SMART PARKING MANAGEMENT AND PLANNING IN URBAN AREAS

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Master's Program in Engineering

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SMART PARKING MANAGEMENT AND PLANNING IN URBAN AREAS

by

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GRADUATE PROJECT

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Engineering Education and Leadership

THE UNIVERSITY OF TEXAS AT EL PASO

May 2022

ACKNOWLEDGEMENTS

I would like to thank my advisors, Dr. Ruey Long (Kelvin) Cheu and Dr. Tomáš Horák for their guidance, knowledge, support, and the opportunity allowing me to work for them. I would also like to thank Dr. Jeffrey Weidner and prof. Miroslav Svítek for serving on my committee and for their guidance over the course of my graduate year at UTEP.

I would also like to thank all current and past members of the Border Intermodal Gateway Transportation Lab (BIG LAB) for the support, suggestions, and discussions during this research.

My sincere thanks also go to Ing. Tomáš Janča and GREEN Center s.r.o. for their help and support through the process of this research.

I would like to thank Czech Technical University in Prague for the financial support it was given to me to cover a part of the expenses during my stay in El Paso.

Finally, I would like to thank my girlfriend Eva and my family for their continuous support and understanding throughout my whole study.

DECLARATION

This thesis/report is an output of the International Dual Master Degrees Program in Smart Cities Science and Engineering, a collaboration between Czech Technical University, Czech Republic, and The University of Texas at El Paso, USA.

This research is jointly supervised by the following faculty members:

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ABSTRACT

Parking management uses different measures to compare different approaches and controls in off-street parking. This thesis provides an overview of parking facilities and their performance measures such as search time, leaving time, attempt, and lost time.

Nowadays, parking is more often extended by smart technologies that provide a better quality of service. This thesis explains the concept of smart parking, describes technologies, and provides an overview of smart parking concepts in San Francisco, U.S., and Los Angeles, U.S.

A simulation model is frequently used to obtain essential outputs and results for traffic and parking studies. This thesis selected AnyLogic software for two different case studies in El Paso, U.S., and Prague, the Czech Republic. Besides simulation of the current situation, four different parking guidance levels are determined: Level 0 – no access control and no guidance, Level 1 – access control and no guidance, Level 2 – access control and zone occupancy guidance, and Level 3 – access control and destination stall guidance. These parking guidance levels are compared in both use cases to understand better the advantages and disadvantages of selected levels and their technologies.

Keywords: parking, parking technology, simulation, smart parking, parking management

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El Paso, Texas, USA

May 14, 2022

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MASTER'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

Student's name and surname (including degrees):

Bc. Martin Čirkov

Study programme (field/specialization) of the student:

master's degree – SC – Smart Cities

Theme title (in Czech): **Smart parkovací management v městské aglomeraci**

Theme title (in English): **Smart parking management and planning in urban areas**

Guidelines for elaboration

During the elaboration of the master's thesis follow the outline below:

- Review the existing parking management practices
- Perform a literature review on smart parking technologies, smart parking systems, and existing smart parking approaches in San Francisco, U.S., and Los Angeles, U.S.
- Analyze best simulation models for off-street parking
- Create a simulation model for smart parking management in El Paso, U.S., and Prague, the Czech republic

Graphical work range: N/A

Accompanying report length: At least 55 pages.

Bibliography:

Sparkman: A Smart Parking Management Tool for University Campuses. The University of Texas at El Paso, 2020. Report. Ruey L. Cheu, Okan Gurbuz

Characterization of University Parking System. The University of Texas at El Paso, 2018. Report. Ruey L. Cheu, Okan Gurbuz, et al.

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Ruey Long Cheu, Ph.D.

Date of master's thesis assignment: **June 30, 2021**

(date of the first assignment of this work, that has be minimum of 10 months before the deadline of the theses submission based on the standard duration of the study)

Date of master's thesis submission: **May 16, 2022**

a) date of first anticipated submission of the thesis based on the standard study duration and the recommended study time schedule

b) in case of postponing the submission of the thesis, next submission date results from the recommended time schedule

L. S.

doc. Ing. Tomáš Horák, Ph.D. head of the Department of Logistics and Management of Transport	prof. Ing. Ondřej Přibyl, Ph.D. dean of the faculty

I confirm assumption of master's thesis assignment.

Bc. Martin Čirkov

Student's name and signature

Prague .... May 3, 2022

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1. INTRODUCTION

1.1. Background of Thesis

Parking is a worldwide topic that affects every driver. Efficient parking management is needed to prevent a lack of parking spaces, parking congestion, and other negative externalities. With growing cities comes an increase in parking demand, which becomes harder to fulfill. In a dense and developed city, there is usually no more land space to expand the parking infrastructure. The only way to improve the parking capacity is through parking management.

Parking is changing with new technologies. The use of technology or smart parking provides more options for drivers to utilize a parking facility better. The majority of European and American cities have already started to use several smart parking technologies that save drivers time, reduce congestion in the streets and parking lots, and reduce vehicle emissions.

Parking can be described as an event consisting of a driver who maneuvers a vehicle searching for a parking stall (parking space for one vehicle). Parking can be on-street (parking stalls along a road) and off-street (parking lot, parking garage). These elements (multiple drivers, their vehicles, and parking stalls) interact with each other and form a complex system. Interaction is the most important component. For example, exchanging data quickly between a driver and a parking lot's server can provide the driver with information about occupancy and increase the time to think about the next steps. Another example could be an interaction between a vehicle and a parking lot, as it can be a way to design the control algorithm of autonomous vehicles.

Smart parking technologies should serve drivers as a helpful tool that provides more safety on the roads, reduces vehicles' exhaust fumes, and saves time and money (less time spent searching for a parking space). Many innovative parking technologies are already being used in parking lots or parking garages, helping drivers with parking, such as dynamic message signs, automatic parking lot barriers, or parking apps. In addition, many new and even smarter technologies are being tested and might come to market in subsequent years. Among those technologies are autonomous parking, parking robots, etc.

Parking modeling tools provide various options to make a parking model as close to reality as possible. Modeling tools can be used for simulation of the current situation as well as for scenarios or predicted future demand. In addition, they provide a range of important outputs and results that can be used to improve the design and operations of parking facilities

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1.2. OBJECTIVES

This thesis has three objectives:

- The first objective is to review and summarize state of the art of smart parking, including parking technology.
- The second objective is to develop simulation models that realistically represent the parking lot operations in the real world. One parking lot in El Paso, Texas, and one parking lot in Prague, Czech Republic, have been selected as the case study sites to build simulation models.
- The third objective is to use the simulation approach to conduct experiments to comparatively evaluate the performances of the selected parking lots that operate at four levels of provision of real-time parking information.

1.3. OUTLINE

The thesis is organized into seven chapters. The first one (the current one) is the introduction to parking problematics, including the objectives of the thesis. The second chapter focuses on a parking review, emphasizing parking facilities, parking demand and supply, performance measures of parking facilities, and parking management strategies. The third chapter reviews smart parking, including smart parking technologies, parking systems, pilot parking technologies, and intelligent parking in San Francisco and Los Angeles. The fourth chapter is focused on simulation models for off-street parking, with subchapters for AnyLogic, PTV Vissim, and their comparison. The fifth chapter is about a case study in El Paso, Texas, where a parking lot at the University of Texas at El Paso (UTEP) was selected and studied. This chapter describes the current situation, collected data, and three different scenarios modeled in AnyLogic. The sixth chapter focuses on the case study in Prague. It also includes a review of the current situation, data processing, and different P+R Holešovice parking lot scenarios. The last chapter, the seventh, is the conclusion summarizing the results, contribution, limitations, and future work.

2. REVIEW OF PARKING MANAGEMENT PRACTICES

2.1. Parking Facilities

This section defines the terms used to discuss parking facilities.

Parking Stall

A parking stall (space) is a paved or unpaved marked area intended for parking a vehicle. There are three different types of parking stalls, namely parallel, angled, and perpendicular. ("Parking Spaces Dimensions & Drawings", 2021).

Parking Lot

A parking lot is an enclosed outdoor area intended for parking vehicles. A parking lot may be covered or uncovered (Bray, 2022).

Parking Garage

A parking garage is a building intended for parking vehicles. There are more options for parking garages, such as single-level garages, multilevel garages, and underground garages. A parking garage may be a building by itself or part of a building (Nash, 2021).

On-Street Parking

On-street parking refers to parking spaces for vehicles along the street within a designated area, usually along a curb. These parking spaces are usually designed for short-term parking and equipped with parking meters (Bray, 2022).

Off-Street Parking

Off-street parking refers to parking spaces for vehicles in enclosed parking lots or parking garages. These parking spaces are often used for long-term parking and could be equipped with access control systems (Bray, 2022).

P+R Parking Facility

A Park and Ride (P+R) parking facility is set aside for drivers to leave their vehicles out of the city center and transfer to public transportation to reach their destinations instead. P+R parking facilities are located next to public transportation stations. The stalls in the facility are intended for day-long parking. An example of a P+R parking facility location is shown in Figure 2.1. (“P+R, B+R, K+R”, 2022).

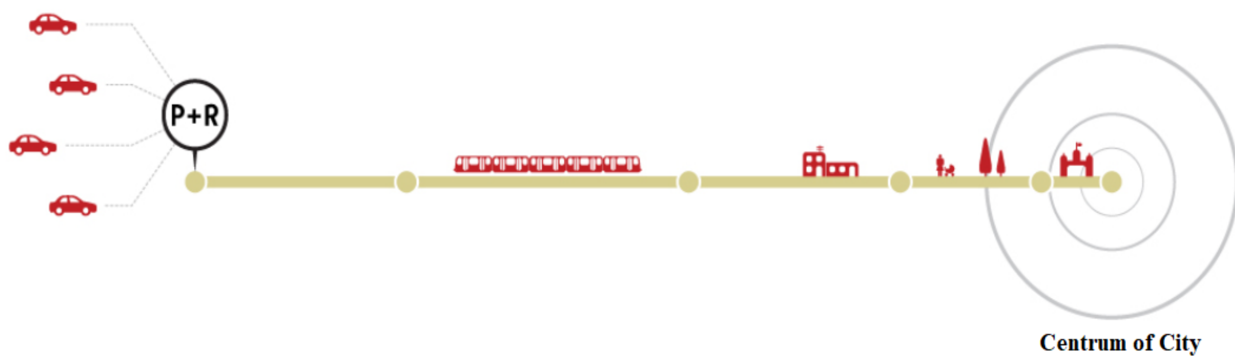

Figure 2.1: P+R parking lot location to the city center (“P+R, B+R, K+R”, 2022).

