a laboratory (indoor) environment and viewed on a 15” or larger monitor. The observer should use the video’s clock to observe the search time to account for any adjustment in the playback speed.

During the playback, the observer tracks an individual vehicle as it enters the parking lot until it first occupies a marked space. The video may be rewound to observe the actions of the next vehicle. The main advantage of the video observation method is the observer can repeat the measurements.

3.3 Applications

3.3.1 Operation Analysis

Operation analysis is the most direct application of the LOS analysis procedure for parking. If an off-street parking facility has been in operation, the procedures described in this section may be applied to evaluate the LOS experienced by a parking facility’s users. Based on the LOS observed, the parking policy may be adjusted (for example, by changing the parking fee or the sale of permits) to encourage usage or to manage the demand and to achieve the targeted LOS.

3.3.2 Design Analysis

Assuming that the dynamic (time-dependent) demand for parking of a new development has been estimated, the designer of a parking facility has to make two design decisions: the number of parking spaces and the layout. The minimum number of parking spaces is usually specified in the local building code but developers may provide more parking spaces than the minimum design criterion. The layout includes the arrangements of the modules, and for a garage, the ramps (also known as the inter-floor travel system). The ideal design scenario is to select a combination of the number of parking spaces and the layout to achieve a pre-specified LOS. An example of the design objective may be: "during the worst 15-minute period in a day the LOS must be C or better". The designer may, based on their experience, pre-select a few candidate designs. From these designs, the designer may look for a similar facility and apply the LOS analysis procedure at the existing facility to measure the search times and then estimate the LOS.

3.4 Example Problems

This subsection presents three example problems to demonstrate the applications of the proposed LOS analysis procedure for off-street parking facilities. The three example problems cover different types of off-street parking facilities.

3.4.1 Open Surface Lots with One Entrance

The first example problem demonstrates the application of the LOS analysis procedure for an open surface parking lot with only one entrance. The University of Texas at El Paso (UTEP) campus and all public parking lots in El Paso were closed during the planned study period because of public health concerns related to the COVID-19 pandemic. The research team made use of a set of data collected in October 2019 for this example problem.

The UTEP Dawson parking lot was selected as the study site. The parking lot's layout is shown in Figure 1. It has one entrance that leads to 178 spaces but does not have access control. The license plate matching method was applied to collect data to calculate search times. Four observers were deployed at points A, B, C, and D as indicated in Figure 1. Observer A at the entrance recorded the license plate number and arrival times while the other observers recorded the license plate numbers and times when vehicles pulled into a parking space. The search times were collected in the following periods to cover the morning, mid-day, and afternoon peaks of the weekday parking demand:

- 9:15 a.m. to 10:15 a.m. on October 2, 2019 (Wednesday).
- 11:15 a.m. to 11:45 a.m. on October 2, 2019 (Wednesday)

- 2:00 p.m. to 2:45 p.m. on October 3, 2019 (Thursday)

Tables 4 to 6 show the search time data collected at the Dawson parking lot.

North is pointing up

Figure 1: Plan View of Dawson Parking Lot

Veh no.	License plate no.	Arrival time at entrance (hh:mm:ss)	Time pulled into parking space (hh:mm:ss)	Search time, t_s (mm:ss)	100% occupancy
1	5405	9:15:02	9:15:12	0:10	yes
2	7442	9:16:04	9:16:20	0:16	yes
3	8359	9:24:56	9:25:07	0:11	yes
4	1232	9:25:25	9:25:30	0.05	yes
5	9578	9:32:23	9:32:57	0:34	yes
6	4908	9:39:54	9:40:24	0:30	yes
7	8964	9:40:15	9:40:47	0:32	yes
8	5321	9:41:21	9:41:36	0:15	yes
9	7965	9:42:21	9:42:29	0.08	yes
10	4433	9:44:09	9:44:44	0:35	yes
11	9203	9:46:32	9:46:49	0:17	yes
12	940	9:46:38	9:46:54	0:16	yes
13	7073	9:46:53	9:47:11	0:18	yes
14	2616	9:51:50	9:52:09	0:19	yes
15	6785	9:52:55	9:53:09	0:14	yes
16	8190	9:53:20	9:53:40	0:20	yes
17	7498	9:56:50	9:57:06	0:16	yes
18	8420	10:02:04	10:02:22	0:18	yes
19	5607	10:04:02	10:04:30	0:28	yes
20	0015	10:05:09	10:05:32	0:23	yes
21	8494	10:05:24	10:06:19	0:55	yes
22	4608	10:07:03	10:07:17	0:14	yes
23	4574	10:10:09	10:10:25	0:16	yes
24	88U1	10:11:54	10:12:26	0:32	yes
25	1897	10:14:20	10:17:30	3:10	yes

Table 4: Search Times at Dawson Parking Lot, 10/2/2019 Morning

Veh no.	License plate no.	Arrival time at entrance (hh:mm:ss)	Time pulled into parking space (hh:mm:ss)	Search time, t_s (mm:ss)	100% occupancy
1	8868	11:15:26	11:16:52	1:26	No
2	9396	11:16:01	11:16:50	0:49	No
3	9787	11:17:32	11:21:08	3:36	Yes
4	7327	11:17:43	11:21:30	3:47	Yes
5	7358	11:19:20	11:21:46	2:26	Yes
6	9642	11:19:51	11:22:00	2:09	Yes
7	27D1	11:20:02	11:23:44	3:42	Yes
8	1648	11:24:51	11:26:32	1:41	No
9	31K8	11:26:23	11:28:19	1:56	Yes
10	8541	11:29:27	11:29:57	0:30	No
11	57YZ	11:30:57	11:33:49	2:52	Yes
12	Z989	11:31:24	11:32:37	1:13	No
13	1898	11:32:39	11:33:10	0:31	No
14	D318	11:33:28	11:33:49	0:21	Yes
15	XL84	11:37:16	11:40:23	3:07	Yes
16	0385	11:37:27	11:37:41	0:14	No
17	Z922	11:39:31	11:40:23	0:52	Yes
18	3855	11:43:03	11:43:18	0:15	No

Table 5: Search Times at Dawson Parking Lot, 10/3/2019 Mid-Day

In Table 5, between 11:15 a.m. and 11:45 a.m., 18 vehicles arrived at the Dawson parking lot. Eight vehicles successfully found spaces to park. The other 10 vehicles arrived when the parking lot had 100% occupancy. These vehicles waited and left. Since these vehicles did not park at Dawson lot, no search time was recorded.

Veh no.	License plate no.	Arrival time at entrance (hh:mm:ss)	Time pulled into parking space (hh:mm:ss)	Search time, t_s (mm:ss)	100% occupancy
1	5575	13:33:42	13:34:01	0:19	No
2	57N9	13:33:58	13:34:55	0:57	No
3	7438	13:45:36	13:47:44	2:08	Yes
4	9667	13:49:06	13:49:51	0:45	No
5	5805	13:55:13	13:58:00	2:47	Yes
6	366	13:57:26	13:57:50	0:24	No
7	2447	13:59:30	13:59:58	0:28	No
8	R908	14:06:32	14:06:48	0:16	No
9	3284	14:07:50	14:09:07	1:17	No
10	6790	14:08:15	14:09:35	1:20	No
11	1285	14:08:42	14:10:04	1:22	No
12	6041	14:25:28	14:26:11	0:43	No
13	7616	14:28:50	14:30:09	1:19	No

Table 6: Search Times at Dawson Parking Lot, 10/3/2019 Afternoon

The search time data collected in Tables 4 to 6 were converted into LOS at 15-minute intervals and summarized in Table 7. Although the parking lot was relatively congested in the mid-day and afternoon, the LOS remained at A most of the time.

Analysis period	Median search time (mm:ss)	LOS
9:15 a.m. – 9:29 a.m.	0:11	A
9:30 a.m. – 9:44 a.m.	0:31	A
9:45 a.m. – 9:59 a.m.	0:17	A
10:00 a.m. – 1:14 a.m.	0:25	A
11:15 a.m. – 11:29 a.m.	2:03	B
11:30 a.m. – 11:44 a.m.	0:41	A
1:30 p.m. – 1:44 p.m.	0:38	A
1:45 p.m. – 1:59 p.m.	0:45	A
2:00 p.m. - 2:14 p.m.	1:19	A
2:15 p.m. – 2:29 p.m.	1:01	A

Table 7: Levels of Service at Dawson Parking Lot

3.4.2 Open Surface Lots with Multiple Entrances

The second example problem demonstrates the application of the LOS analysis procedure for an open surface parking lot with multiple entrances. The video observation method was used to extract the search times.

The parking lot studied was located at Den Burg, Texel, the Netherlands. Two video files were found on YouTube, under the channel "The Parking Lot". They were named Video 1 and Video 2 respectively in this report. A screenshot of the Den Burg parking lot is shown in Figure 2. The two entrances are marked by X and Y respectively. The parking lot has a capacity of 58 vehicles. The parking lot appeared to serve customers going to a grocery store. The two videos each recorded vehicle movements for approximately 22 minutes. The date and time of the recording were not posted. The video files were uploaded by the owner in January 2020.

An observer was asked to watch a 15-minute segment of each of the videos played back at normal speed on a desktop computer. The observer tracked individual vehicles and used the clock time in the video to measure the search times of vehicles. The observed data from Video 1 and Video 2 are presented in Tables 8 and 9 respectively. The median search times were 1 minute 22 seconds and 1 minute 32 seconds respectively. They both correspond to LOS A.

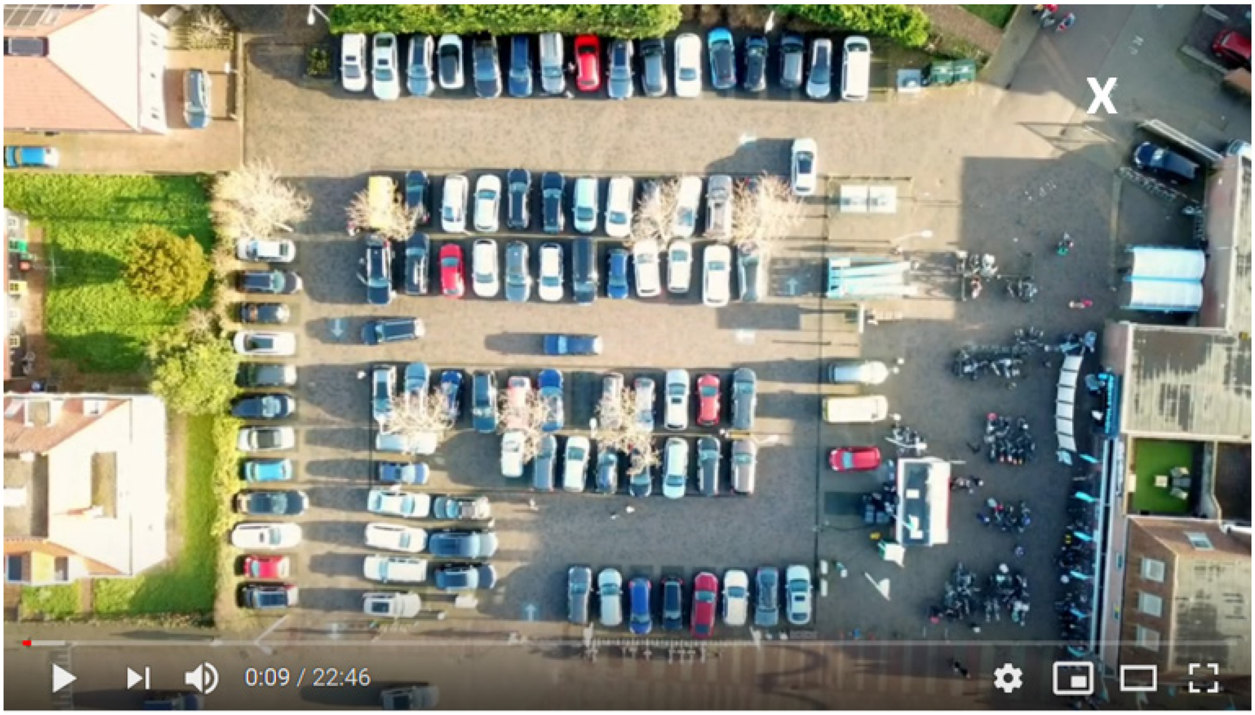

Figure 2: Screen Shot of Den Burg Parking Lot

(from https://www.youtube.com/channel/UCr0UtKhvy96qEDUUhDi-5Lg**)**

Veh no.	Vehicle color	Arrival time at entrance (hh:mm:ss)	Time pulled into parking space (hh:mm:ss)	Search time, t_s (mm:ss)	Entrance
1	Black	00:00:18	00:01:20	01:02	Y
2	Grey	00:01:18	00:02:00	00:42	Y
3	Grey	00:02:02	00:02:49	00:47	Y
4	White	00:02:50	00:04:03	01:21	X
5	White	00:03:20	00:04:09	00:49	X
6	White	00:04:19	00:04:37	00:18	Y
7	Grey	00:04:28	00:04:59	00:31	Y
8	Black	00:04:46	00:05:09	00:23	Y
9	Black	00:05:26	00:07:09	01:43	Y
10	White	00:05:34	00:07:33	01:59	Y
11	Red	00:05:58	00:06:30	00:32	X
12	Black	00:07:10	00:07:43	00:33	Y
13	Grey	00:07:17	00:08:24	01:07	X
14	Black	00:07:37	00:08:31	00:54	X
15	Grey	00:07:53	00:09:45	01:38	Y
16	Grey	00:08:26	00:14:16	05:50	Y
17	Black	00:08:44	00:14:12	05:28	X
18	Black	00:09:00	00:14:32	05:32	Y
19	Blue	00:10:02	00:13:11	03.09	Y
20	Black	00:11:11	00:16:23	04:12	Y
21	Grey	00:11:45	00:15:16	03:31	Y
22	White	00:13:14	00:16:17	03.03	X
23	Grey	00:13:41	00:16:05	02:34	Y
24	Black	00:14:25	00:16:04	01:39	Y

Table 8: Search Times at Den Burg Parking Lot from Video 1

Veh no.	Vehicle color	Arrival time at entrance (hh:mm:ss)	Time pulled into parking spaace (hh:mm:ss)	Search time, t_s (mm:ss)	Entrance
1	Black car	00:00:56	00:02:22	01:26	X
2	Black	00:02:03	00:05:10	03:07	Y
3	Big sunroof	00:02:08	00:04:02	01:54	Y
4	Black car	00:02:24	00:04:24	02:00	Y
5	Pink car	00:02:34	00:05:33	02:59	Y
6	White car	00:02:50	00:04:40	01:50	Y
7	White car	00:02:56	00:05:12	2:16	X
8	White car	00:03:48	00:05:40	01:52	Y
9	Grey car	00:04:28	00:05:03	00:35	X
10	Black car	00:04:56	00:07:21	02:20	Y
11	Grey car	00:06:03	00:06:57	00:39	Y
12	White car	00:07:30	00:09:38	02:08	Y
13	White car	00:07:49	00:08:06	00:17	X
14	Blue car	00:08:25	00:09:06	00:41	Y
15	White car	00:08:55	00:10:04	01:09	Y
16	White car	00:09:24	00:12:28	02:59	Y
17	Blue car	00:09:37	00:11:15	01:38	Y
18	Black car	00:12:07	00:12:21	00:14	Y
19	Grey car	00:12:21	00:12:41	00:20	Y
20	White car	00:13:29	00:13:55	01:26	X
21	Black car	00:14:19	00:14:35	00:16	Y
22	Pink car	00:14:23	00:14:42	00:19	X
23	Black car	00:14:25	00:16:29	02:04	Y
24	Grey car	00:14:42	00:15:54	01:12	Y

Table 9: Search Times at Den Burg Parking Lot from Video 2

3.4.3 Garages with One Entrance

This example problem illustrates how the proposed LOS procedure can be applied to a garage with one entrance. The Schuster parking garage on the UTEP campus was selected as the study site. This five-level garage has an asymmetrical trapezoidal footprint with a capacity of 700 parking spaces. There are two entrances/exits (one in level one facing west and one in level two facing east) but the east entrance at level two is always closed. The access control systems are located on the driveways, at mid-point between the access roads and the garage's entrances. Parking spaces are arranged as 90-degree stalls on both sides of two-way aisles along the four edges. At the center of the garage are two-way ramps, with 90-degree parking spaces on both sides, connecting two levels. The plan view of the garage is shown in Figure 3.

North is pointing to the left-top corner

Figure 3: Plan View of Schuster Garage

The test vehicle method was applied to measure search time at this garage. The Schuster garage was divided into 22 parking modules ($m = 22$). Field work was performed on August 3, 2020, from 1:00 p.m. to 4:00 p.m. to measure search times $t_s, s = 1, 2, 3, \dots, m$. The measured search times are presented in Table 9.

Space no., s	Level	Module	Search time, t_s (mm:ss)
1	1	1-NORTH	0:48
2	1	1-SOUTH	0:28
3	Ramp between levels 1 & 2	1-2-RAMP	0:24
4	2	2-EAST	0:36
5	2	2-NORTH	0:50
6	2	2-WEST	0:52
7	2	2-SOUTH	1:04
8	Ramp between levels 2 & 3	2-3-RAMP	1:02
9	3	3-EAST	1:26
10	3	3-NORTH	1:32
11	3	3-WEST	1:59
12	3	3-SOUTH	2:18
13	Ramp between levels 3 & 4	3-4-RAMP	1:37
14	4	4-EAST	2:10
15	4	4-NORTH	2:15
16	4	4-WEST	2:25
17	4	4-SOUTH	2:30
18	Ramp between levels 4 & 5	4-5-RAMP	2:27
19	5	5-EAST	2:34
20	5	5-NORTH	2:33
21	5	5-WEST	3:13
22	5	5-SOUTH	2:54

Table 10: Search Times at Schuster Garage

The LOS for a multistory parking garage may be analyzed in several ways. The LOS may be calculated for the entire garage or individual levels. The LOS for individual levels is of interest if a user has a preference to park at a certain level or a level is designated for a certain type of permit. Based on the search times in Table 10, the LOS was determined as in Table 11. The LOS for a level only included the parking spaces which belong to the modules at that level. It did not include the parking spaces along the connecting ramps.

Area of garage	Median search time (mm:ss)	LOS
Entire garage	1:48	A

Level 1	0:38	A
Level 2	0:51	A
Level 3	1:45	A
Level 4	2:20	B
Level 5	2:44	B

Table 11: Levels of Service at Schuster Garage

The median search times for the entire garage, and at levels 1 to 3 were determined to be LOS A, while the median search times that lead to levels 4 and 5 were LOS B. The higher levels had worse LOS simply because of the time it took to go around the ramps and internal circulation aisles to reach the higher levels. The search times in Tables 10 and 11 were towards the optimistic values because during the data collection there were no vehicle and pedestrian obstructions in the garage. In normal day-to-day operations, there may be congestion at the entrance, pedestrians walking in the garage, and vehicles turning in and out of parking spaces, which may cause the search time to increase. The assumption of one search time measurement per module may not follow the actual distribution of available space to park. This assumption may be valid when the garage is almost full. When the facility is not fully occupied, users tend to park at locations that are convenient to them, such as near the elevator or walkway to the adjacent building. Therefore, whenever possible, the measurement of search time should be made when the garage is in operation. A garage may be filled up from the lower level to the upper level. The level-specific LOS in Table 11 may be used to evaluate the LOS as parking spaces are gradually filled up from the lowest to the highest levels.

4 Smart Garages: Performance Measurement Systems and Concept of Operations

4.1 Performance Measurement Systems for Smart Garages

4.1.1 Characteristics of Garages

Parking garages or simply garages are multi-story structures dedicated to parking. They are also known as multi-story carparks in other countries. The construction of garages, instead of open surface parking lots, arises from the need to accommodate the increased parking demand or building code requirement in the same area of the footprint.

A typical garage has one entrance, one exit, and ramps that connect between the floors. The ramps are also called inter-floor travel systems. Parking spaces are laid out on the respective floors. Certain ramp designs allow for parking spaces to be placed on either or both sides of the ramps. There are many combinations of ramp-floor systems and aisle-space layouts (Roess et al, 2019; Kimley-Horn 2008). Some garages are designed at the basement of a building while other garages are independent structures but have connected walkways on selected floors to access the adjacent facilities they serve.

The simplest form of garage is just the structure with markings for parking spaces. This kind of garage is open for anyone to park. Payment, if it is not free, is based on an honor system. The garage owner also provides a minimal level of security. This type of self-service, park-at-your-own-risk garage may be found in shopping malls in suburban areas. For demand and revenue management purposes, garage owners usually implement access and egress control systems at the entrance and exit respectively. Revenue control systems (manual, semi-automated, or fully automated payment systems) may also be added. These types of garages are known in this report as *conventional garages*. In conventional garages, drivers who have gained access to the facility search for a parking space on their own.

A major challenge of conventional garage operation is the search time for parking spaces. In a garage, drivers prefer to park next to the elevators or access points to the adjacent buildings, for convenience. It is for these reasons that the lower floors of garages tend to be filled first. Late comers will need to go around from the entrance, floor by floor until a desired empty parking space is found. Therefore, the search time of a garage with parking spaces available on the first-come-first-serve basis increases with the garage's occupancy. The worst scenario happens when the occupancy reaches 100%. That is, a driver circles from the lowest to the highest level and found out that there is no space left. To go out to look for an alternative facility to park, the driver must drive the vehicle from the highest level of the garage to the exit point. Driving in a garage takes a longer time than driving in an open surface lot because the aisles are narrower, the radius of turns is smaller and the driver's sight distance is shorter because of the obstructions caused by the structural elements.

4.1.2 Smart Garages

Smart garages are garages equipped with ITS technologies to improve their service to customers. The emerging trends have been to use technologies to help to improve access control and payment, and to locate parking spaces (IPMI, 2018).

The most advanced form of smart garage is Fully Automated Garage (FAG), also known as Automated Parking Systems (Car and Driver, 2020). This kind of garage is similar to the Automated Storage-Retrieval Systems (ASRS) in warehouses. In a FAG, a driver only needs to leave his/her vehicle at a designated drop-off area. The robotic mechanism of the FAG will move the vehicle to a storage location. Because the driver does not drive around to search for space, there is practically no search time.

4.1.3 Performance Measures for Garages

The performance measures of a garage may be evaluated by a metric as shown in Table 1. This metric applies to conventional as well as smart garages, and for users and owners. Some of the performance indicators are static, meaning that once a garage has been designed and built, the measure's qualitative or quantitative values do not vary from day to day. The dynamic indicators are the ones which measured values vary by the hour. The values of dynamic indicators can be improved by converting a conventional garage into a smart garage. Such improvements are evaluated by a PMS. As mentioned in Section 2, a PMS collects, integrates, analyzes data, and determines quantitative and qualitative performance measures.

4.2 Concept of Operations for Smart Garages PMS

A Concept of Operations (ConOps) is a document that describes a proposed system from the end users' perspective. It communicates the functional features of an integrated system to the users and stakeholders (IEEE, 1998).

4.2.1 Functional Description

It has been stated that the benefit of converting a conventional garage into a smart garage is to improve the dynamic performance indicators: occupancy and search time. Other dynamic measures that are related to the revenue depend on and may be derived from occupancy.

Occupancy is measured by (1) counting how many vehicles are in the garage at any time (by comparing the number of vehicle entries and exits) and then divide this by the total number of spaces in the garage; or (2) counting the number of parking spaces that are occupied and then divide this by the total number of spaces. This dimensionless ratio is also known as the occupancy ratio.

Search time may be measured by tracking a vehicle, a user, or a smartphone from the time it enters the garage until it is parked in a space. To measure an individual vehicle's (or user's) search time, the PMS must be able to identify and match the same vehicle, user, or smartphone between the garage's entrance and the space it is parked.

4.2.2 Operational Description

The PMS of a smart garage consists of the following components:

- *Sensors*. The purpose of the *sensors* is to detect the presence of vehicles in the garage to estimate the garage's occupancy in real-time. Sensors may be instrumented at the entrance, exit, strategic locations along a driveway or an aisle, or every parking space.
- *Computer server*. A computer server houses a database that stores all the individual transaction records, and the smart garage's management software that monitors the occupancy ratio, median search time in real-time, makes decisions to guide drivers, and determines the information to disseminate via *DMSs* and *mobile applications*. The computer server also includes a terminal/console that interfaces with the smart garage's *operations manager*. The *computer server* is also linked to other garage systems such as access control, revenue management, and security monitoring systems.
- *DMSs*. The function of the *DMSs* is to communicate the guidance messages to the driver.
- *Mobile application*. A mobile application in a user's smartphone enables the user to make queries and requests to, and display messages received from the *computer server*.
- *Communication*. All of the above components must be linked by communication lines or channels to form an integrated system. The directional data flows are represented in Figure 4. Different data links in the system may use different communication technologies, such as copper wire, fiber optic, Dedicated Short Range Communication (DSRC), 4G LTE, or wireless Internet.

There are two types of users (actors) of a smart garage PMS:

- *Drivers*. *Drivers* are customers of the system. A garage usually has two types of drivers: (1) long-term parkers or season pass holders; and (2) short-term users who pay by the duration they park. Short-term users are occasional visitors who are not familiar with the garage and whom the smart parking PMS should be designed for. Long-term parkers are daily users who have reserved areas or spaces. However, they can still benefit from certain features of the smart garage PMS. A *driver* may communicate with the *computer server* via the *mobile application*. A *driver* may also receive messages or parking guidance instructions from *DMSs*. The communications between the *driver* and the *computer server* are two-way while that between the drivers and the *DMSs* is only one-way.
- *Operations manager*. The operations manager is the person responsible for the day-to-day operations of the smart garage.

Figure 4 illustrates a smart garage's PMS components, the actors, and their linkages. In this figure, a one-way arrow indicates that the communication is one-way in the direction of the arrow, while a two-way arrow represents two-way communications.