2.2. Parking Demand and Supply

Parking is an everyday task for drivers. According to a survey by the American Automobile Association in 2017, the average travel time per vehicle is just 48.2 minutes a day; the remainder of the time, the vehicle is parked. (Cheu et al. 2018) For that reason, there must be spaces available to meet the parking demand. Every vehicle trip makes a minimum of two stops: an origin and a destination. When the parking stalls in the destination have filled or are almost filled to their capacity, the driver will spend an increasing amount of time searching for an empty space. This extends trip completion time, increases traffic congestion, and increases emission (Cheu et al., 2018; Cheu and Gurbuz, 2020).

When the demand for parking spaces is higher than the capacity of a parking lot, parking congestion occurs. As a city grow, the demand for parking grows; however, there is a limited land space in the city for parking. Thus, many parking offices turn to management strategies and Intelligent Transport Systems (ITS) to cope with the parking congestion problems. (Cheu et al., 2018; Cheu and Gurbuz, 2020).

The demand for a parking facility depends on several factors such as types of users, their needs, their points of interest (trip purposes), and the overall permit price. Parking demand is also affected by many other factors such as geography, demography, and the economy. Consider a university campus as an example. Research has found that the average parking demand rates in suburban and urban campuses differ; parking demand at suburban campuses is 0.33 stalls per student, faculty, and staff while at urban campuses is 0.22 stalls per student, faculty, and staff (Cheu et al., 2018). Parking demand can be reduced between 20 to 40 % with effective parking management (Cheu et al., 2018).

Parking supply consists of two components: (1) providing physical space (parking stalls) and (2) implementing policies that control who can use the parking stall at what time and at what price. Short-term solutions for improving parking availability of a facility focus on zoning and pricing. Long-term solutions are the construction of new parking facilities (capacity expansion).

The increase of parking supply by constructing new parking facilities is an easy solution if both space and budget are available. The construction costs for a parking stall differ based on the parking facility type. The cheapest stalls to construct are usually parking spaces in an open surface parking lot. The construction cost is about three times more expensive in a multi-story garage. The most expensive parking spaces are those in an underground parking garage (Cheu et al., 2018).

A parking facility's performance indicators are the outcome of a supply-demand interaction. Examples of these indicators are turnover rate, occupancy, and search time. Two congestion level indicators are parking lot occupancy and search time for a space. Occupancy reflects the percent of stalls that are occupied at any time (Cheu et al., 2018).

2.3. Performance Measures of Parking Facilities

Search Time

The search time for an empty parking stall is defined as the time when a vehicle starts to search for a parking stall until it moves into a stall. For an off-street parking lot, search time may be defined as the time to travel from the entrance of the parking lot until it is wholly parked in a parking stall (Cheu et al., 2018).

Leaving Time

The leaving time for a vehicle in an off-street parking lot is the time for the vehicle to travel from a parking stall to the parking lot's exit.

Attempt

An attempt describes an event when a driver tries to navigate his/her vehicle to a selected stall and try to park in the intended stall. If a driver successfully parks his/her vehicle in the intended parking stall, the attempt is successful. On the other hand, if the driver selects a parking space but before he/she reaches the stall that another driver has occupied the space, the attempt is unsuccessful.

Lost Time

The lost time is the time that a driver spends in a parking facility in search of an empty stall without success and eventually leaves the facility.

2.4. Parking Management Strategies

Zoning

Zoning in parking means that parking facilities are identified by the types of permits with which vehicles can park. To manage a limited supply of parking stalls, zoning and assigning permits to zones are key factors for improving parking efficiency. Every city, university, or sports facility decides its own zoning and permit systems (Cheu et al., 2018).

Permit Price

The permit price of parking is usually dependent on the zone's proximity to the city center or points of interest. The price for a parking permit is an essential tool to manage the parking demand. Many parking providers also use it as the primary tool to collect revenue. However, there should always be an appropriate balance between raising revenue from permit sales and driving away parking demand. A parking facility with an overpriced parking permit may divert drivers to find a different location to park, which could cause problems elsewhere (Cheu et al., 2018; Cheu and Gurbuz, 2020).

Availability of Transit

There are two potential ways transit systems can change the parking demands. However, these options need to offer drivers an advantage to persuade them to change their travel behavior. The first option is to use a shuttle bus system as an alternative form of transportation by bringing drivers from remote parking facilities to the point of interest. There must be a balance between the search time for an empty parking stall and the time to take a shuttle bus. The second option is to improve the city public transport system such that travelers are willing to switch from driving vehicles to public transport (Cheu et al., 2018).

3. REVIEW OF SMART PARKING

3.1. CONCEPT

Smart Parking represents a new strategy to manage parking lots. It combines new, innovative technologies that help to use as few resources (fuel, time, and space) as possible to achieve faster, denser, and more efficient parking of vehicles (Wessel, 2016).

Smart parking technologies contain a wide range of functions that assist drivers to park quickly and with ease. There are, for example, mobile applications that help drivers locate, book, and pay for parking stalls in parking lots. Other examples include intelligent entrances and exits with license plate recognition systems, dynamic message signs displaying current parking lot occupancy, or lights above parking stalls informing drivers about the parking stall's occupancy. With real-time data collection and information provision, these technologies offer opportunities for improving a parking facility's operations. ("How Smart Technologies Are Revolutionising Car Parks", 2021).

3.2. PARKING TECHNOLOGIES

This subsection focuses on smart parking technologies currently being implemented.

Automated parking lot barrier

Every off-street parking lot has at least an entrance and an exit. Barriers often present at the entrances and exits control vehicle access and egress. The barriers keep parking lots for use only by drivers with authorized access (e.g., permits). They also serve as parts of the mechanisms to collect parking fees ("How Do Car Park Barriers Work?", 2022).

Automated vehicle barriers can be operated by access control devices such as license plate recognition cameras, pushbuttons, smartphones, or even fingerprint recognition systems. An example of an automated parking lot barrier is shown in Figure 3.1 (“How Do Car Park Barriers Work?”, 2022; “Automatic Gate Barrier”, 2022).

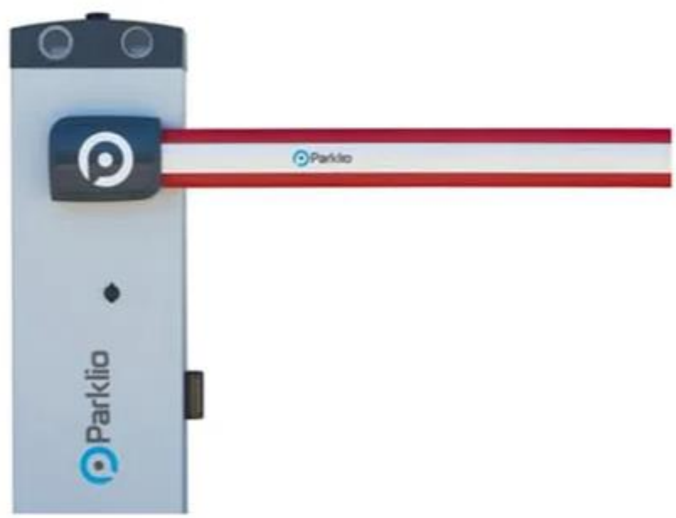

Figure 3.1: Parking technology - automated vehicle park barrier (“Automatic Gate Barrier”, 2022).

License Plate Recognition

License Plate Recognition (LPR) is a technology that captures and recognizes license plates via digital images or video in real-time. The technology typically can differentiate between different license plate designs with different font types and sizes. The LPR process itself has four stages:

a) Localization

- Identify the license plate within the entire image.

b) Segmentation

- Separate every character in the license plate into zones.

c) Identification

   - Recognize the character in each zone.

d) Regionalization

   - Interpret the string of characters, apply the syntax, correct, and infer the outcome ("What Is License Plate Recognition?", n.d.).

Automatic Vehicle Sensors

Automatic vehicle sensors collect and report vehicle volume in real-time. The types of sensors could be inductive loops, magnetic sensors, infrared radar, Doppler microwave, video detectors, etc. There are two possible ways to count the vehicles. The first is at the parking lot entrances and exits. The second way is to count vehicles in individual parking spaces ("Wireless Car Counters", n.d.).

Occupancy Sensor Lights

Occupancy counters can be connected to occupancy sensor lights installed above each parking stall that indicates the stall's availability. This provides drivers visual information and guidance to the available parking stalls ("Best Parking Guidance with Occupancy Sensors", 2021).

Occupancy sensor lights have various colors to identify the different parking stall types and occupancy status. For example, green for empty space, red for occupied, pink lights for families, blue for disabled drivers, yellow for reserved, and any other colors for an electrical vehicle charging station. Examples of occupancy sensor lights are shown in Figure 3.2 ("Best Parking Guidance with Occupancy Sensors", 2021).

Figure 3.2: Parking technology - occupancy sensor lights. (Phasura 2022)

Smart parking mobile app

Mobile apps usually provide real-time data about the parking lot occupancy and related services such as booking, paying, and extension of the time needed for parking. There is a wide assortment of smart parking apps, but the provided features are similar or the same across the applications (“4 Park - Smart Parking App”, n.d.).

"PayByPhone" was chosen as an example of an intelligent parking application in this thesis. The app works in many American and European cities for parking payments via smartphone. It allows a driver to enter the location code (general vicinity) where the driver wishes to park, fill out the vehicle's license plate information, choose a parking lot, enter the desired parking duration, and pay the parking fee. The driver can also extend the paid parking duration anytime via the mobile application. The application also includes a countdown timer to inform the owner about the remaining time until the paid session expires. (“Pay for Car Park by Phone or via Our Parking App”, n.d.; “MIT”, 2017).

3.3. Future and Pilot Technologies

As new parking technologies are being introduced to the market every year, many pilot projects and prototypes are being tested.

Autonomous Parking

Autonomous parking enables vehicles to navigate in search of a parking space and pull into a parking stall on their own, without the control of a human driver. ("Autonomous Parking in Parking Garages", 2022).

An existing project by Bosch is currently under development in Stuttgart, Germany in airport garages. Their automated valet parking project provides users with a parking space reservation option and vehicle registration via LPR. After a successful reservation, an entrance camera scans the license plate and allows the vehicle into the parking garage. The driver reaches the drop-off point and activates the self-parking application that sends the automated vehicle to the parking space. The system communicates with the vehicles from the parking garage's server. ("Autonomous Parking in Parking Garages", 2022).

Autonomous parking is expected to improve the safety of a parking facility for pedestrians. In addition, as the vehicles navigate by themselves precisely to the intended stall, more vehicles can fit into the same area. The last significant improvement would be search time for the parking stall and automatic fee collection via LPR. ("Autonomous Parking in Parking Garages", 2022).

Automated valet parking robots

A similar solution to autonomous parking is the automated parking system that uses robots to pick up vehicles and park them more efficiently in a traditional parking space. The system provides a safe and effective way to park a vehicle and was already installed at the Lyon-Saint Exupéry Airport in 2018 (Karsten, 2020).