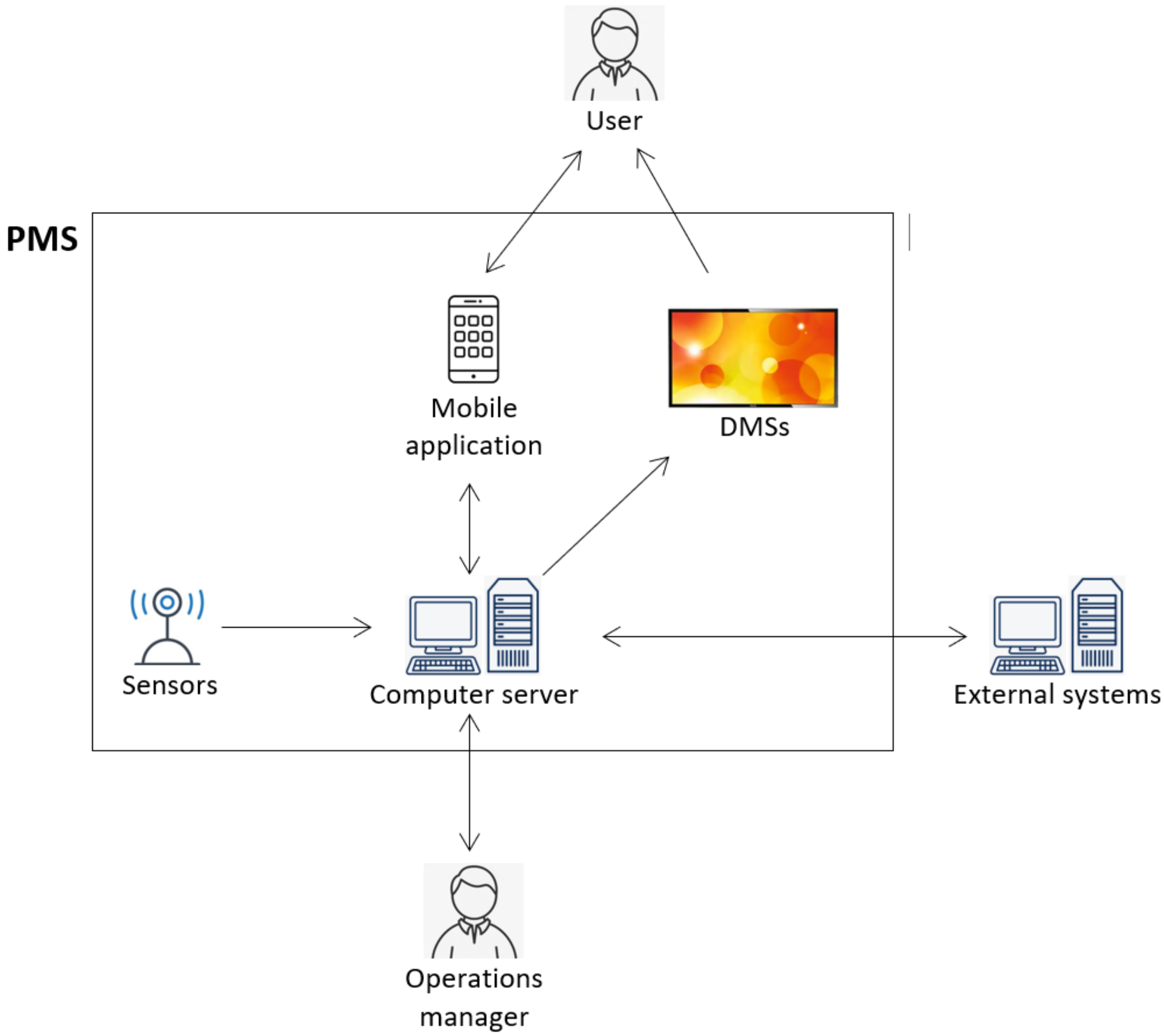

Figure 4: Level 0 Diagram of a Smart Garage Performance Measurement System

Figure 5 shows the use case from a driver's perspective. A use case is a methodology used to identify, clarify, and organize the services provided by the system. A use case diagram depicts the services provided by a system by identifying the actors and services requested by these actors (Alexander and Zink, 2003). This figure shows that the *driver* interacts with a smart parking PMS through a *mobile application*. He/she can:

- Make a query on the availability of parking space at a specific time of interest.
- Make a reservation for a particular space.
- Pay a parking fee (this *computer server* merely serves as the gateway; the processing of financial transactions takes place in an external, secured payment system).
- Make incident reports (such as a reserved space taken by someone else, suspicious activity).

The driver can also receive parking guidance information via the *mobile application* and *DMSs.*

A *driver* (short-term user) typically interacts with the smart garage PMS as described below:

- Before the driver begins his/her trip to the garage, he/she uses his/her *mobile application* to check the availability (number) of parking spaces for a given period and the cost of parking in the garage.
- The *computer server* receives the queries and returns the information.
- The *driver* requests to reserve a space for a specific period.
- The *computer server* returns with a list of available spaces and their respective costs.
- The driver *selects* his/her space and proceeds to authorize the payment of a deposit.
- The *computer server* sends a digital parking pass to the *mobile application*.
- When the *driver* is approaching the entrance of the garage, the *computer server* reminds the driver on his/her *mobile application* of the location and time of the reserved space.
- At the entrance of the garage, the *driver* lets the access control system scan the digital parking pass on the screen of his/her smartphone and gain entry to the garage.
- The *computer server* sends a welcome message and the reserved space information on the *DMSs* located at the entrance and on each floor to guide the *driver*.
- The *driver* proceeds to the reserved space and parks his/her vehicle.
- The *sensor* in the parking space detects the presence of the vehicle and notifies the *computer server* which in turn sends a confirmation message to the *mobile application*.
- Near and before the expiration of the paid parking time, the *computer server* sends an expiration notice to the *mobile application* with an option to extend the time and add payment.
- The *driver* moves his/her parked vehicle out of the space.
- The *sensor* detects that the space is no longer occupied and notifies the *computer server*.
- At the exit of the garage, the *driver* lets the exit control system scan the digital parking pass on the screen of the smartphone.
- The *computer server* calculates the fee and sends a confirmation message to the *mobile application*.
- The *driver* confirms the transaction amount.
- The *computer server* instructs the payment system to proceed with the transaction.

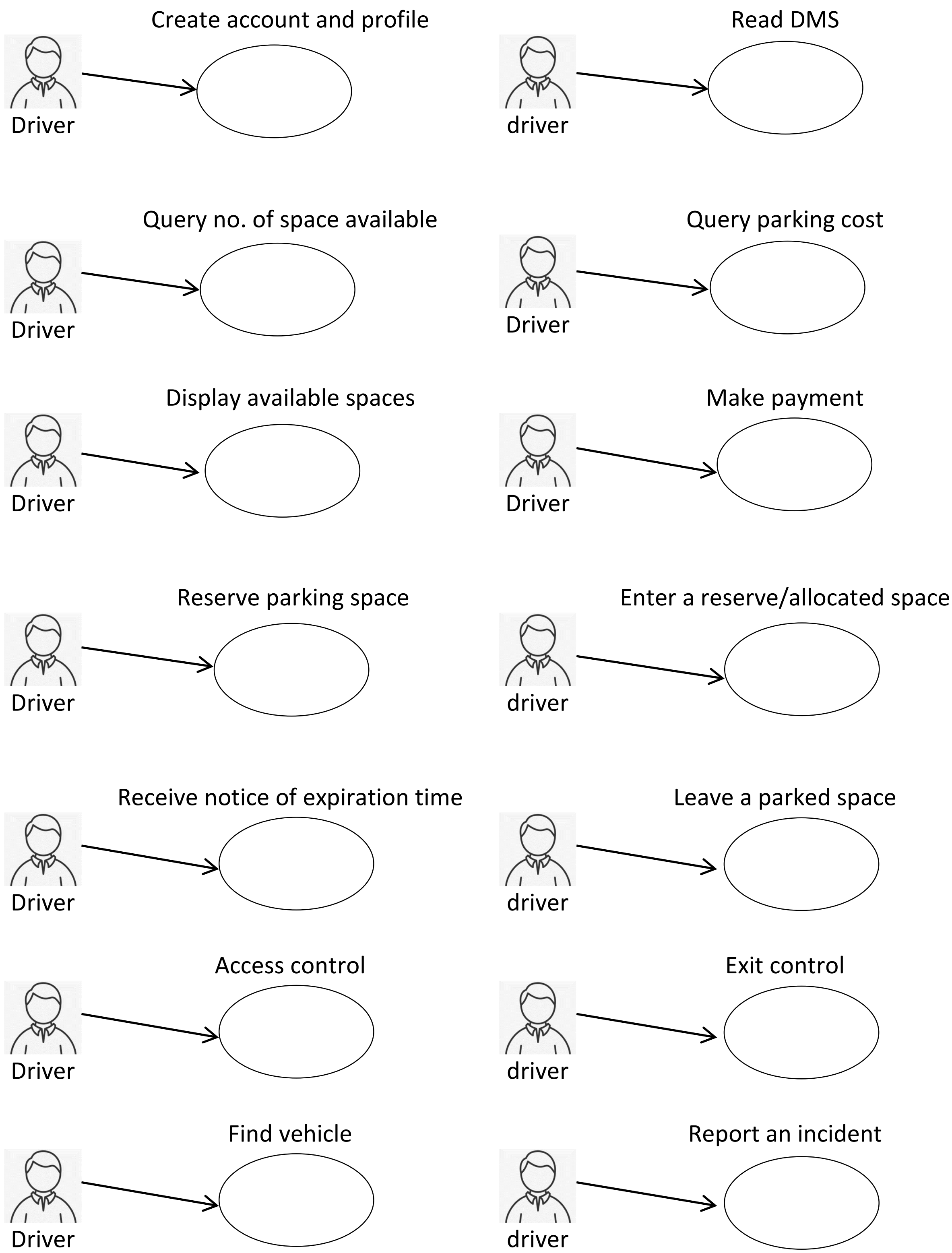

Figure 5: Use Case Diagram for a Smart Garage Performance Measurement System

4.2.3 Alignment with National ITS Architecture

An architecture is a framework that defines the functions of a system and how the components of the systems exchange information. An architecture is a functional specification and not a product or technology-specific specification. It provides the system designers the flexibility to mix and match components that are compatible as long as they deliver the prescribed functions. The Intelligent Transportation Systems (ITS) architecture, as its name suggests, defines certain ITS services and the functions of different components that may be put together to deliver a service.

The U.S. National ITS Architecture provides a consistent framework to guide engineers in the design and deployment of ITS services (USDOT, 2019). The U.S. National ITS Architecture divides an ITS system into four sub-systems and the communication links between them. The sub-systems and the communications between them are typically laid out in a figure following the format of Figure 6. This figure shows the layout and the connections of sub-systems for a smart garage PMS.

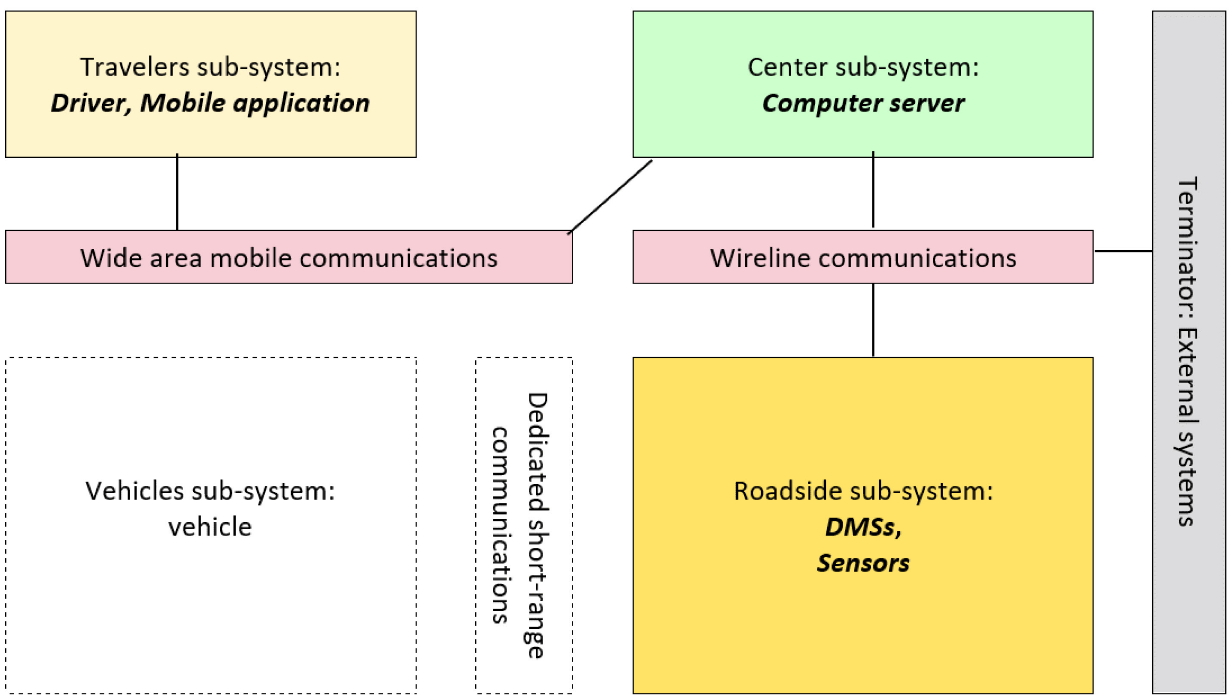

Figure 6: Architecture of a Smart Garage Performance Measurement System

The U.S. National ITS Architecture also defines Service Packages. A service package is a collection of several physical components of sub-systems and the data flow between them to deliver a specific ITS service. Six service packages have been defined under the functional area of Parking Management (PM). The following three packages are directly related to a smart garage PMS:

- PM01: Parking Space Management
- PM03: Parking Electronic Payment
- PM05: Parking Reservations

PM01 Parking Space Management has the potential to improve the garage's turnover ratio and occupancy ratio. PM03 Parking Electronic Payment impacts revenue and its related performance measures. PM05 Parking Reservations is expected to reduce search time.

4.3 Estimation of Benefits of Smart Garages

The purpose of this subsection was to estimate the reduction in search time that comes with the smart parking PMS. This experiment used the Schuster Garage, a conventional garage on the UTEP campus as the test site. An experiment was performed to measure the search time at 22 selected parking spaces. The measurements of the search times before converting this garage from a conventional garage into a smart garage have been reported in Example Problem 3 in Section 3.

This experiment followed up by collecting search times assuming that the Schuster Garage has been upgraded to a smart garage. This experiment was performed on September 27, 2020, from 9:00 a.m. to 11:00 a.m. The same driver who implemented the test vehicle method earlier repeated the runs to capture the travel times from the garage's entrance to the same 22 spaces. The difference from the previous experiment was this time the driver knew exactly the locations of the spaces to park.