Drivers book a parking stall on the airport website and then park their vehicles at dedicated hangars, where the vehicles are scanned to confirm their make and model. After that, the valet robot drives into the hangar, slides a platform underneath the vehicle, lifts it, and carries it to a parking lot. As a result, the robot can park the vehicle more efficiently, fitting up to 50 percent more vehicles into the same area. In addition, the valet parking robots eliminate the need for spaces between vehicles, which is necessary with human parking. The system also takes track of the time of the owner’s return and is ready to put the vehicle back into the hangar whenever necessary. An example of a valet parking robot is shown in Figure 3.3 (Karsten, 2020; Vincent, 2019).

Figure 3.3: Valet parking robots (“Stanley Robotics” 2018)

3.4. SMART PARKING IN SAN FRANCISCO, U.S.

The parking in the City of San Francisco is operated by the San Francisco Municipal Transportation Agency, which is the city's department responsible for managing all ground transportation ("About the SFMTA", 2022). In 2017, San Francisco was the first U. S. city to implement demand-responsive pricing for the city's on-street parking meters and on all parking lots operated by San Francisco Municipal Transportation Agency. The demand-responsive pricing applies the basic economics of supply and demand to manage parking. The higher the parking occupancy of a facility, the higher the price for its occupation will be. Meter prices can go up or down gradually or stay the same, based on the demand. The price change happens once every three months by 25-cents/hour. All changes are communicated to drivers in advance and are based on occupancy data made available to the public (Jose, 2017).

The demand-responsive pricing has resulted in:

a) Lower parking rates:
    - On-street average parking meter rates were reduced by 4% (down by $0.11/hour), and the parking rates at garages went down by 12% (down by $0.42/hour)

b) Decrease in search time:
    - Reported search time went down by 43% during the pilot test.

c) Decrease in vehicle miles traveled:
    - The reduction in search time also led to a 30% decrease in vehicle-miles traveled, benefiting safety, fewer congestions, and reduce emissions (Jose, 2017).

3.5. Smart Parking in Los Angeles, U.S.

The agency responsible for transportation planning, project delivery, and operations in the City of Los Angeles is the Los Angeles Department of Transportation (LADOT) ("About - LADOT", 2022).

LADOT operates about 35,000 parking lots across the whole city. On top of that, LADOT provides and develops digital tools that facilitate parking in the city. The list of offered services can be found on LADOT's parking management website. Below are different services provided by LADOT: ("Parking in LA", n.d.).

a) Online parking meter payment
   - Cashless payment option for payment via mobile app.
b) LA Express Park
   - Mobile application that guides drivers to the nearest available parking stall. The app allows drivers to choose the parking space based on the price as Los Angeles uses dynamic pricing the same as San Francisco.
c) Residential parking permits
   - For better parking management, Los Angeles has a parking permits program that requires parking permits to park in certain parts of the city.
d) Parking enforcement and traffic control
   - Los Angeles employs about 500 officers to patrol parking spaces, control traffic when there is a signal outage, and respond to service requests from residents.
e) Prevention of parking lot occupancy
   - To keep people safe and make parking available to everyone, Los Angeles may tow or place a boot on a vehicle for reasons such as five or more unpaid tickets,

illegal parking, vehicle registration has expired, and the vehicle does not have evidence of registration (“Parking in LA”, n.d.).

LADOT provides real-time data about parking stall occupancy. Each parking space is equipped with a sensor that sends data about the occupancy state and its timestamp. All collected data are archived in csv files and published for public. (“LA City Open Data”, n.d.).

Hourly rates for parking are adjusted in selected areas based on the parking demand. The main objective is to maintain occupancy between 70% and 90% through pricing. Higher prices in higher demand areas should reduce the search time and thus congestion in adjacent streets (“FAQ - LADOT”, 2022).

4. SIMULATION MODELS FOR OFF-STREET PARKING

Simulation is a commonly used technique for operations, research, and management science that allows for modeling of complex, real-world systems. In this thesis, simulation is used to obtain important data for the evaluation of different smart parking management strategies. (M. Law 2015)

In order to select the appropriate analysis tool, this section provides an overview of two categories of traffic analysis tools: macroscopic and microscopic simulation models.

4.1 MACROSCOPIC SIMULATION MODELS

Macroscopic models are based on the deterministic relationships of the traffic stream's flow, speed, and density. Macroscopic simulation models take place on a section-by-section basis, using traffic flow as an aggregated quantity, meaning they do not model the movement of individual vehicles on a network (“Traffic Analysis Toolbox Volume XII”, 2020)

Similar to travel demand models, macroscopic simulation models are designed to model a large geographic area. The simulation can be set up and run relatively quickly by simulating aggregate flows. However, the simple representation of traffic movement is also a disadvantage as it limits the detail of the results. (“Traffic Analysis Toolbox Volume XII”, 2020)

Macroscopic simulation models are not suitable for representing the operations of a parking lot.

4.2 MICROSCOPIC SIMULATION MODELS

Microscopic simulation tools were developed to represent the movement of individual vehicles based on lane-changing and car-following theories. Vehicles usually enter a transportation network using a statistical distribution of arrivals, and the position of vehicles updates as they move through a network. In addition, each vehicle is typically assigned a destination, a vehicle type, and a driver type to account for the diversity of vehicles and driving styles encountered in real-world traffic. ("Traffic Analysis Toolbox Volume XII", 2020)

Microscopic simulation models have been used in the evaluation of a broad range of scenarios, complex geometric configurations, and analysis of crucial bottlenecks, roads, intersections, or parking lots, where the movement of each vehicle needs to be represented. ("Traffic Analysis Toolbox Volume XII", 2020)

The limitation of microscopic simulation models is the data requirements for roadway geometry, traffic control, and traffic pattern data. In addition, the model development is often time-consuming, and sometimes specialized training is needed. ("Traffic Analysis Toolbox Volume XII", 2020)

Microscopic simulation models simulate every vehicle individually and thus are suitable for representing the operations of parking lots.

4.3 AnyLogic

AnyLogic is an agent-based simulation tool designed to model and visualize the behavior of various systems. The development of a model uses a multiagent modeling environment with three simulation methods: discrete event, agent-based, and system dynamics. The three methods can be used to simulate systems of any complexity ("Features - Anylogic Simulation Software", n.d.).

AnyLogic unique feature is a suite of industry-specific libraries provided at no additional cost. The list of unique libraries is following: ("Features - Anylogic Simulation Software", n.d.).

a) Process modeling library

b) Fluid library

c) Rail library

d) Pedestrian library

e) Road traffic library

f) Material handling library

For traffic simulation, the road traffic library is used to model, simulate, and visualize vehicle traffic. It is suitable for modeling highway traffic, street traffic, parking lots, and other systems with vehicles (“Parking Lot”, n.d.).

For parking lot modeling, AnyLogic uses the element “Parking Lot.” That element allows drawing parking spaces along the road. AnyLogic supports only parallel and perpendicular parking spaces, which the stall length can be modified. The width of the parking space is defined by the width of the lane where is parking space located (“Parking Lot”, n.d.).

Among the main advantages of a modeling parking lot in AnyLogic is the logic model that provides important data, such as the number of vehicles present in the parking lot, the number of vehicles from the selected entrance, or the number of vehicles in the different types of parking stalls. Other advantages are the simple options for building a parking lot and the possibility of 2D and 3D views. AnyLogic also provides many options to collect data during the simulation run and draw graphs. An example of a 3D view of the parking lot is shown in Figure 4.1.

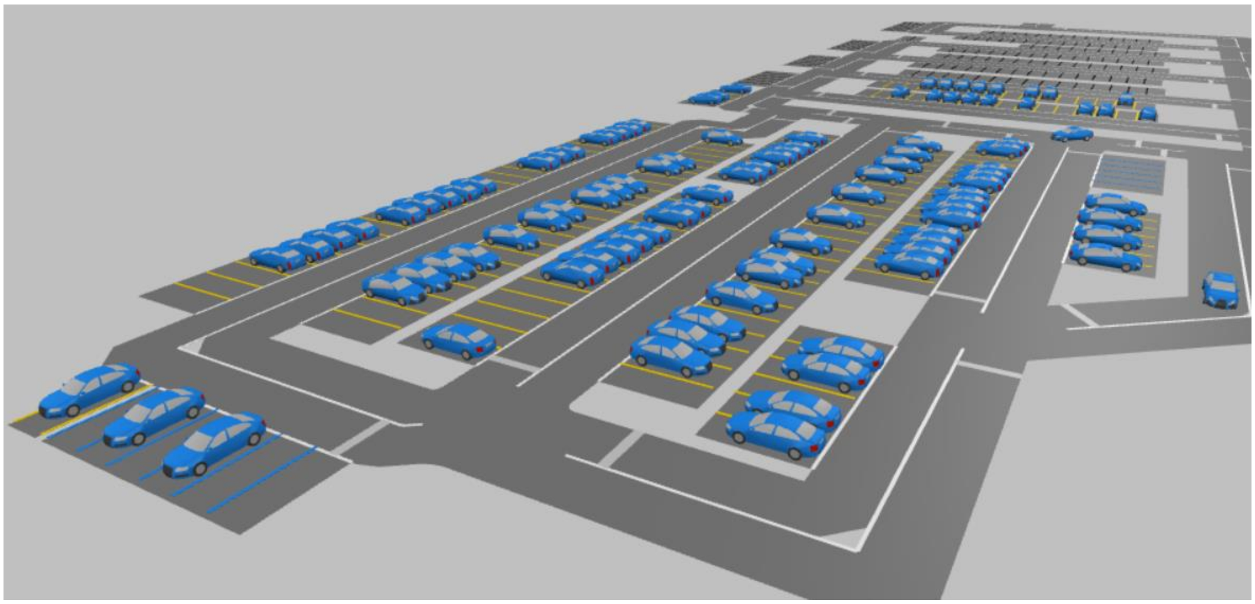

Figure 4.1: Example of a parking lot modeled in AnyLogic.

4.4 PTV VISSIM

PTV Vissim is a microscopic traffic simulation software that focuses on the interaction of signal controllers, vehicles, pedestrians, bikes, trams, and trucks. Unlike AnyLogic, PTV Vissim is focused only on the traffic simulation ("Comparison Software for Traffic Simulation". n.d.).

PTV Vissim provides its users with many features that help beginners to create a model. It also has an option to upload externally created images or create objects that can be adjusted to make the simulation environment even more realistic ("Comparison Software for Traffic Simulation", n.d.).

There is a wide range of options and features that can be used to simulate parking. For example, the parking stalls can be adjusted to every angle. The length and width of the parking stall are also adjustable. Another feature is reduced speed area, which allows setting a lower speed limit in the aisles within a parking facility.

In addition, it allows users to create very realistic simulations using a real image and to import specific objects such as roundabouts, trees, or even buildings. A 3D example of a parking garage is shown in Figure 4.2.

Figure 4.2: Example of a parking garage modeled in PTV Vissim. ("Parking Garage Simulation" 2022)

4.5 AnyLogic and PTV Vissim Comparison

The comparison of modeling parking lots in AnyLogic and PTV Vissim is a challenging task as each software was developed for different applications. Anylogic's advantage is the ease of use for beginners who do not have experience with modeling. On the other hand, PTV Vissim provides many more options and features to adjust the parking lot to build a more realistic model. The 2D view is comparable as both software have a similar look in 2D. The 3D view is the advantage of PTV Vissim because it allows the import of other buildings or traffic signs. In AnyLogic, all agents (vehicles) are the same, and the 3D model does not allow the user to import high-quality objects. The output is easily obtained in both software, but AnyLogic provides more options and features that can be easily obtained or set. Overall, AnyLogic is the preferred tool for beginners and users who want to adjust the logic of parking. On the other hand, PTV Vissim provides more options and features but needs advanced knowledge to take advantage of these features. For this thesis, AnyLogic software was chosen to develop the simulation models for the case studies.

5 CASE STUDY IN EL PASO

5.1 UTEP PARKING

UTEP is located south of El Paso near the U.S. – Mexico border. UTEP provides over 160 degree programs and is attended by 24,879 students. The University campus ensures many services such as canteens with food, a library, gyms, sports grounds, specialized buildings, and many others to provide students the best possible education. On top of that, UTEP provides a wide range of parking possibilities to ensure the availability of all buildings to all students. (“At a Glance” n.d.)

At UTEP is Parking & Transportation Services responsible for the operation and management of parking and shuttle services. The university had 6623 parking stalls for students, faculty, and staff on campus in 2017. UTEP also uses parking with zoning and pricing of the permits. All parking permits are sold through the online parking portal. (Cheu et al., 2018)

Students' parking lots at UTEP are grouped into five zones with different permit fees. The first group are garages that cost 400$ per year in garages near campus and 300$ in Glory Road Garage that is situated near Don Haskins Center and Memorial Gym. The second group are silver open lots, which cost 300$ per year. The third group are perimeter lots, and students can buy them for 225$ per year. The fourth group are residents lots (purple permits) near student houses, which costs 225$ per year. The last fifth group are green remote lots which could be purchased for 165$ per year and lie farthest from the center of the campus. The map of UTEP parking with different groups is shown in Figure 5.1. (“Student Permits” n.d.)

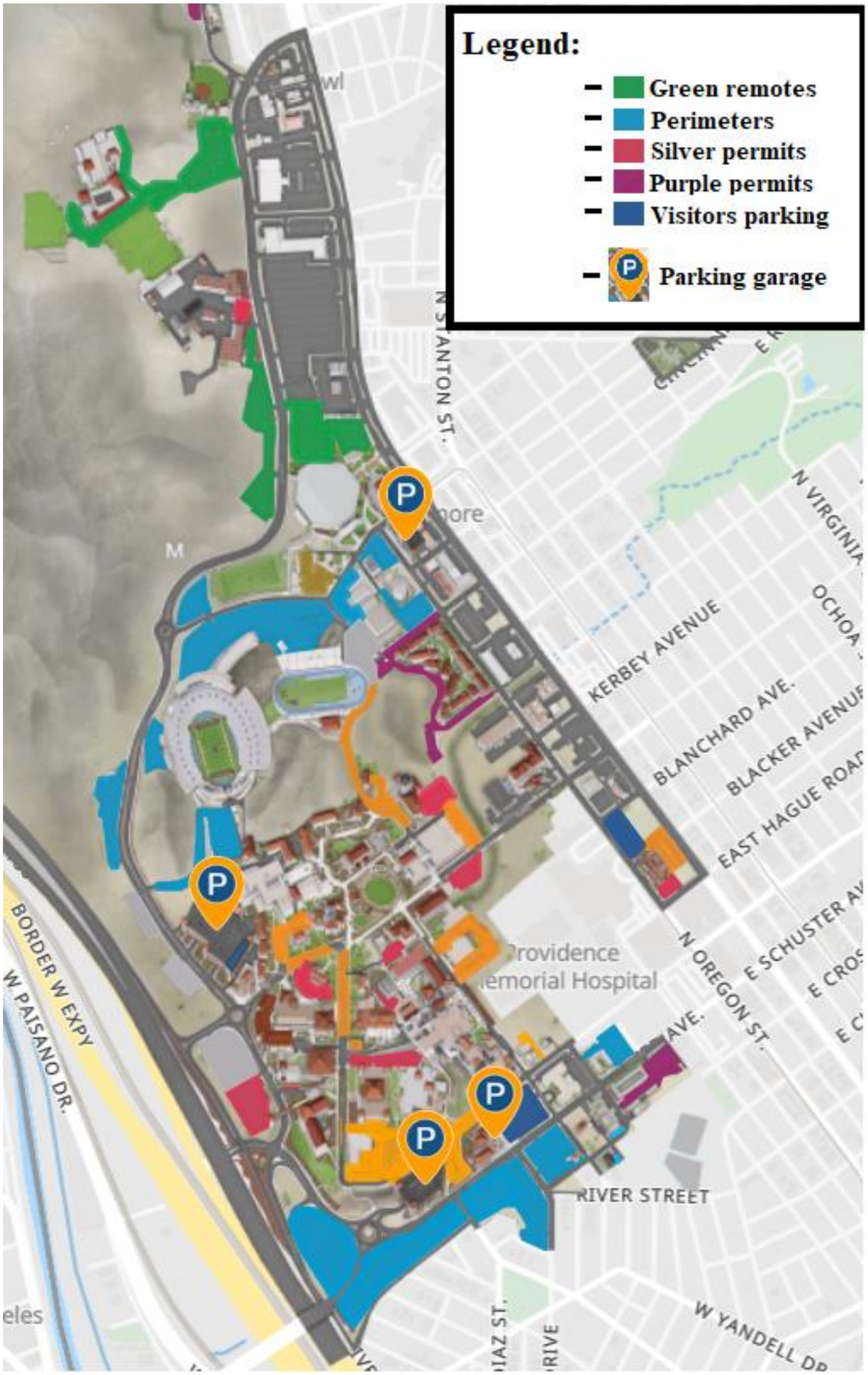

Figure 5.1: UTEP parking – All groups of UTEP parking. (“Campus Map” n.d.)

UTEP operates a campus shuttle bus service called Miner Metro. This service is free for all employees, students, and visitors. Four different routes cover all the important locations, including parking lots throughout the campus (Cheu et al., 2018).

The city of El Paso operates a bus transit system called Sun Metro. Students are provided with a 33% discount over the regular fare, and the routes of Sun Metro are around the campus of UTEP (Cheu et al., 2018).

5.2 Study Site

The UTEP SB2 parking lot was chosen for the case study in this chapter. That parking lot is situated on Sun Bowl Drive, near the I-10 Freeway exit and next to the Mining Minds roundabout. Users of this SB2 parking lot are students, faculty, and staff from the College of Health Sciences and School of Nursing, University Library, Undergraduate Learning Center, or Interdisciplinary Research Building. The exact location of the parking lot can be found in Figure 5.2.

Figure 5.2: UTEP SB2 parking lot – location map.

The SB2 parking lot has a length of approximately 195 meters (640 feet) and a width of 82 meters (269 feet). The parking lot has one entrance/exit that lies between the I-10 Freeway exit and the Mining Minds roundabout and one entrance/exit at Sun Bowl Drive. It has 349 parking spaces, including 16 parking spaces for the disabled that are situated near Sun Bowl Drive. An aerial view of the parking lot is shown in Figure 5.3. A pedestrian bridge starts on the south side of the parking lot, spans across Sun Bowl Drive, and connects to the School of Health Sciences building.

Figure 5.3: UTEP SB2 parking lot – physical layout in 2022.

From Tuesday, 1st of February, 2022 to Thursday, 17th of February, 2022, several weekdays were chosen at random to collect data for a better understanding of the parking lot's operations. Among the collected data were the number and locations of preferred parking spaces, the number of vehicles entering the parking lot from the I-10 Freeway entrance, the number of vehicles entering the parking lot from the Sun Bowl Drive entrance, leaving time, and search time. In addition, on Wednesday, 16th of February 2022, the numbers and locations of occupied parking spaces were recorded every hour from 7:00 a.m.to 6:00 p.m.

5.3 DATA COLLECTION AND PROCESSING

5.3.1 2022 Data

Among the data collected are the entrance/exit utilization ratio. About 81% and 86% of the parked vehicles used the Sun Bowl Drive to enter and exit this parking lot respectively I-10 Freeway. Table 5.1 below shows the total number of vehicles observed with I-10 and Sun Bowl Drive entrance/exit and entrance proportion.

Table 5.1: UTEP SB2 parking lot - number of vehicles at entrances and exits on 1st, 2nd 15th and 17th February, 2022.

Observation (8:00 a.m. – 9:00 a.m.)	Number of vehicles	Percentage
Total Number of vehicles Entered	257	100 %
Sun Bowl Dr Entrance (vehicles)	207	81 %
I-10 Freeway Entrance (vehicles)	50	19%
Total Number of vehicles Exited	61	100 %
Sun Bowl Dr Exit (vehicles)	8	13 %
I-10 Freeway Exit (vehicles)	53	87 %

The average search time differs based on the hour of the day. Drivers approaching the parking lot at 1:00 p.m. took longer to find a preferred stall near the pedestrian bridge because the parking lot had the highest occupancy at that time. On the other hand, vehicles took the longest time to leave the parking lot from 2:00 p.m. to 5:00 p.m. because many students and university staff departs the campus at these hours. p.m. The average observed search time from 11:00 a.m. to 12:00 p.m. is 43.6 seconds and the average leaving time at that time is 39:00 seconds. The average leaving time collected from 4:00 p.m. to 5:00 p.m. is 50.8 seconds, which is almost 12 seconds longer because of the traffic congestion. The summary of collected search time and leaving time data can be found in Tables 5.2 and 5.3 below.

Table 5.2: UTEP SB2 parking lot - observed leaving time on 15th February, 2022.

Leaving Time – 15th February 4:00 p.m. – 5:00 p.m.		Number of Vehicles
Average Leaving Time (s)	50,9	28
Sun Bowl Dr Exit Average Leaving Time (s)	50,6	25
I-10 Freeway Exit Average Leaving Time (s)	52,7	3

Table 5.3: UTEP SB2 parking lot - observed search time and leaving time on 17th February, 2022.

Leaving Time – 17th February 11:00 a.m. – 12:00 p.m.		Number of Vehicles	Search Time – 17th February 11:00 a.m. – 12:00 p.m.		Number of Vehicles
Average Leaving Time (s)	39,1	12	Average Search Time (s)	43,6	30
SB Exit Average Leaving Time (s)	35,5	10	SB Exit Average Search Time (s)	43,8	28
I-10 Freeway Exit Average Leaving Time (s)	57	2	I-10 Freeway Exit Average Search Time (s)	41	2

The parking occupancy data was collected on Wednesday, 16th of February, 2022, from 7:00 a.m. to 6:00 p.m. The occupancy at 5:00 p.m., due to technical issues, was not collected. The occupancy level rapidly started to grow at 9:00 a.m., when almost 100 vehicles arrived at the parking lot. The peak occupancy was at 1:00 p.m. when 220 vehicles were present. After the peak hour, the number of parked vehicles started to decrease, and at 6:00 p.m., there were only 42 parked vehicles. Table 5.4 shows the exact numbers of vehicles parked in the parking lot from 7:00 a.m. to 6:00 p.m.