The assumptions that dictated the driver's behavior, and how they were implemented are listed herein:

- In the smart garage, the driver was paired with a specific available space by the mobile application. To replicate this, the driver was told the specific spots by the accompanying researcher.
- The driver took the shortest route from the garage's entrance to the assigned space either via familiarity with the garage's internal circulation system or through instructions from the mobile application. To replicate this, the driver was informed of the level and location within the structure (cardinal direction) of each assigned space.
- The space would be indicated to the driver via DMSs and graphical display on a smartphone screen via the smart parking application. This was replicated by two timekeepers standing adjacent to each assigned parking space and directed the driver to park there.

Table 12 compares the search times measured in the conventional garage setting and the assumed smart garage setting. It can be observed that, as expected, the search times all reduced from the conventional garage to the smart garage. The average improvement was 22.38 seconds per space.

To the drivers, this difference corresponds to an average reduction in search time of 22.38 seconds per transaction. Assuming that the Values-of-Time (VoTs) is $0.137/minute for students (Gurbuz, 2019) and $0.183/minute for other adults (USDOT, 2016), the time saving of 22.38 seconds is equivalent to $0.051 and $0.070, respectively. This also means that each student and other adults may be willing to pay up to $0.051 and $0.070 respectively per transaction.

Among the performance measures for owners is revenue per year, revenue per transaction, and revenue per space (see Table 2). The following assumptions were made to calculate these revenue related performance measures:

- The garage had 700 parking spaces.
- Its turnover ratio was 1.767.
- The occupancy ratio was 95%.
- The owner charges an additional parking fee to recover the cost of upgrading the garage to a smart garage.
- Each student used the garage for 32 weeks per year at four days per week.
- If the garage is located in an office district, the offices are open for business 50 weeks per year at five days per week.

Based on the above assumptions, the following performance measures have been calculated:

- Garage in a university campus for students:
    - Additional revenue per year: $7,670
    - Additional revenue per transaction: $0.051
    - Additional revenue per space per year: $10.96
- Garage in an office district:
    - Additional revenue per year: $20,563
    - Additional revenue per transaction: $0.070
    - Additional revenue per space: $29.38

Space no., *s*	Level	Edge	Experiment 1 Search time (mm:ss)	Experiment 2 Search time (mm:ss)	Difference (seconds)
1	1	1-NORTH	0:48	0:43	0:05
2	1	1-SOUTH	0:28	0:21	0:07
3	Ramp between levels 1 & 2	1-2-RAMP	0:24	0:21	0:03
4	2	2-EAST	0:36	0:30	0:06
5	2	2-NORTH	0:50	0:44	0:06
6	2	2-WEST	0:52	0:48	0:04
7	2	2-SOUTH	1:04	0:40	0:24
8	Ramp between levels 2 & 3	2-3-RAMP	1:02	0:54	0:08
9	3	3-EAST	1:26	1:04	0:22
10	3	3-NORTH	1:32	1:19	0:13
11	3	3-WEST	1:59	1:25	0:34
12	3	3-SOUTH	2:18	1:13	1:05
13	Ramp between levels 3 & 4	3-4-RAMP	1:37	1:29	0:08
14	4	4-EAST	2:10	1:38	0:32
15	4	4-NORTH	2:15	1:51	0:24
16	4	4-WEST	2:25	1:55	0:30
17	4	4-SOUTH	2:30	1:40	0:50
18	Ramp between levels 4 & 5	4-5-RAMP	2:27	1:57	0:30
19	5	5-EAST	2:34	2:06	0:28
20	5	5-NORTH	2:33	2:12	0:21
21	5	5-WEST	3:13	2:31	0:42
22	5	5-SOUTH	2:54	2:18	0:36

Table 12: Search Times at Schuster Garage with Performance Measurement System

5 Smart On-Street Parking: Performance Measurement Systems and Concept of Operations

5.1 Performance Measures for On-Street Parking

5.1.1 Challenges of On-Street Parking

On-street parking is usually managed by the city or its appointed agent. Unlike off-street parking lots and garages which have limited access points, every parking space on the street is open to passing traffic. Parkers can move their vehicles in and out of any space directly from/to an adjacent travel lane. These open access facilities have given rise to challenges in access and revenue controls, and the measurement of parking search time.

5.1.2 Smart On-Street Parking

An SOSP system makes use of a PMS to implement policies and monitor performance measures. One of the policies is to use parking fees to manage the parking demand to achieve the desired occupancy ratio, and hence the desired LOS. The most basic form of collecting occupancy data is by manual surveys. Alternatively, different levels of ITS technology may be implemented in a PMS to automate the fees and occupancy data collection processes. In this report, the authors proposed six levels of PMS for on-street parking. The six levels are distinguished by access control, method of payment, verification, and enforcement. They also facilitate the implementation of a variety of fee structures and the dissemination of real-time parking space information. The six levels are named by the modes of the payment transaction and occupancy data collection:

- **Level 0: No PMS.** Free parking, no demand control, and no revenue collection.
- **Level 1: Zone-Based PMS.** Parking fees are charged by zone. Parking fees are collected via vending machines or by attendants. Payment is enforced by attendants.
- **Level 2: Meter-Based PMS.** Parking fees are collected via parking meters (by cash or credit card). This enables space-specific transaction data to be collected. Payment is enforced by attendants.
- **Level 3: Hybrid Meter-App-Based PMS.** Parking fees are still collected via meters, but the modes of payment include a mobile application. Selected parking spaces may have sensors to randomly verify occupancy and payments. Occupancy is monitored by integrating data in the meter as well as the mobile applications. Payment is enforced by attendants.
- **Level 4: App-Based PMS.** Parking meters are no longer in use. All payments are made via a mobile application. All the parking spaces have sensors to verify and enforce payments. Occupancy is monitored by the applications and sensors. Payment may be enforced by attendants.
- **Level 5: Smart On-Street Parking (SOSP) PMS.** This includes all features of Level 4 parking plus dynamic pricing and parking space reservation. Parking fees vary by zone or space. Each space

available for reservation may be instrumented with mechanical access control. This level of SOSP will be covered in Subsection 5.2.

Table 13 compares the six levels of PMS for on-street parking.

Level	Name	Access control	Method of payment	Verification & enforcement	Fee structure	Real-time space info.
0	No PMS	No	None	None	None	None
1	Zone-based PMS	No	By vending machine, pre-paid coupon, attendant	Attendants	Fixed rate, by zone	None
2	Meter-based PMS	No	By meter (cash or credit card)	Attendants	Fixed rate, by space	None
3	Hybrid Meter-App-Based PMS	No	By meter or smartphone application	Attendants, limited sensors	Fixed rate, by space	Limited
4	App-Based PMS	No	By smartphone application	100% sensors	Fixed rate, by space	Smartphone application
5	SOSP PMS	Yes	By smartphone application	100% sensors	Dynamic, by space	Smartphone application

Table 13: Levels of Smart On-Street Parking Performance Measurement System

5.1.3 Performance Measures for On-Street Parking

The level of congestion of on-street parking spaces is measured by the occupancy ratio, Ω. It is the fraction of available parking spaces or space-time in a zone that is occupied by vehicles. A zone may be one or several blocks. A few cities have on-street parking policies aiming to achieve an occupancy ratio of 0.85 (SFPark, 2020; SDOT 2019). An occupancy ratio lower than 0.85 implies that the spaces in the zone are underutilized. On the other hand, an occupancy ratio higher than 0.85 leads to a longer search time.

Since on-street parking search time is difficult to measure objectively, a feasible alternative is therefore to measure a parking zone's occupancy ratio Ω, and use Equations (1), (2), or (3) to estimate the average parking search time T. Once T has been obtained, the LOS criteria may be applied to map T into LOS A to F for on-street parking. This LOS analysis procedure assumes that the parameter values for $\alpha, \beta, \gamma, \varphi, \rho, \theta$ in Equations (1), (2) or (3) are still valid. Table 14 shows the availability of occupancy data to compute occupancy ratio Ω for different levels of PMS for on-street parking. Levels 2 and 3 of PMSs for on-street parking can do so if the parking meters are connected to the PMS and the payment transaction data are used to derive occupancy. Levels 4 and 5 of PMS for on-street parking are fully instrumented with vehicle sensors to directly measure occupancy in real-time.

Level	Name	Space occupancy	Ω , occupancy ratio
0	No PMS	No	No
1	Zone-Based PMS	No	Possible, from vending machine data, not in real-time
2	Meter-Based PMS	Yes, if the meter has time stamps	Yes, if the meter has time stamps
3	Hybrid Meter-App-Based PMS	Yes, if the meter has time stamps	Yes, if the meter has time stamps
4	App-Based PMS	Yes	Yes
5	SOSP PMS	Yes	Yes

Table 14: Occupancy Data for On-Street Parking Performance Measurement System

5.2 Concept of Operations for Smart On-Street Parking PMS

This section describes the ConOps for a Level 5 SOSP PMS.

5.2.1 Functional Requirements

A Level 5 SOSP PMS needs to provide to the management, among other functions, to:

- Monitor the occupancy of every parking space in real-time.
- Collect parking fees.
- Hold a parking space that has been reserved by a driver.
- Verify the identity of a vehicle that is parking in a reserved space with a reservation record.
- Verify that a vehicle parking in a space has made payment.
- Automatically set or change the parking fees for dynamic pricing.
- Maintain records of violations (e.g., did not pay the fee, occupied space reserved by another driver).

A Level 5 SOSP PMS should have the capability for drivers to:

- Create an account and set up a driver profile.
- Query the available parking spaces and fees.
- Pay parking fee (by connecting to an external payment system).
- Reserve a parking space.
- Receive route guidance to a parking space.

- Report an incident.
- Gain access to a rightfully reserved space.
- Extend the parking duration and top up the payment.

5.2.2 Operational Description

To implement the above functions, a Level 5 SOSP PMS should have the following components:

- *Sensors*. Every parking space should be instrumented with a vehicle *sensor*. The purpose of the *sensor* is to detect the presence of a vehicle in a parking space in real-time so that the SOSP system can verify if the occupant has paid or is committed to pay the parking fee, or if a space that has been reserved by a driver has been taken by another driver. The readings from multiple sensors in a zone at any time may be aggregated to form the zone's occupancy ratio Ω.
- *DMSs*. Every parking space should be equipped with a small screen *DMS*. The *DMS* may display messages or icons to indicate if the space is "available", "reserved", "paid", "fee expired", "violation", etc.
- *Computer server*. A computer server houses a database that stores all the driver accounts, transaction records, and violation records. It also houses the PMS's software that monitors the occupancy in real-time, guides drivers, and disseminates information via the *mobile application*. The *computer server* also includes a terminal/console that interfaces with the *operations manager*. The *computer server* is also linked to other sub-systems such as enforcement, access control, revenue (payment) management, and security monitoring systems.
- *Mobile application*. A *mobile application*, when installed in a driver's smartphone, enables the driver to make queries, and displays messages received from the *computer server*. The *mobile application* also allows the owner to report incidents to and perform financial transactions via the *computer server*.
- *Communication*. All of the above components must be linked by communication lines or channels to form an integrated system. The directional data flows are represented in Figure 7.

There are two types of actors in a Level 5 SOSP PMS: *Drivers* and *Operations managers*. Figure 7 illustrates SOSP system components, the actors, and their linkages.

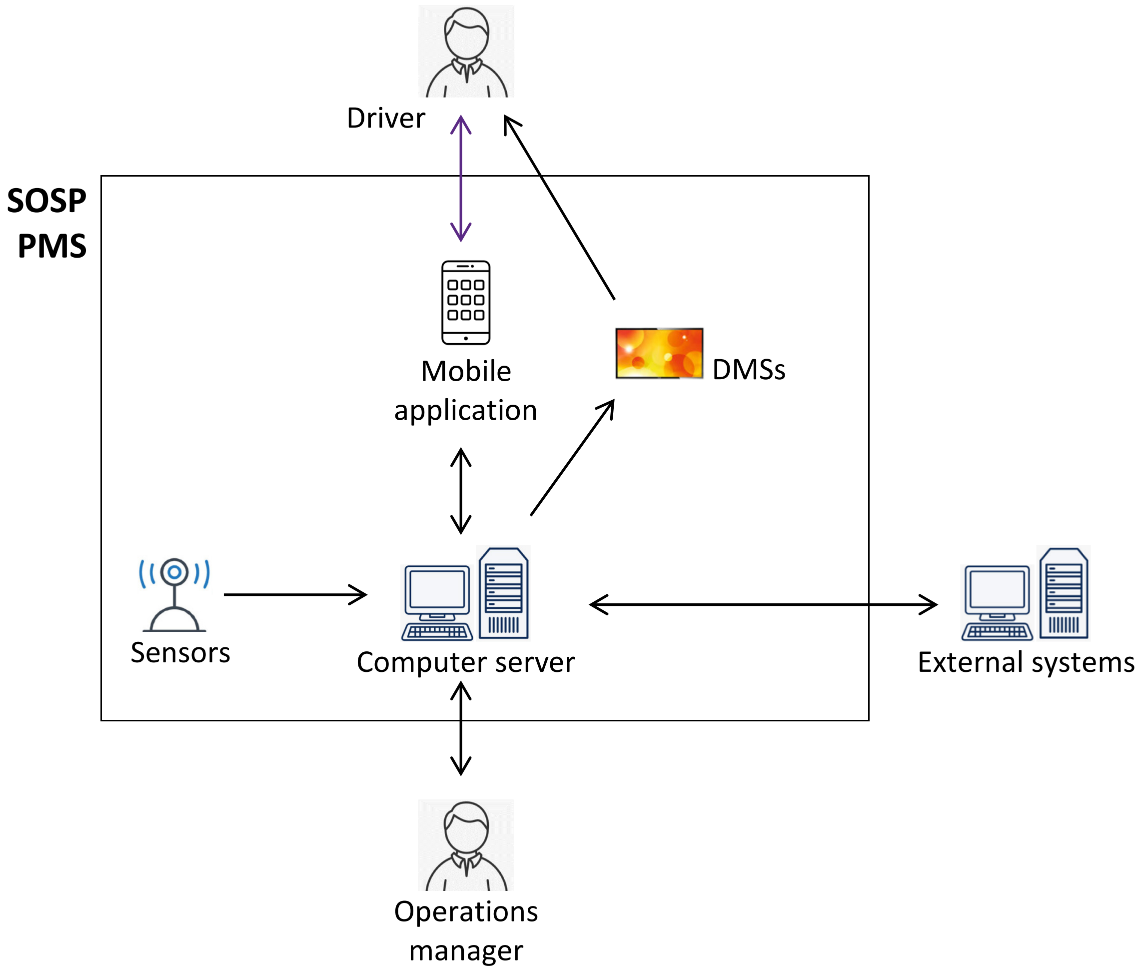

Figure 7: Level 0 Diagram of a Smart On-Street Parking Performance Measurement System

Figure 8 shows the use case of a Level 5 SOSP PMS. A *driver* (short-term user) typically interacts with the SOSP system as described below:

- The driver uses his/her *mobile application* to check the availability (number and locations) of parking spaces for a given period and the costs of parking.
- The *computer server* receives the queries and returns the information.
- The *driver* requests to reserve a space for a specific period.
- The *computer server* checks its database and returns with a list of available spaces and their respective fees.
- The *driver* selects his/her space and proceeds to authorize the payment of the deposit.
- The *computer server* proceeds with the financial transaction (with an external revenue management system) and sends an digital parking pass to the *mobile application*.
- The *computer server* updates the status on the *DMS* associated with the reserved space.

- When the *driver* is approaching the zone, he/she is reminded via the *mobile application* of the location and time of the reserved space.
- The *driver* turns on the route guidance function of the *mobile application* and lets it lead the *driver* to the reserved parking space.
- When the *driver* has reached the reserved space, the *mobile application* automatically sends a message to the *computer server* to request access to the parking space.
- The *computer server* checks the identity of the *driver*, returns an approved message to the *mobile application,* and proceeds to allow the *driver* to park.
- The *driver* proceeds to park his/her vehicle.
- The *sensor* detects the presence of a vehicle in the space and notifies the *computer server* which in turn sends a confirmation message to the *mobile application*.
- The *computer server* updates the status on the *DMS* of the parking space.
- Near and before the expiration of the paid parking time, the *computer server* sends an expiration notice to the *mobile application* with an option to extend the time and add payment.
- The *driver* moves his/her parked vehicle out of the space.
- The *sensor* detects that the space is no longer occupied and notifies the *computer server*.
- The *computer server* updates the status on the *DMS*.
- The *computer server* sends a confirmation message with an invoice of the parking fee to the *mobile application*.
- The *driver* uses the *mobile application* to authorize the payment.
- The *mobile application* then sends a message to the *computer server* which informs the ecternal revenue management system to proceed with the financial transaction.

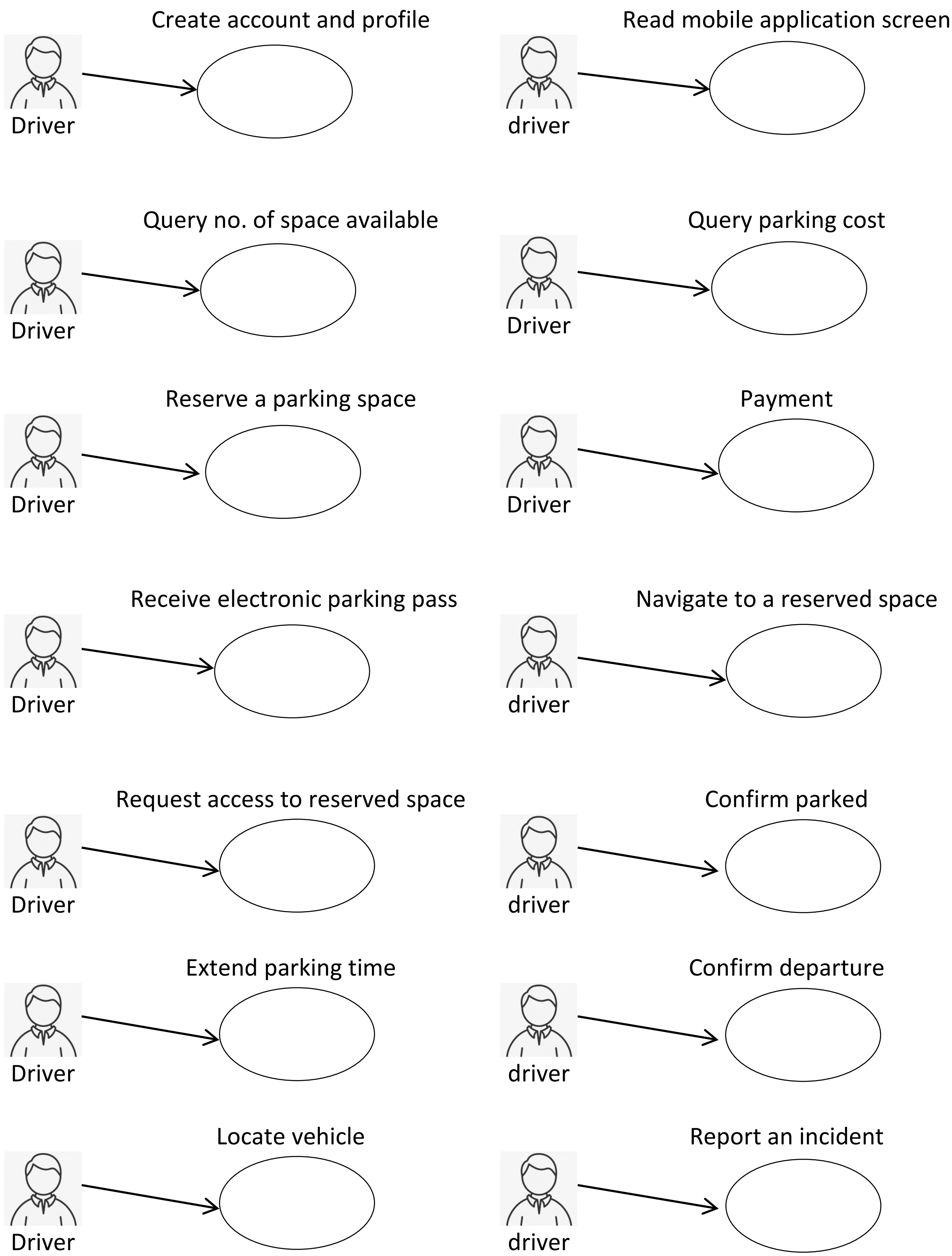

Figure 8: Use Case Diagram of a Smart On-Street Parking Performance Measurement System

5.2.3 Alignment with National ITS Architecture

The U.S. National ITS Architecture (USDOT, 2019) divides an ITS system into four sub-systems and the communication links between them. Figure 9 shows the layout and the connections of sub-systems for a Level 5 SOSP system.

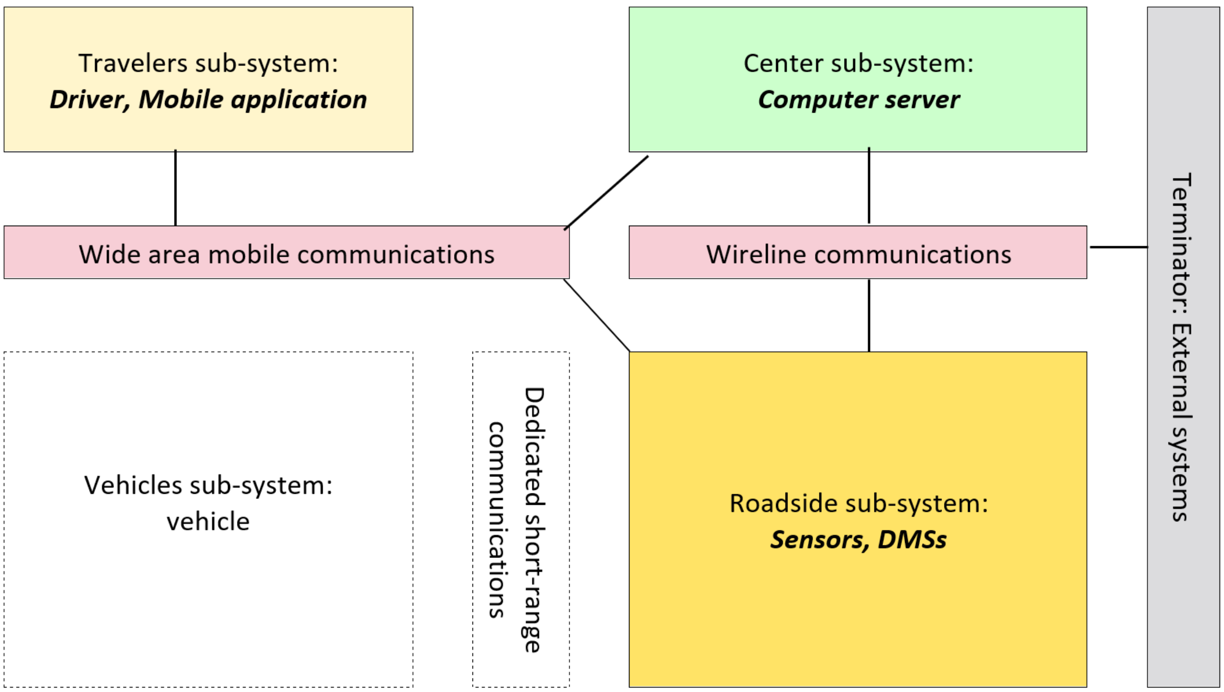

Figure 9: Architecture of a Smart On-Street Parking Performance Measurement System

The U.S. National ITS Architecture has defined six service packages under the functional area of Parking Management (PM). Five of these six service packages are directly related to a Level 5 SOSP PMS. PM01 Parking Space Management has the potential to improve the occupancy rate. PM03 Parking Electronic Payment impacts revenue and its related performance measures. PM04 Regional Parking Management analyzes the occupancy rate in a zone and adjusts the parking fees. PM05 Parking Reservations is expected to reduce search time. PM06 may be a special SOSP sub-system that has dedicated space for loading /unloading by commercial vehicles.

5.3 Estimating Level of Service for On-Street Parking

This section develops and demonstrates procedures to estimate the average search time and LOS for on-street parking. Two sites, namely Los Angeles, California, and El Paso, Texas, with different PMS data availabilities were used in the two example problems.

5.3.1 Level of Service Analysis Procedure for On-Street Parking

The proposed LOS analysis procedure for on-street parking first estimates a zone's occupancy ratio Ω and then uses Ω to estimate the search time T utilizing Equations (1), (2), or (3).

5.3.2 Example Problem 1: Los Angeles On-Street Parking Data

The first example problem used the parking data in the City of Los Angeles, California. The study site was along South Grand Avenue between West Pico Boulevard and West 8th Street. Figure 10 shows the location and layout of the site. South Grand Avenue was a one-way street with traffic running in the southbound direction. There were two travel lanes with parking spaces along the curbs on both sides. All the parking spaces were instrumented with sensors. Parking fees were managed by the LA Express Park system (LA Express Park, 2020). The LA Express Park may be considered as a Level 4 App-Based PMS.

The Los Angeles Department of Transportation (LADOT) publishes its LA Express Park PMS data on a public website (City of Los Angeles, 2020). Sensor data on March 2, 2020, for the 75 parking meters within this study site were downloaded. However, LADOT did not publish any payment transaction data. The downloaded data contained, for every parking space, the occupancy time at 15-minute intervals from 7:00 a.m. to 9:00 p.m. Table 15 shows, as an example, the occupancy time for seven parking spaces along South Grand Avenue between West Pico Boulevard and West 8th Street, from 7:00 a.m. to 12:00 p.m. The occupancy time ranged from 0 to 15 minutes. Although the seven parking spaces were in the same street block, the space-specific occupancy times were very different. In this analysis, a zone was defined as a street block on one side of the travel lanes. The 15-minute occupancy time data were aggregated into hourly occupancy ratios at the block level. Table 16 shows the computed hourly occupancy ratio $\Omega_{b,h}$ at block b at hour h. Equations (1) to (3) were modified to use $\Omega_{b,h}$ (dimensionless) as an input to calculate the corresponding average search time $T_{b,h}$ (in seconds):

$$T_{b,h} = \frac{26.1}{1-\Omega_{b,h}} \quad (4)$$

$$T_{b,h} = 0.307e^{7.407\Omega_{b,h}} \quad (5)$$

$$T_{b,h} = 6 + 19.2\Omega_{b,h} \quad (6)$$

The estimated search times $T_{b,h}$ and LOS are presented in Tables 16 and 17 respectively. Each cell in Tables 16 and 17 has three values separated by "/". They represent the $T_{b,h}$ calculated from Equations (4), (5), and (6) respectively, and the corresponding LOS.