Table 5.4: UTEP SB2 parking lot - number of vehicles parked on 16th February 2022.

Time	Number of Vehicles
7:00 a.m.	5
8:00 a.m.	47
9:00 a.m.	130
10:00 a.m.	155
11:00 a.m.	177
12:00 p.m.	187
1:00 p.m.	220
2:00 p.m.	171
3:00 p.m.	145
4:00 p.m.	121
5:00 p.m.	NA
6:00 p.m.	42

5.3.2 2017 Data

The second set of data, collected by students in the CE5358 Traffic Engineering course in November 2017 at the UTEP SB2 parking lot, was available for this thesis. The data were collected on the 7th and 14th of November but together they covered the daytime hours from 7:00 a.m. to 6:00 p.m. Therefore, the AnyLogic simulation model created for the SB2 parking lot in 2022 could also be used with the parking demand data from 2017 to predict the search time, leaving time, and other performance measures. Table 5.5 contains the observations from the 2017 data.

Table 5.5: UTEP SB2 parking lot - number of vehicles parked on 7th and 14th, November, 2017.

Time	Number of Vehicles
7:00 a.m.	20
8:00 a.m.	110
9:00 a.m.	245
10:00 a.m.	286
11:00 a.m.	275
12:00 p.m.	266
1:00 p.m.	261
2:00 p.m.	276
3:00 p.m.	268
4:00 p.m.	268
5:00 p.m.	212
6:00 p.m.	96

The peak hour in 2017 weekday was 10:00 a.m. The number of vehicles started to decrease after 4:00 p.m. The differences between the 2022 and 2017 data may be due to several reasons. First, the 2017 data was collected before Covid-19. At that time, working online from home was not common. Another reason could be a different class schedule, as more students had classes on campus in 2017. Last, a possible reason is that there was a building under construction across the parking lot, and workers parked their vehicles at this SB2 parking lot. There was even a capacity reduction, as the construction site office occupied some parking stalls in SB2. This reduced capacity from 409 parking spaces to 286. This means that the occupancy of the parking lot from 10:00 a.m. to 4:00 p.m. was above 90%.

The difference in the number of vehicles present in the parking lot is significant. The old layout of the SB2 parking lot in 2017 is shown in Figure 5.4.

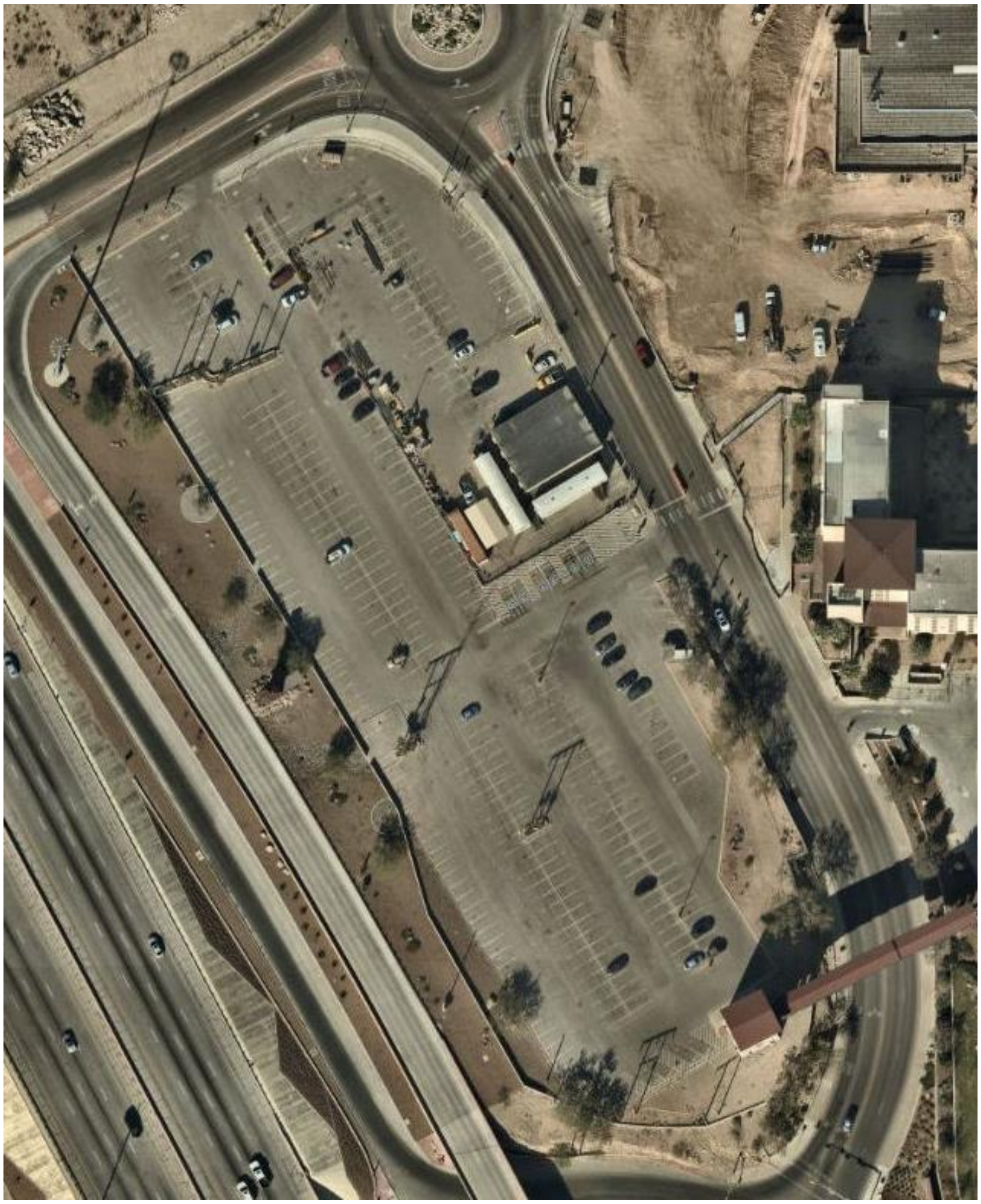

Figure 5.4: UTEP SB2 parking lot – physical layout in 2017.

The number of vehicles present in the parking lot shows that the total number of parked vehicles decreased in 2022. The comparison of 2017 and 2022 parking demand can be seen in Figure 5.5 below.

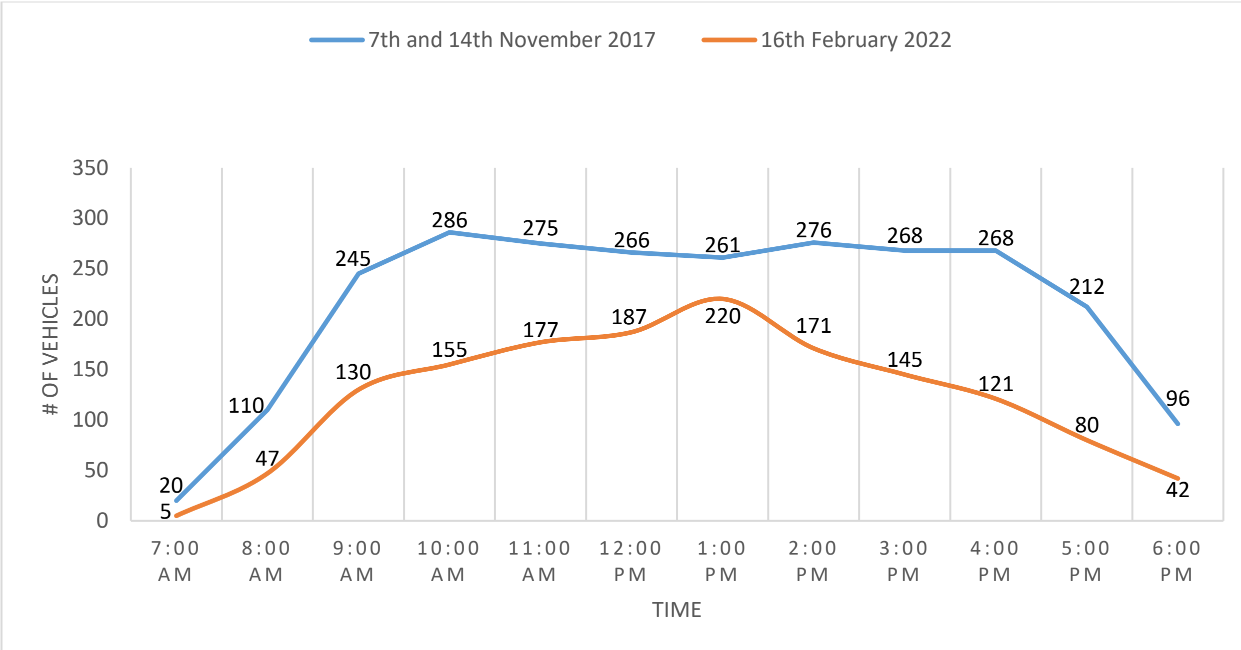

Figure 5.5: UTEP SB2 parking lot – parking demands on selected weekdays in 2017 and 2022.

5.4 Simulation Experiments

The UTEP SB2 parking lot was simulated in AnyLogic. The simulation model consists of several parts. The physical layout of the parking lot, which includes all the parking spaces, aisles, entrances, exits, and intersections, was represented in AnyLogic to scale, which is essential for a realistic model. Figure 5.6 shows the physical layout of the UTEP SB2 parking lot in AnyLogic.