Figure 10: Los Angeles On-Street Parking Study Site

S Grand Ave, Los Angeles
March 2, 2010

	Occupancy time (minutes)						
Parking space ID number	CB3587	CB3588	CB3591	CB3593	CB3592	CB3590	CB3586
7:00am– 7:15am	15	15	0	15	15	14	15
7:15am– 7:30am	15	15	1	15	15	15	15
7:30am– 7:45am	12	15	15	5	15	8	15
7:45am– 8:00am	15	15	15	0	15	7	15
8:00am– 8:15am	15	15	15	0	15	5	15
8:15am– 8:30am	15	15	8	0	15	11	15
8:30am– 8:45am	0	15	3	0	15	2	15
8:45am– 9:00am	3	15	2	0	15	0	15
9:00am– 9:15am	14	14	0	0	15	0	15
9:15am– 9:30am	10	15	0	0	15	0	15
9:30am– 9:45am	15	8	7	0	15	0	15
9:45am– 10:00am	11	7	15	0	15	0	15
10:00am– 10:15am	7	4	13	0	15	2	15
10:15am– 10:30am	3	7	15	0	9	0	15
10:30am– 10:45am	0	14	15	3	9	6	15
10:45am– 11:00am	0	14	15	0	15	2	15

Table 15: On-Street Parking Occupancy Time by Space at Los Angeles Site

S Grand Ave, Los Angeles March 2, 2010	Parking search time $T_{b,h}$ (seconds)				
Block number	800-899	900-999	1000-1099	1100-1199	1200-1299
Upstream cross street	W 8th St	W 9th St	W Olympic Blvd	W 11th St	W 12th St
Downstream cross street	W 9th St	W Olympic Blvd	W 11th St	W 12th St	W Pico Blvd
No. of parking spaces	8	2	11	14	14
7am-8am	124/107/25	26/0/0	31/1/5	77/41/21	82/47/22
8am-9am	45/7/14	30/1/4	41/4/11	79/44/22	62/23/19
9am-10am	43/6/13	30/1/4	42/5/12	69/30/20	77/41/21
10am-11am	54/14/17	64/24/19	51/12/16	57/17/17	61/21/18
11am-12pm	100/74/24	97/68/23	65/26/19	62/23/19	73/35/21
12pm-1pm	145/133/26	43/6/13	58/18/18	84/51/22	58/18/18
1pm-2pm	154/144/27	65/26/19	64/24/19	100/74/24	43/6/13
2pm-3pm	119/99/25	62/23/19	58/18/18	97/68/23	53/13/16
3pm-4pm	56/16/17	51/12/16	67/28/19	54/14/17	53/13/16
4pm-5pm	43/6/13	∞[#]/506/32	61/21/18	57/17/17	52/12/16
5pm-6pm	52/12/16	100/74/24	61/21/18	71/33/20	75/38/21
6pm-7pm	201/193/28	57/17/17	124/107/25	201/193/28	84/51/22

In Equation (1), search time approaches infinity when occupancy ratio approaches 1.0.

Table 16: On-Street Parking Hourly Search Time by Block at Los Angeles Site

S Grand Ave, Los Angeles March 2, 2010	Parking LOS				
Block number	800-899	900-999	1000-1099	1100-1199	1200-1299
Upstream cross street	W 8th St	W 9th St	W Olympic Blvd	W 11th St	W 12th St
Downstream cross street	W 9th St	W Olympic Blvd	W 11th St	W 12th St	W Pico Blvd
No. of parking spaces	8	2	11	14	14
7am-8am	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
8am-9am	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
9am-10am	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
10am-11am	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
11am-12pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
12pm-1pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
1pm-2pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
2pm-3pm	B/A/A	A/A/A	A/A/A	A/A/A	A/A/A
3pm-4pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
4pm-5pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
5pm-6pm	A/A/A	F/D/A	A/A/A	A/A/A	A/A/A
6pm-7pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A

Table 17: On-Street Parking Hourly Level of Service by Block at Los Angeles Site

5.3.3 Example Problem 2: El Paso On-Street Parking Data

The second case study used the parking data in the City of El Paso, Texas. The system deployed in the City of El Paso belonged to Level 3 Hybrid-Meter-App-Based PMS. The study site in the City of El Paso was along Texas Avenue, between North Oregon Street and Ange Street. Texas Avenue was a two-way street with one travel lane in each direction. Figure 8 shows the location and layout of the site, with parking spaces of interest. This analysis assumed that a parking zone was a street block.

The parking data of the site was provided by the City of El Paso's International Bridges Department. This department was responsible for the management of parking meters in the City of El Paso. The provided data included anonymized payment transaction records (by cash, credit card, or smart card at the parking meters, or the Park915 mobile application) at all the paid spaces. The data were provided hourly, between January 1 to December 31, 2019. The City of El Paso charged a fixed parking rate of $0.25 for every 15 minutes, between 8:00 a.m. to 6:00 p.m. from Monday to Saturday. The calculation of LOS could only be made when fees were being collected. In this example problem, the hourly LOS were estimated between

8:00 a.m. to 6:00 p.m. from Monday to Friday. The data on Saturday was not used because most of the downtown offices were closed.

Table 18 shows part of the payment transaction data. These are the hourly transaction payments on July 3, 2019 (Wednesday) at the parking space with identification number 32746. On this day, this parking space was used every hour between 8:00 a.m. to 5:00 p.m. Most of the users paid by cash at $0.25 for every 15 minutes. Payment by credit card carries an additional $0.03 transaction fee. Assuming that every parker paid exactly according to the duration they parked, the hourly transaction records were converted into hourly occupancy ratio $\Omega_{s,h,d}$. The subscript s, was added to denote a particular space, while h and d denoted hour and day-of-the-week respectively The computed hourly occupancy ratios are shown in Table 19.

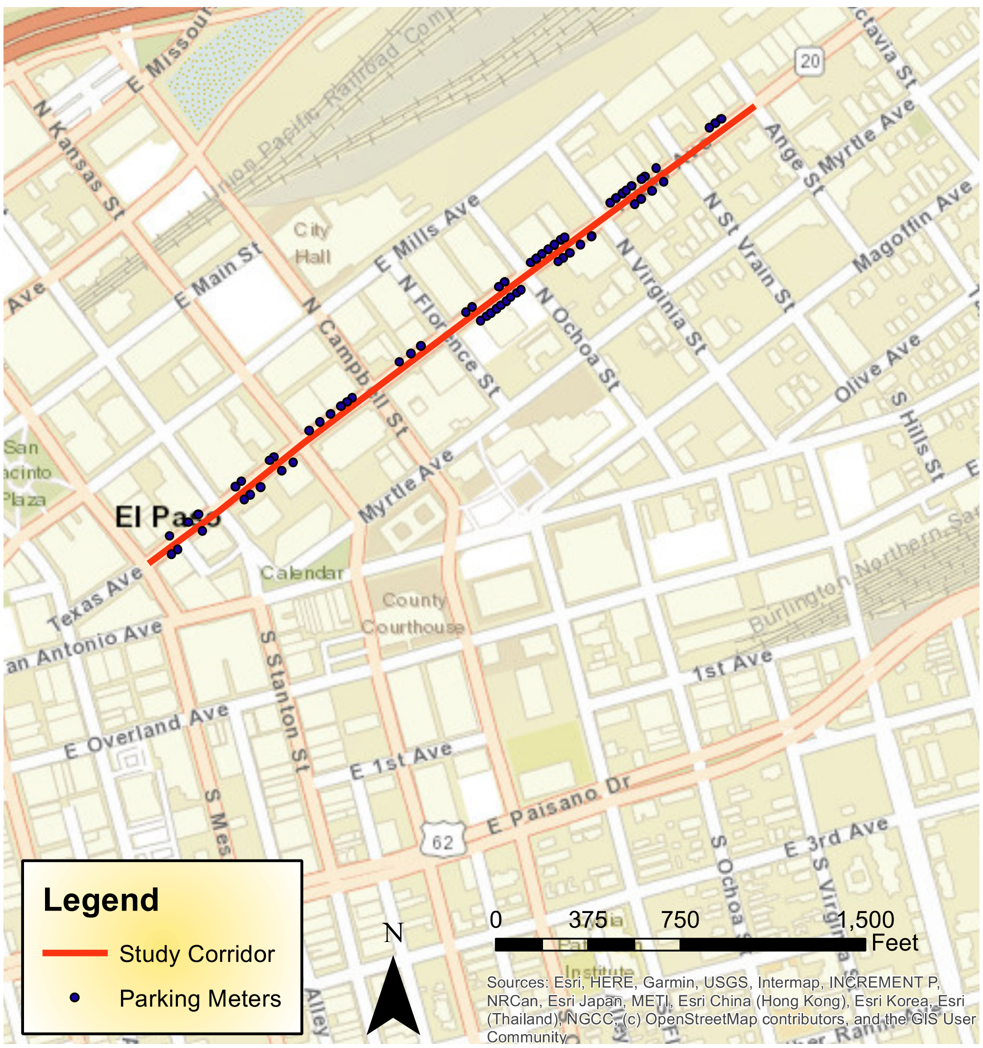

Figure 11: El Paso On-Street Parking Study Site

Meter 32476 7/3/2019	# cash Trans.	Cash trans. ($)	# credit card trans.	Credit card trans. ($)	# phone trans.	Phone trans. ($)	# smart card trans.	Smart card trsns. ($)	Total transc. #	Total transc. ($)
8am-9am	1	0.75	0	0.00	0	0.00	0	0.00	1	0.75
9am-10am	0	0.00	1	1.03	0	0.00	0	0.00	1	1.03
10am-11am	1	0.50	0	0.00	0	0.00	0	0.00	1	0.50
11am-12pm	1	0.50	0	0.00	0	0.00	0	0.00	1	0.50
12pm-1pm	1	1.00	0	0.00	0	0.00	0	0.00	1	1.00
1pm-2pm	1	0.50	0	0.00	0	0.00	0	0.00	1	0.50
2pm-3pm	1	0.50	0	0.00	0	0.00	0	0.00	1	0.50
3pm-4pm	2	1.50	0	0.00	0	0.00	0	0.00	2	1.50
4pm-5pm	1	0.50	0	0.00	0	0.00	0	0.00	1	0.50
5pm-6pm	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00

Table 18: Transaction Records of a Space at El Paso Site

Meter 32476 7/3/2019	Total transactions (no.)	Total transactions ($)	Hourly occupancy ratio, $\Omega_{s,h,d}$
8am-9am	1	0.75	0.75
9am-10am	1	1.03	**1.00**
10am-11am	1	0.50	0.50
11am-12pm	1	0.50	0.50
12pm-1pm	1	1.00	1.00
1pm-2pm	1	0.50	0.50
2pm-3pm	1	0.50	0.50
3pm-4pm	2	1.50	**1.00**
4pm-5pm	1	0.50	**1.00**
5pm-6pm	0	0.00	0.00

Table 19: Conversion of Transaction Records into Occupancy Ratio at a space at El Paso Site

The occupancy ratio $\Omega_{s,h,d}$ in Table 19 was only for a particular parking space s, at a particular hour h, and in a weekday d. With n_d weekdays in a year, and $n_{s,b}$ parking spaces in street block b, the Annual Average Hourly Block Occupancy Ratio (AAHBOR) on weekdays or, $\overline{\Omega}_{b,h,d}$ was calculated from:

$$\overline{\Omega}_{b,h,d} = \frac{1}{n_{s,b}} \sum_{s=1}^{n_{s,b}} \left[\frac{1}{n_d} \sum_{d=1}^{n_d} \Omega_{s,h,d} \right] \quad (7)$$

Equations (1), (2), and (3) were then modified to calculate the Annual Average Hourly Block Search Time (AAHBST) in seconds:

$$\overline{T}_{b,h} = \frac{26.1}{1-\overline{\Omega}_{b,h,d}} \quad (8)$$

$$\overline{T}_{b,h} = 0.307 e^{47.429\overline{\Omega}_{b,h,d}} \quad (9)$$

$$\overline{T}_{b,h} = 6 + 19.2\overline{\Omega}_{b,h,d} \quad (10)$$

Table 20 shows the calculated AAHBOR ($\overline{\Omega}_{b,h}$) of the Texas Avenue site based on the 2019 data. Table 21 shows the AAHBOST ($\overline{T}_{b,h}$) obtained from Equations (8) to (10), and Table 22 displays the Annual Average Hourly Block LOS (AAHBLOS) converted from $\overline{T}_{b,h}$.

	AAHBOR, $\overline{\Omega}_{b,h}$							
Block no. *b*	200-299	300-399	400-499	500-599	600-699	700-799	800-899	900-999
Upstream cross st.	Mesa	Stanton	Kansas	Campbell	Florence	Ochoa	Virginia	St Vrain
Downstream cross st.	Stanton	Kansas	Campbell	Florence	Ochoa	Virginia	St Vrain	Ange
No. of spaces, $n_{s,b}$	10	5	8	4	14	19	17	5
8am-9am	.29	.36	.28	.34	.15	.18	.40	.10
9am-10am	.29	.30	.31	.39	.33	.19	.42	.16
10am-11am	.32	.34	.29	.37	.33	.20	.45	.29
11am-12pm	.33	.44	.33	.44	.39	.29	.47	.76
12pm-1pm	.36	.47	.36	.44	.36	.28	.49	.69
1pm-2pm	.36	.43	.36	.45	.29	.21	.49	.59
pom-3pm	.48	.48	.34	.58	.18	.20	.41	.32
3pm-4pm	.60	.53	.50	.55	.08	.22	.36	.21
4pm-5pm	.57	.46	.44	.49	.03	.18	.24	.21
5pm-6pm	.26	.21	.15	.17	.01	.07	.06	.10

Table 20: On-street Parking Hourly Block Occupancy Ratio at El Paso Site

Table 21 indicates that for this study site, the longest AAHBST occurred along Texas Avenue, between Saint Vrain Street and Ange Street between 11 a.m. to 12 a.m. At this hour on an average weekday, the occupancy ratio was 0.79 (see Table 22). That is, approximately four out of five spaces in the block were occupied. Omly one remaining space was available. The search time of 85 or 105 seconds may account for passing vehicles circulating the blocks and returning to park in the only available space. According to the data in Table 22, the entire site had LOS A all the time.