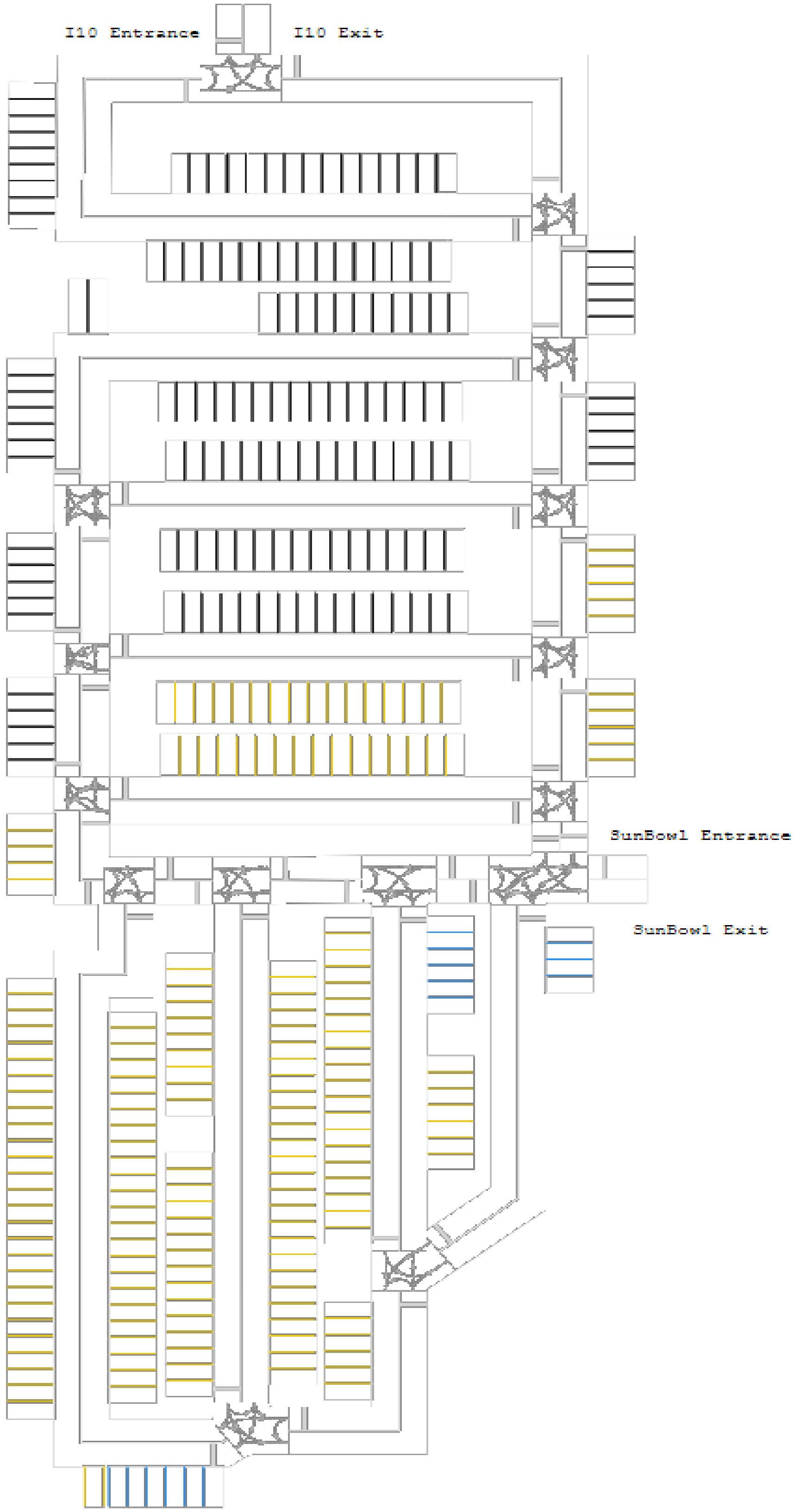

Figure 5.6: UTEP SB2 parking lot – layout of simulation model in AnyLogic.

The model contains 349 parking spaces. These spaces were divided into three categories and coded in different colors. The first category of parking spaces with blue lines are parking spaces for the disabled. The second category of spaces with yellow lines are preferred parking spaces observed during the data collection. Finally, the last category of spaces with black lines consists of regular parking spaces. Drivers will first go to park at the preferred spaces. They will only park in the regular spaces if they cannot find an empty space in the preferred area.

The second important part of the model is the logic model. It determines the vehicles' behavior and the ways performance measures are calculated. Figure 5.7 shows the logic model used for the UTEP SB2 parking lot.

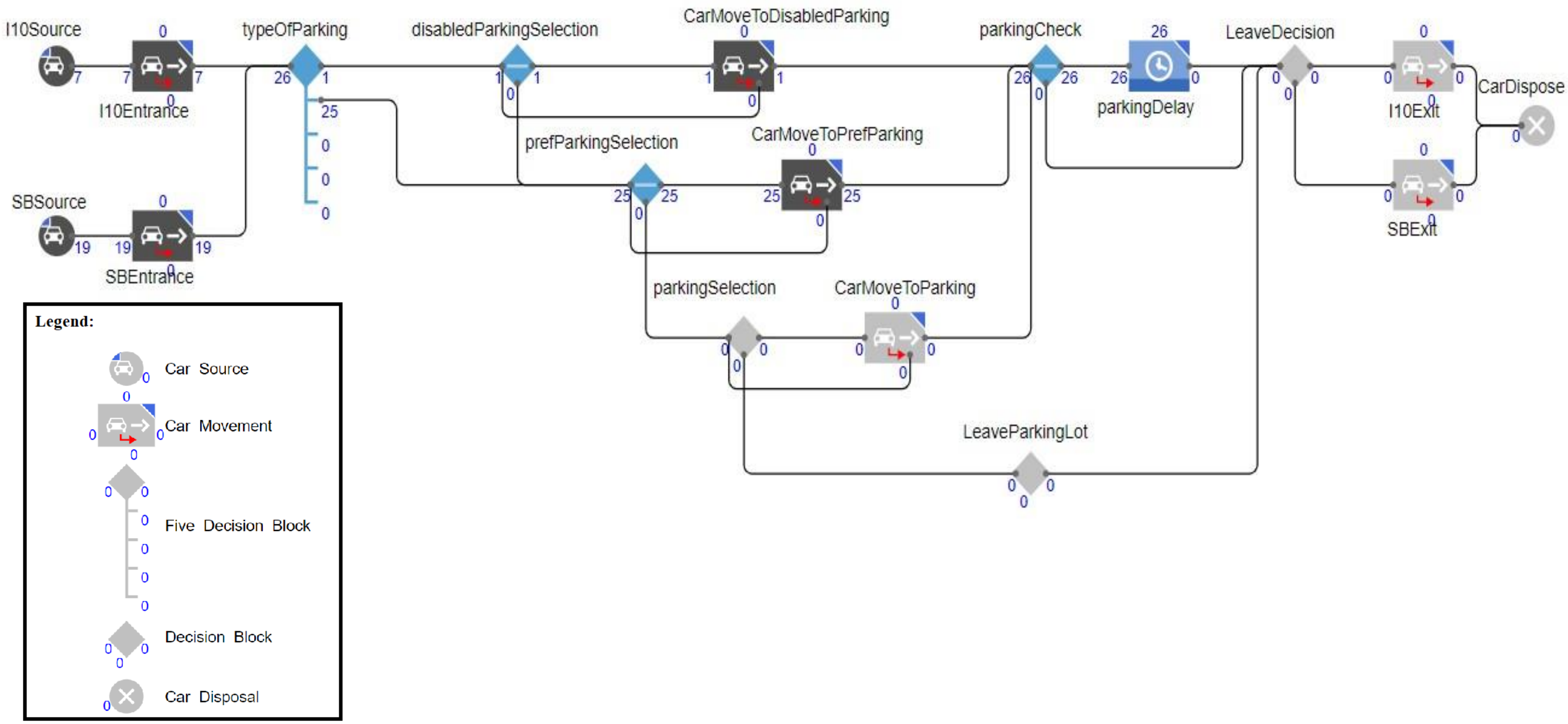

Figure 5.7: UTEP SB2 parking lot – logic model for existing operations.

The logic model starts with two vehicle sources (source nodes) that generate vehicles. One is for the I-10 Freeway entrance, and the second one is for the Sun Bowl Drive entrance. At the selected entrance, each vehicle decides what category of parking space (disabled, preferred, or general) it is looking for. The next decision is parking space selection. A vehicle selects an empty parking space at random in the category of interest and sets it as the destination. If two vehicles select the same stall, the one who arrives at the parking stall later needs to select a different one. This vehicle will register an (unsuccessful) attempt. A vehicle has a maximum of three attempts. If the vehicle does not reach a selected stall in three attempts, it leaves the parking lot. If an attempt to park in a selected stall is successful, search time is counted and updated to overall data. After a vehicle has parked, a parking delay is assigned (equivalent to time spent in the parking stall). The parking delay was taken from the collected data. It is set to a triangular distribution with a minimum of 60 minutes, an average of 300 minutes, and a maximum of 360 minutes. When a vehicle leaves the parking lot, it is assigned to one of the two exits based on the probability set according to the collected data. After reaching the exit, leaving time is counted and updated to overall data. When the vehicle reaches the end of the exit lane, it disappears in a sink node. Input data used in the logic model are shown in Table 5.6.

Table 5.6: UTEP SB2 parking lot – simulation inputs.

Initial Vehicle Speed	18 km/h (11,18 mph)
Minimum Vehicle Speed	12 km/h (7,46 mph)
Maximum Vehicle Speed	18 km/h (11,18 mph)
Average Vehicle Speed	15 km/h (9,32 mph)
Proportion of Disabled Drivers	2%
Minimum Parking Delay	60 minutes
Maximum Parking Delay	360 minutes
Average Parking Delay	300 minutes
Probability of choosing I-10 Freeway Exit	15%
Probability of choosing SB Exit	85%

The third important part of the model is the specification of the outputs. The outputs of a simulation run can be obtained from the logic model itself, or in some cases, there is a need to create variables that count more specific values. The most valuable results obtained are search time, leaving time, the number of attempts, time lost during the unsuccessful parking, number of vehicles parked in preferred parking spaces, and more. AnyLogic generates outputs in graphical and csv format. Examples of measured values are shown in Figure 5.8.

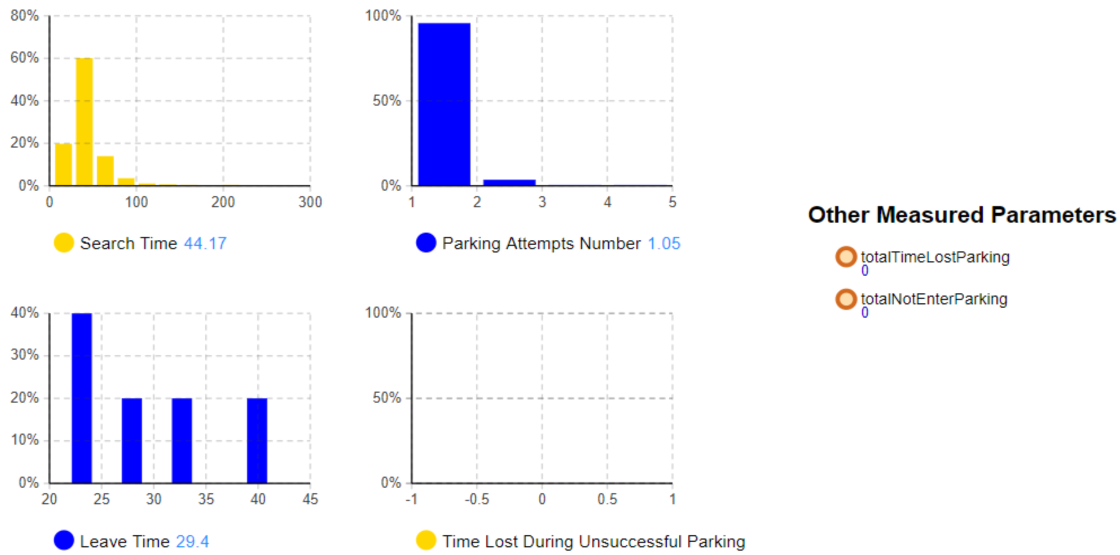

Figure 5.8: UTEP SB2 parking lot - measured parameters.