	AAHBOST, $\overline{T}_{b,h}$ (seconds)							
Block no. *b*	200-299	300-399	400-499	500-599	600-699	700-799	800-899	900-999
Upstream cross street	Mesa	Stanton	Kansas	Campbell	Florence	Ochoa	Virginia	St Vrain
Downstream cross street	Stanton	Kansas	Campbell	Florence	Ochoa	Virginia	St Vrain	Ange
No. of spaces, $n_{s,b}$	10	5	8	4	14	19	17	5
8am-9am	37/3/12	41/4/13	36/2/11	40/4/13	31/1/9	32/1/9	44/6/14	29/1/8
9am-10am	37/3/12	37/3/12	38/3/12	43/6/13	39/4/12	32/1/10	45/7/14	31/1/9
10am-11am	38/3/12	40/4/13	37/3/12	41/5/13	39/4/12	33/1/10	47/9/15	37/3/12
11am-12pm	39/4/12	47/8/14	39/4/12	47/8/14	43/6/13	37/3/12	49/10/15	109/85/21
12pm-1pm	41/4/13	49/10/15	41/4/13	47/8/14	41/4/13	36/2/11	51/12/15	84/51/19
1pm-2pm	41/4/13	46/7/14	41/4/13	47/9/15	37/3/12	33/1/10	51/12/15	64/24/17
2pm-3pm	50/11/15	50/11/15	40/4/13	62/23/17	32/1/9	33/1/10	44/6/14	38/3/12
3pm-4pm	65/26/18	56/16/16	52/12/16	58/18/17	28/1/8	33/2/10	41/4/13	33/1/10
4pm-5pm	61/21/17	48/9/15	47/8/14	51/12/15	27/0/7	32/1/9	34/2/11	33/1/10
5pm-6pm	35/2/11	33/1/10	31/1/9	31/1/9	26/0/6	28/1/7	28/0/7	29/1/8

Table 21: On-street Parking Hourly Block Search Time by at El Paso Site

	AAHBLOS							
Block no. *b*	200-299	300-399	400-499	500-599	600-699	700-799	800-899	900-999
Upstream cross st.	Mesa	Stanton	Kansas	Campbell	Florence	Ochoa	Virginia	St Vrain
Downstream cross st.	Stanton	Kansas	Campbell	Florence	Ochoa	Virginia	St Vrain	Ange
No. of spaces, $n_{s,b}$	10	5	8	4	14	19	17	5
8am-9am	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
9am-10am	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
10am-11am	A/AA	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
11am-12pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
12pm-1pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
1pm-2pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
2pm-3pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
3pm-4pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
4pm-5pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A
5pm-6pm	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A

Table 22: On-Street Parking HourlyBlock Level of Service at El Paso Site

6 Estimating Search Time for On-Street Parking

6.1 Search Time as a Function of Occupancy Ratio

The literature review has found that the average search time for on-street parking was a function of the occupancy ratio. That was, $T = f(\Omega)$. Equations (1) to (3) were different functional forms of $T = f(\Omega)$. The respective parameter values were calibrated with local data. Section 5 assumed that the calibrated parameter values were applicable to the conditions in the downtowns of Los Angeles and El Paso.

This section compares the average on-street parking search time represented by Equations (1) to (3) against the equations fitted to the data generated by a microscopic traffic simulation model that replicated one square block of an area in downtown El Paso. A *square block* is defined as an approximately square area bounded by streets on four sides. VISSIM 2021 (PTV, 2021) was used to code the model, simulate the traffic operations, and generate parking events to collect search time and occupancy data. Customized functions of $T = f(\Omega)$ was fitted to the simulated data. The simulation approach was preferred over field observation because the simulation model enabled the research team a systematic way of measuring search time and occupancy ratio. The gathering of such data simultaneously would require more resources which was beyond the time and financial budget of this project.

6.2 Simulation Experiment

6.2.1 Coding of the Base Model

A square block of the area in downtown El Paso bounded by N. Kansas Street, N. Campbell Street, E. Arizona Avenue and E. Rio Grande Avenue was selected as the area to model (see Figure 12). This area was selected because the site geometry was symmetrical. Each of the four streets has one-way traffic in three travel lanes. On-street parking spaces were located along the curbs on both sides of the travel lanes. The four intersections were signalized, coordinated and with fixed time, two-phase signal plans. The center-to-center distance between two adjacent intersections were all 100 m. Each 100 m segment that formed one side of the square block is referred to as a *street block*. There were 11 parking space along the left curb in a street block. In this experiment, only the parking spaces along the left curb of a street block are of interest. For the purpose of discussion, the parking spaces were numbered from 1 to 44 according to the direction of traffic flow: (a) E. Rio Grande Avenue: 1 to 11; (b) N. Campbell Street: 12 to 22; (c) E. Arizona Avenue: 23 to 33; (d) N. Kansas Street: 34 to 44.

Figure 12: Aerial Photo of Simulated Site

(Source: Google Inc.; North is facing up)

The site's dimensions were coded using the default aerial photo provided with VISSIM. The travel lanes, permitted turning movements, and on-street parking spaces were represented in the model by 12 links and 20 connectors. Traffic signal timing data of the four intersections were provided by the City of El Paso. They were translated into VISSIM format and entered into the model. The City of El Paso also provided intersection traffic counts during the morning peak hour (7:00 a.m. to 8:00 a.m.) on weekdays. These counts, after adjusting for consistency in terms of conservation of vehicles, were set as the background traffic with 100% passenger cars. An additional vehicle class/type called *parking vehicle* was created. These vehicles were released into the network at E. Rio Grande Avenue, one street block upstream of the N. Kansas Street intersection. They traveled in the eastbound direction and started to look for parking spaces after crossing the N. Kansas Street. Each parking vehicle initially searches for a parking space along the left curb of the street block of E. Rio Grande Avenue. If all the parking spaces along E. Rio Grande Avenue were occupied, the parking vehicle would make a left turn and continue to search for a parking space along the left curb of N. Campbell Street. If all the parking spaces along N. Campbell Street were occupied, the search would continue along E. Arizona Avenue followed by N. Kansas Street. Therefore, parking vehicles circulated the square block in the anticlockwise direction.

Figure 13 shows a screenshot of the coded model in VISSIM. In this model (known as the base model), the vehicles in blue were the background traffic. The vehicles in red were parking vehicles. One vehicle was entering parking space 12, while two other vehicles were searching for spaces to park.

Figure 13: Screenshot of the Base Model coded in VISSIM

The parking vehicles were programmed such that, once parked, these vehicles remained in the parking spaces until the end of the simulation run. This scheme forced the 44 parking spaces to be filled up one by one, in approximate order from spaces 1 to 44 in the anticlockwise fashion. This gave a spread of occupancy ratio between 0% and 100%. The occupancy ratio was the fraction of the 44 parking spaces that were occupied during a parking vehicle's search process. The search time of a parking vehicle was the time when it entered the upstream end of the E. Rio Grande Avenue street block (immediately upstream of parking space 1) until it began to pull into an available parking space.

After initial trial runs, the volume of parking vehicles was set to 100 veh/h. The simulation was run for 35 minutes. The data collection period was from 0 to 45 minutes, without a warm-up time. As mentioned, each run simulated 44 parking events which fill up the 44 parking spaces.

6.2.2 Simulation Runs

It was expected that, given the same occupancy ratio, intersection delay contributes a significant portion of the search time. Three other models were created by modifying the base model. The four models differed in the traffic circulation (turn direction) and intersection control type. Their features are listed in Table 23. Each model produced 44 data points of search time and occupancy ratio for 44 parking events in one simulation run. The simulations were run with four replications, each starting with a different random number seed. Therefore, at the end of the experiment, each model had 176 data points that covered 0% to 100% occupancy ratio.

Model	Model name	Parking vehicles circulation	Parking vehicles turning direction	Intersection control type
Base	LT-Signal	Anticlockwise	Left turn (LT)	Fixed time, coordinated signals
1	RT-Signal	Clockwise	Right turn (RT)	Fixed time, coordinated signals (right-turn-on-red permitted)
2	LT-Stop	Anticlockwise	Left turn (LT)	All-way-stop-control
3	RT-Stop	Clockwise	Right turn (RT)	All-way-stop-control

Table 2: Features of Simulation Models

6.3 Evaluation of Search Time Functions

Figures 14 to 17 plots the search time versus occupancy ratio, for the LT-Signal, RT-Signal, LT-Stop and RT-Stop models respectively.