5.4.1 Scenario 1 – 2022 Parking Demand

This subsection reports the results of the UTEP SB2 parking lot simulation model in AnyLogic with 2022 parking demand. The simulated day was Wednesday, 16th of February, 2022. The simulated hours were from 6:00 a.m. to 12:00 a.m. Ten repetition runs of the simulation were done, and the average value was taken out of the ten runs. Table 5.7 shows the number of parked vehicles at each hour in all the runs, with the average value in the rightest column.

Table 5.7: UTEP SB2 parking lot - number of parked vehicles from Scenario 1 simulations.

Number of parked vehicles (vehicles)												
Time	Real	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Average
6:00 a.m.	0	0	0	0	0	0	0	0	0	0	0	0
7:00 a.m.	5	6	4	6	5	7	6	3	5	4	6	5,2
8:00 a.m.	47	46	48	44	40	58	50	59	44	46	54	48,9
9:00 a.m.	130	130	125	118	130	133	138	128	123	131	130	128,6
10:00 a.m.	155	155	143	154	166	152	165	150	142	148	153	152,8
11:00 a.m.	177	176	159	174	196	165	166	175	160	167	192	173
12:00 p.m.	187	186	168	180	206	183	179	183	180	190	190	184,5
1:00 p.m.	220	224	202	218	248	214	223	208	214	230	220	220,1
2:00 p.m.	171	173	163	174	186	171	183	170	174	195	176	176,5
3:00 p.m.	145	143	122	143	153	146	152	140	154	165	148	146,6
4:00 p.m.	121	120	101	110	129	112	129	105	140	147	123	121,6
5:00 p.m.	NA	82	72	87	78	70	90	56	88	103	72	79,8
6:00 p.m.	42	43	37	53	38	45	50	26	52	60	42	44,6
7:00 p.m.	NA	31	24	31	27	23	30	13	33	35	23	27
8:00 p.m.	NA	15	13	13	15	13	13	6	14	19	11	13,2
9:00 p.m.	NA	1	1	2	4	4	5	3	2	1	3	2,6
10:00 p.m.	NA	0	0	0	0	1	0	0	0	0	0	0,1
11:00 p.m.	NA	0	0	0	0	0	0	0	0	0	0	0

As the AnyLogic model works with probability, each run is expected to be unique, and the results of multiple runs vary. For example, if we compare the vehicle count at 1:00 p.m., run 2 has 202 vehicles, and run 4 has 248 vehicles. The difference is 46 vehicles. However, after ten simulation runs, we can see that the average number of vehicles at 1:00 p.m. is 220.1, which is just

0.1 different from the actual number of observed vehicles. A comparison of the real number of vehicles present in the parking lot and the average of 10 simulation runs is shown in Figure 5.9.

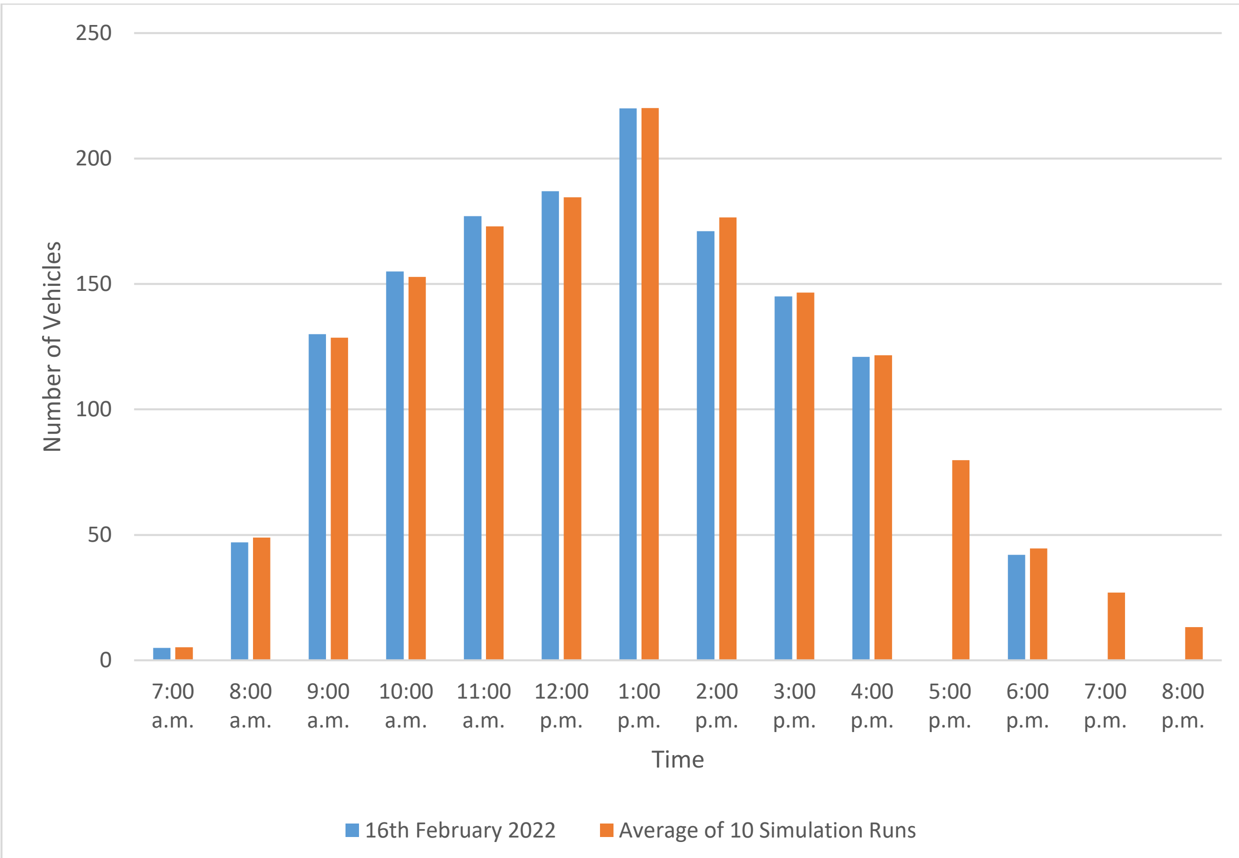

Figure 5.9: UTEP SB2 parking lot – comparison of 16th February 2022 and average of 10 simulation runs.

Other results can be found in Table 5.8.

Table 5.8: UTEP SB2 parking lot – simulation outputs of Scenario 1.

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Average
Total Demand (vehicles)/Day	376	353	373	395	378	405	347	383	407	386	380,3
Demand for Disabled Stalls (vehicles)	12	5	2	10	11	5	6	4	4	11	7
Demand for Preferred Parking Stalls (vehicles)	333	331	338	325	341	359	318	345	355	345	339
Demand for General Parking Stalls (vehicles)	31	16	33	59	26	40	23	32	44	30	33,4
Unsuccessful Search (vehicles)	0	1	0	1	0	1	0	2	4	0	0,9
I-10 Freeway Entrance (vehicles)	59	47	52	51	49	54	52	58	44	55	52,1
SB Entrance (vehicles)	317	306	321	344	329	351	295	325	363	331	328,2
I-10 Freeway Exit (vehicles)	58	57	56	48	57	61	46	63	60	56	56,2
SB Exit (vehicles)	318	296	317	347	321	344	301	320	347	330	324,1
Average Search Time (s)	43	43,6	44,08	47,35	42,34	43,59	45,42	45,47	44,98	44,52	44,5
Average Leaving Time (s)	41	42,44	41,8	40,8	41,53	42,09	40,92	41,71	41,86	41,4	41,6
Average Attempt	1,1	1,08	1,06	1,14	1,04	1,08	1,09	1,1	1,12	1,08	1,08
Total Time Lost (min)	0	3,17	0	3,28	0	3,2	0	5,12	13,74	0	2,85

Among the simulation outputs are the number of unsuccessful drivers, average search time, average leaving time, and average time lost because of unsuccessful parking. As seen from the data, unsuccessful drivers can be found even for simulations where the maximum capacity is not reached. That could be caused by a limited number of attempts (maximum of 3) and the chance that one vehicle chooses the same stall as other vehicles in the parking lot three times in a row.

The average search time and average leaving time obtained from the simulation results are very close to the observed times, which means that the speed of the vehicles in the simulation is close to reality. Time lost because of unsuccessful parking has an average of 171 seconds. If the vehicles had more than three attempts, they would find their stalls in the parking lot.

5.4.2 Scenario 2 – 2017 Parking Demand

As the simulation model run with data collected in February 2022 provided very realistic outputs, it was applied to study other scenarios.

After that arises a robust model that can predict the future or find the bottlenecks for selected changes in parking demand. 2017 and 2022 are different in many aspects, either undergoing works, Covid-19 or changing the physical layout. However, it can still provide a better idea of the situation than just comparing the number of vehicles present in the parking lot. The results of 2017 compared to 2022 are shown in Tables 5.9 and 5.10.

Table 5.9: UTEP SB2 parking lot - comparisons of number of parked vehicles between Scenarios 1 and 2.

Number of Parked Vehicles (vehicles)				
	2022		2017	
Time	Model	Real	Model	Real
7:00 a.m.	5,2	5	19,7	20
8:00 a.m.	48,9	47	106	110
9:00 a.m.	128,6	130	235,5	245
10:00 a.m.	152,8	155	292,2	286
11:00 a.m.	173	177	289,7	275
12:00 p.m.	184,5	187	270,3	266
1:00 p.m.	220,1	220	250,1	261
2:00 p.m.	176,5	171	269,3	276
3:00 p.m.	146,6	145	261,7	268
4:00 p.m.	121,6	121	256,3	268
5:00 p.m.	79,8	NA	201,1	212
6:00 p.m.	44,6	42	106,3	96
7:00 p.m.	27	NA	62,3	NA
8:00 p.m.	13,2	NA	27,2	NA
9:00 p.m.	2,6	NA	6,7	NA
10:00 p.m.	0,1	NA	0,2	NA

Table 5.10: UTEP SB2 parking lot – comparison of simulation outputs between Scenarios 1 and 2.