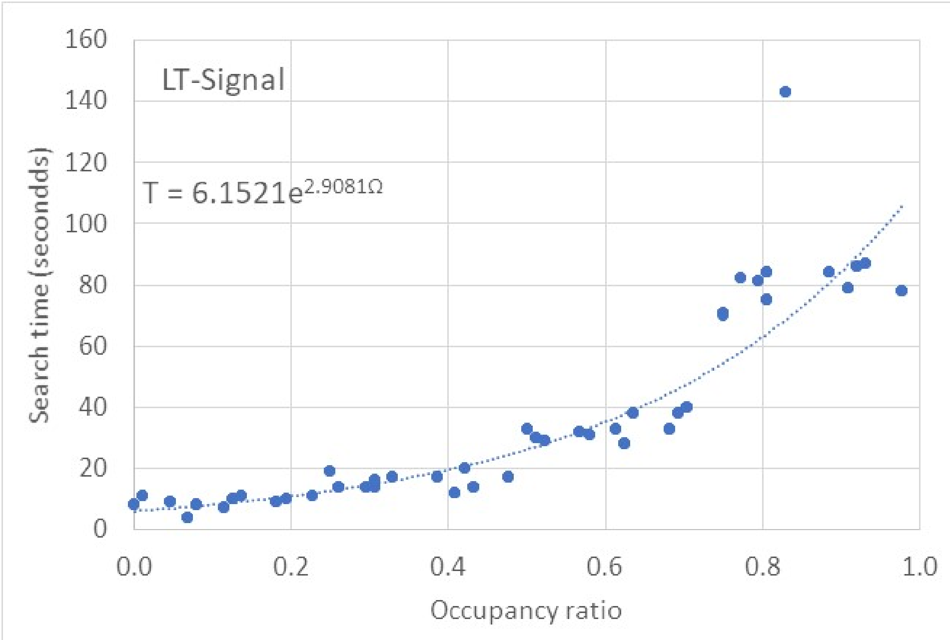

Figure 14: Search Time Versus Occupancy Ratio for LT-Signal Model

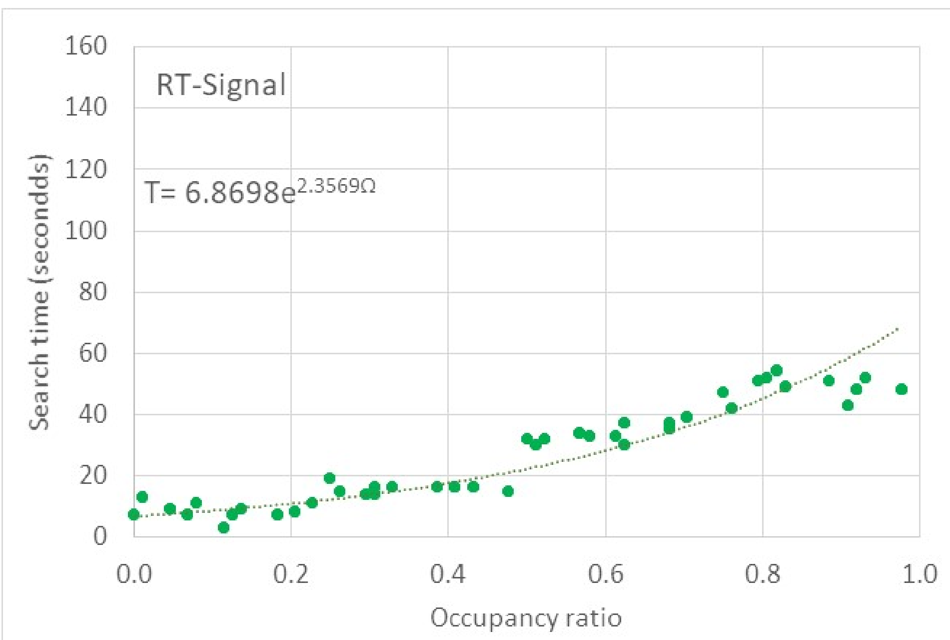

Figure 15: Search Time Versus Occupancy Ratio for RT-Signal Model

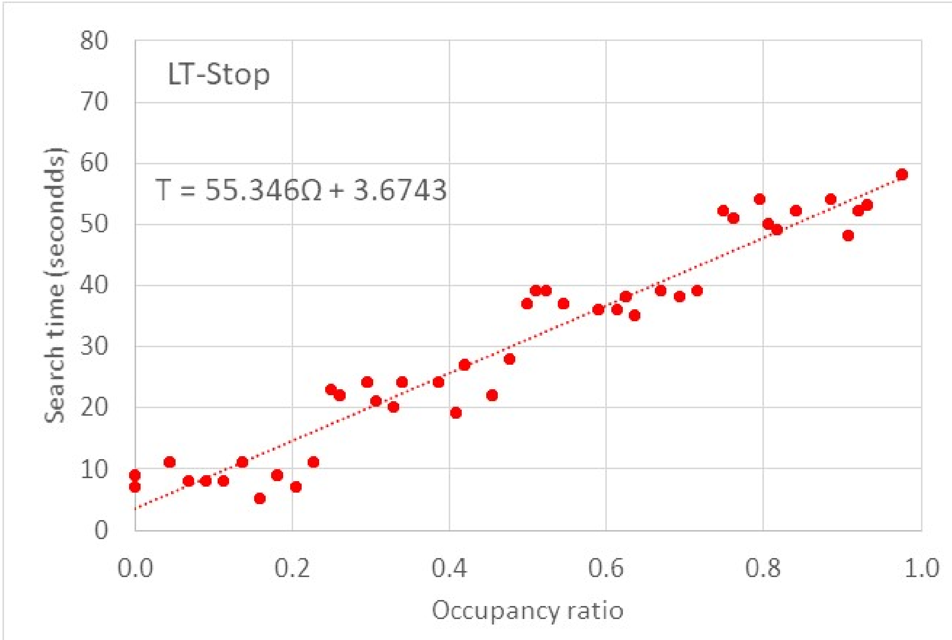

Figure 16: Search Time Versus Occupancy Ratio for LT-Stop Model

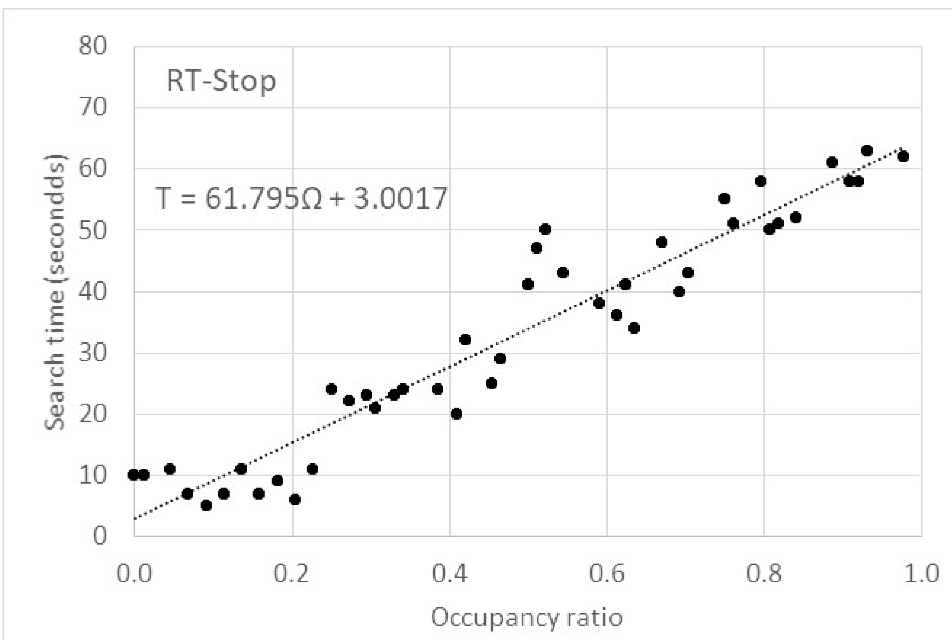

Figure 17: Search Time Versus Occupancy Ratio for RT-Stop Model

The following observations were made by inspecting the data points in Figures 14 to 17:

- The data points produced by the LT-Signal and RT-Signal models followed exponential functions.
- The data points produced by the LT-Stop and RT-Stop models followed linear functions.
- For the two models that were subjected to the same type of intersection control, the data points when occupancy ratio $\Omega \leq 0.25$ were similar. These data points corresponded to parking in spaces 1 to 11, before the parking vehicles make a left or right turn at the first intersection.
- Between the LT-Signal and RT-Signal models, the search times in the RT-Signal model were lower when $\Omega > 0.75$ because the parking vehicles were able to perform right-turn-on-red. In contrast, left-turn vehicles in the LT-Signal model were stopped by the red signal phase.
- In the two graphs that corresponded to the LT-Stop and RT-Stop models (Figures 16 and 17), the search time experienced sudden increases at $\Omega = 0.25$, 0.50 and 0.75 because parking vehicles were making left or right turns between parking spaces 11-12, 22-23, and 33-34, respectively.

The following average search time functions were fitted to the respective models:

LT-Signal model:	$T = 6.1521e^{2.9081\Omega}$	$R^2 = 0.807$	(11)
RT-Signal model:	$T = 6.8698e^{2.3569\Omega}$	$R^2 = 0.950$	(12)
LT-Stop model:	$T = 3.6743 + 55.346\Omega$	$R^2 = 0.935$	(13)
RT-Stop model:	$T = 3.0017 + 61.795\Omega$	$R^2 = 0.918$	(14)

Belloche (2015) presented an exponential function of:

$$T = 0.307e^{7.407\Omega} \quad (15)$$

The parameter values are different from the counterparts in Equations (11) and (12). The average search time in Equation (15) starts with a small value T but increases rapidly with Ω, compared to Equations (11) and (12). Caicedo (2009) has average search time as a linear function of occupancy ratio:

$$T = 0.1 + 0.32\Omega \quad (16)$$

Caicedo (2009) did not clarify the unit of T. Assume that T in Equation (16) is in minute. The equation, expressed in second is

$$T = 6 + 19.2\Omega \quad (17)$$

The constants and intercepts in both Equations (16) and (17) are very different in values than the constants and intercepts in Equations (13) and (14). Therefore, it was concluded that the parking search time function was not transferable from one city to another. The effect of road geometry and traffic control on average search time deserve further study.

7 Conclusions

7.1 Summary of Work Performed

Subsection 7.1.1 Outputs

This research has developed a LOS analysis procedure for off-street parking facilities. The LOS analysis procedure uses off-street parking search time as the LOS indicator. Three methods, namely the license plate matching method, the test vehicle method, and the video observation method have been suggested as ways to collect search time data. Each of these methods has its advantages and limitations. The three search time observation methods have been applied to an open surface parking lot with one entrance, an open surface lot with multiple entrances, and a conventional garage in three example problems.

The ConOps of PMS for smart garages has been described. The ConOps of PMS includes the functionalities, equipment, level zero diagram, and use cases. It also included a typical user's experience when interacting with the PMS. The savings in parking search time by converting a conventional garage into a smart garage, from the user's perspective, has been estimated at a five-level garage with a capacity of 700 vehicles.

This research has also defined six levels of PMS for on-street parking according to the system's capability in the collection of occupancy data and payment. They ranged from Level 0: No PMS (free parking, no occupancy data collection) to Level 5: SOSP PMS. The ConOps of Level 5 Smart On-Street Parking PMS has been described. The ConOps of Smart On-Street Parking PMS included the functionalities, equipment, level 0 diagram, and use cases. It also included a typical user's experience when interacting with the PMS.

The research into on-street parking included the development of a LOS analysis procedure for on-street parking facilities using occupancy or payment transaction data collected at different levels of on-street parking PMS. The LOS analysis procedure for on-street parking facilities was applied to two example problems. The first example problems used the occupancy data collected at a Level 4 parking PMS in Los Angeles, California to estimate search time and then used the search time as the indicator to determine the LOS. The second example problem used the payment transaction data collected at a Level 3 parking PMS to estimate the occupancy ratio and then used it to calculate the search time before converting to LOS.

Because of the need to estimate search time from occupancy ratio, four equations of average search time as linear and exponential functions of occupancy ratio, have been calibrated using data generated by VISSIM simulations.

Subsection 7.1.2 Outcomes

This research has developed a LOS analysis procedure for off-street parking facilities. Transportation engineers now have three methods of observing parking search times for three types of off-street parking facilities.

This research has discussed the functions, components, and operational features of smart garages. Transportation engineers and ITS systems architects now have guidelines on how smart garages should be designed to serve customers (drivers). The case study has demonstrated the savings in search time as a benefit of upgrading a conventional garage to a smart garage. This is an important input that may encourage more garage owners to implement smart garages.

This research has defined six levels of on-street parking PMSs. The functions, components, and operational features of the Level 5 SOSP PMS were discussed in detail. Transportation engineers and ITS systems architects now have guidelines on how on-street parking PMS, especially the Level 5 SOSP PMS should be designed to serve customers (drivers).

This research has developed a LOS analysis procedure for on-street parking facilities. Transportation engineers now have a procedure for estimating the LOS for on-street parking zones. This procedure includes equations to estimate average search time as a function of occupancy ratio.

7.1.3 Impacts

This report is the first to document the LOS analysis procedure for off-street parking facilities in the same format as the Highway Capacity Manual. It can potentially be included in the next edition of the Highway Capacity Manual.

The ConOps for PMS for smart garages and on-street parking facilities are guidelines for transportation engineers and ITS system architects to design parking PMS.

The estimation of search times and LOS for on-street parking from occupancy or payment transaction data opens a new approach for the analysis of on-street parking performance that may be linked to dynamic parking pricing.

7.2 Limitations and Suggestions for Future Research

The LOS analysis procedure for off-street parking facilities has not been developed nor demonstrated. However, these can be done by modifying the already established procedure and search time measurement methods described in Section 3 of this report.

The LOS analysis procedure has been applied to a Level 4 and a Level 4 on-street parking PMS. Although the benefits of converting a conventional garage to a smart garage have been estimated, the benefits of upgrading an on-street parking zone’s PMS have not been estimated.

In Section 6, four equations have been developed to estimate search time as functions of occupancy ratio. The four equations are for the combinations of left turn/right turn and signal/stop control at intersections. The street block is limited to 100 m. The impacts of block size, and intersection control should be investigated in more detail in future projects.

References

AASHTO (2018). "*A Policy on Geometric Design of Highways and Streets*, 7th Edition." American Association of State and Highway Transportation Officials. Washington DC.

Alexander, I. and Zink, T. (2003) "An introduction to systems engineering with use cases." Computer and Control Engineering, January, 2003. DOI: 10.1049/ccej:20020607.

Axhausen, K. W., Polak, J. W., Boltze, M., and Puzicha, J. (1994). Effectiveness of the Parking Information Guidance System in Frankfurt am Main. *Traffic Engineering and Control*, 35(5), 304-309.

Belloche, S. (2015). On-street parking search time modelling and validation with survey-based data. *Transportation Research Procedia*, 6, 313-324.

Caicedo, F. (2009). "The use of space availability information in PARC systems to reduce search times in parking facilities." *Transportation Research*, 17C, 56-68.

Car and Driver (2020). "What is an Automated Parking System?" Car and Driver Research, Hearst Auto Inc. <https://www.caranddriver.com/research/a31995865/automatic-parking-systems/>

Chrest, A. P., Smith, M. S., Bhuyan, S., Iqbal, M., and Monahan, D. R. (2012). "*Parking Structures: Planning, Design, Construction, Maintenance, and Repair."* Springer Science & Business Media, New York, USA.

City of Los Angeles (2020). "LADOT Parking Meter Occupancy." City of Los Angeles, California. < https://data.lacity.org/Transportation/LADOT-Parking-Meter-Occupancy/e7h6-4a3e>

Das, D., and Ahmed, M. A. (2018). "Level of service for on-street parking." *KSCE Journal of Civil Engineering*, *22*(1), 330-340.

FHWA (2020). "Performance Measurement Fundamentals." Federal Highway Administration., <https://ops.fhwa.dot.gov/perf_measurement/fundamentals/index.htm>

Gurbuz, O. (2019). "Decision Support Tools for Parking Management at University Campuses." Ph.D. Dissertation, The University of Texas at El Paso, El Paso, TX.

Gurbuz, O., and Cheu, R. L. (2020). "Survey to explore behavior, intelligent transportation systems needs, and level of service expectations for student parking at a university campus." *Transportation Research Record: Journal of the Transportation Research Board*, 2674(1), 1-10.

He, Y., Sun, X., Du, L., Jinmei, R., and Das, S. (2012). "Level of service for parking facilities." *Proceedings of The IEEE 15th International Conference on Intelligent Transportation Systems.* Anchorage, Alaska, 1161-1165.

He, Y, Sun, X., Du, L., Jinmei, R. and Das, S. (2015). "Level of Service for Parking Facilities." *Journal of Traffic and Transportation Engineering*, 3, 35-41.

IEEE Computer Society, March 19, 1998, IEEE Guide for Information Technology—System Definition—Concept of Operations (ConOps) Document (IEEE Std 1362-1998).

IPMI (2018). 2018 Emerging Trends in parking. International Parking Mobility Institute, Fredericksburg, VA.

Kimley-Horn. (2016). Parking Structure Design Guidelines. Raleigh, NC.

LA Express Park. (2020). Benefits of LA Express Park, <http://www.LA Express Park.org> (Jun. 16, 2020).

Parkmobile (2020). Reserve Parking for Later, <https://parkmobile.io/how-it-works/> (Jun. 16, 2020).

PTV (2021). VISSIM 2021 User Gride. PTV America, Portland, OR.

Revenue Hub (2020) The Dating Game – Parking Revenue Seeks KPI Companionship. Revenue Hub,<https://revenue-hub.com/parking-revenue-seeks-kpi/ >

Roess, R., Prasas, E. and McShane, W. (2019). Traffic Engineering. 5th edition, Pearson.

Smith, M. S., Butcher, T. A. (2008) How far should parkers have to walk? Parking, National Parking Association, <www.npapark.org>

SDOT. (2019). Paid Parking Rates Reports and Studies. Seattle Department of Transportation, Document Library, <http://www.seattle.gov/transportation/document-library/reports-and-studies#parking> (Jun. 16, 2020).

SFPark. (2020). About the Project. San Francisco Municipal Authority, <http://sfpark.org/about-the-project/> (Jun.16, 2020).

Smith, M. S., and Butcher, T. A. (2008). "How far should parkers have to walk?" *Parking*, *47*(4), 28-31.

SpotHero (2020). Find and Reserve Parking, <https://www.parkingpanda.com/> (Jun. 16, 2020).

TRB (2010). *Highway Capacity Manual*. Transportation Research Board, Washington, DC, USA.

USDOT. (2016). Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis. U.S. Department of Transportation Memorandum to Secretarial Officers Modal Administrators, <https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20Travel%20Time%20Guidance.pdf>

USDOT (2019). The National Reference ITS Architecture ARC-IT Version 8.3.

Volkswagen Financial Services. (2020). How it works-Parking, <https://www.paybyphone.com/how-it-works/parking> (Jun.16, 2020).