	2022	2017
Total Demand (vehicles)/Day	380,3	671,8
Demand for Disabled Stalls (vehicles)	7	14,4
Demand for Preferred Parking Stalls (vehicles)	339	463,5
Demand for General Parking Stalls (vehicles)	33,4	192,7
Unsuccessful Search (vehicles)	0,9	1,2
I-10 Freeway Entrance (vehicles)	52,1	126,3
SB Entrance (vehicles)	328,2	545,5
I-10 Freeway Exit (vehicles)	56,2	96,9
SB Exit (vehicles)	324,1	574,9
Average Search Time (s)	44,5	49,7
Average Leaving Time (s)	41,6	41,9
Average Attempt	1,08	1,13
Total Time Lost (min)	2,85	3,9

The parking demand in 2017 was much higher than in 2022. An essential thing visible from the results is the average search time and average time lost because of unsuccessful parking. Search time in 2017 was higher by 5 seconds, which was probably caused by the congestion during the morning peak hour. The time lost was about 60 seconds longer than in 2022.

5.4.3 Scenario 3 – Smart Parking

One of the possible parking management improvements is the use of smart parking technologies, which are described in Chapter 3. In this scenario of the case study, four different parking guidance levels have been tested.

Each level has its advantages and disadvantages, which will be discussed with the results of the simulations.

a) Level 0 – No access control and no guidance: The parking lot has no access control. No occupancy information is provided to users. The users are left to search for any empty stall by themselves.

b) Level 1 – Access control and no guidance: The parking lot has access control at the entrance. The number of empty parking spaces in the lot is displayed in DMS to inform drivers. However, once the drivers have entered the parking lot, they have to search for empty stalls by themselves.

c) Level 2 – Access control and zone occupancy guidance: The parking lot has access control at the entrance. The number of empty parking spaces in the various zones (sub-areas inside the lot) is displayed on DMSs to inform drivers.

d) Level 3 – Access control and destination stall guidance: The parking lot has access control at the entrance. Each driver is assigned a parking stall (according to his/her preference) upon entering the parking lot. In addition, a smartphone app or DMSs at the entrance and intersections in the parking lots guides the driver to the exact parking space.

As the parking demand at UTEP does not reach total capacity, a unique parking demand scenario was created to show the advantage of the increased level of information. The 2022 parking demand used in Scenario 1 was increased by 80% so that the demand at the peak hour reached capacity. That unique situation might seem unrealistic. However, from the trend observed in the 2017 demand, this assumed 80% increase is possible if the schedule for the Fall semester changes so more students come to the campus to attend classes at the same time. Further, the closure of an adjacent parking lot will push the demand for this SB2 parking lot. The parking demand for this scenario is in Table 5.11.

Table 5.11: UTEP SB2 parking lot – parking demand for Scenario 3.

Time	No. of vehicles (vehicles)
7:00 a.m.	9
8:00 a.m.	84,6
9:00 a.m.	234
10:00 a.m.	279
11:00 a.m.	318,6
12:00 p.m.	336,6
1:00 p.m.	396
2:00 p.m.	307,8
3:00 p.m.	261
4:00 p.m.	217,8
5:00 p.m.	144
6:00 p.m.	75,6

Another change to show the smart parking technologies was made in the logic model. Again, several blocks were added or slightly adjusted as the information about occupancy level is needed before the vehicle enters the parking lot. The adjusted logic model is shown in Figure 5.10.

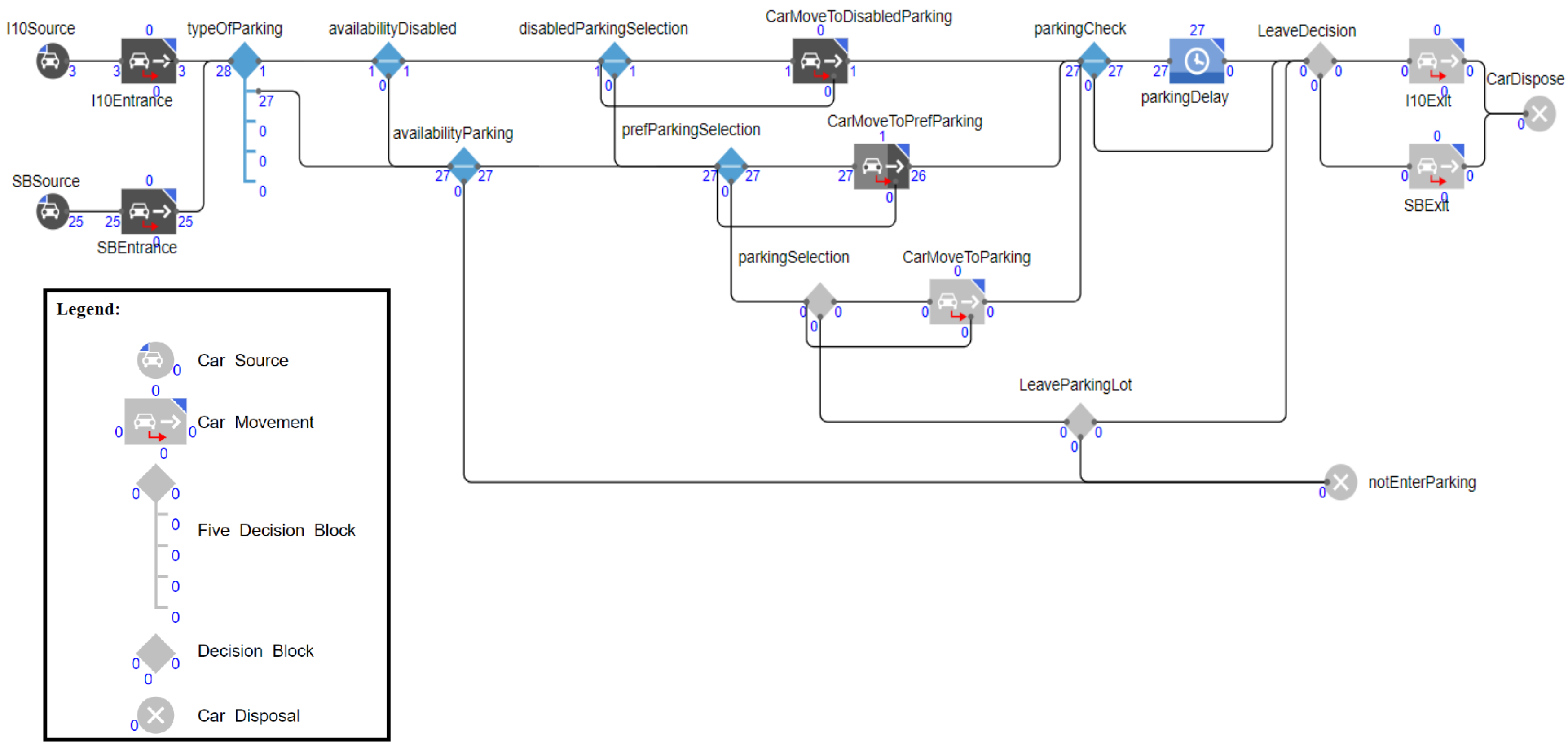

Figure 5.10: UTEP SB2 parking lot – logic model for Levels 1, 2 and 3.

The adjusted logic model contains new decision blocks “availabilityDisabled” and “availabilityParking” that check the parking lot's availability. If there are no free spaces and the driver knows it before he enters the parking lot, he will not enter, and for that, there is also a new vehicle disposal block named "notEnterParking". For Level 1 – access control and no guidance, are those new blocks the only thing different from Level 0 – no access control and no guidance. Level 2 – access control and zone occupancy guidance has a different number of attempts than Level 1 for preferred parking lots as there is a higher probability of getting a free stall in the general zone. Level 3 – access control and destination stall guidance, check the parking space availability. If the vehicle can choose a parking space before entering the parking lot, it will allow the vehicle to enter. That will provide only one attempt for every vehicle entering the parking lot.

Similar to the previous results evaluation, even with each parking management approach, ten runs were done, and the final result is the average number of all the results. The average number at each hour of the day of each parking technology approach is shown in Table 5.12.

Table 5.12: UTEP SB2 parking lot - number of parked vehicles from Scenario 3 simulations.

Number of Parked Vehicles (vehicles)					
Time	Level 0	Level 1	Level 2	Level 3	Observed
7:00 a.m.	9,8	8,8	9,5	8,1	9
8:00 a.m.	84,5	81,7	82,8	80,3	84,6
9:00 a.m.	233	232,2	231,6	230,6	234
10:00 a.m.	277,9	274,5	275,9	274,2	279
11:00 a.m.	314,9	317,1	318,9	314,1	318,6
12:00 p.m.	335,9	339,5	341,6	334,3	336,6
1:00 p.m.	345,9	346,5	342,8	344,1	396
2:00 p.m.	271,2	262,6	264,2	266,7	307,8
3:00 p.m.	216,8	210,1	214	214,3	261
4:00 p.m.	178	178,2	176,8	179,7	217,8
5:00 p.m.	115,6	119	117,8	119,7	NA
6:00 p.m.	67,6	72,7	67,6	74,3	75,6
7:00 p.m.	41,9	44,4	42	46,7	NA
8:00 p.m.	20,8	23,4	20,3	22,2	NA
9:00 p.m.	5,8	5,9	5,4	4,7	NA
10:00 p.m.	0,4	0,5	0,5	0,6	NA

The first half of the table shows very close results to the expected numbers. The change comes at 1:00 p.m. when the expected demand exceeds the parking lot capacity. As a result, the number of vehicles after 1:00 p.m. is about 50 vehicles less than expected, which corresponds to exceeding the capacity. The number of vehicles present at the parking lot is getting back to expectations after 5 hours at 6:00 p.m.

The output data obtained from the simulation runs (average of 10 replications) is shown in Table 5.13.

Table 5.13: UTEP SB2 parking lot – outputs of Scenario 3 simulations.

	Level 0	Level 1	Level 2	Level 3
Total Demand (vehicles)/Day	685,1	678,1	681,7	680,3
Demand for Disabled stalls (vehicles)	9,1	7,6	8,6	8,5
Demand for Preferred parking stalls (vehicles)	415,8	411,3	416,6	421,5
Demand for General parking stalls (vehicles)	206	207	205,4	198,4
Unsuccessful search (vehicles)	54,2	35,8	27,8	0
Rejected Demand (vehicles)	0	16,4	23,3	51,9
I-10 Freeway Entrance (vehicles)	100,4	98	102,1	96,6
SB Entrance (vehicles)	584,7	580,1	579,6	583,7
I-10 Freeway Exit (vehicles)	105,5	100,6	98	93,6
SB Exit (vehicles)	579,6	571,1	560,4	534,8
Average Search Time (s)	52,5	52,0	50,6	41,2
Average Leaving Time (s)	42,4	42,0	42,0	42,0
Average Attempt	1,21	1,20	1,19	1
Total Time Lost (min)	136,86	100,1	71,38	0

The first two essential facts that have to be checked are that the total number of vehicles (total demand) is similar in the four levels, and the sum of unsuccessful drivers plus the number of drivers that did not enter the parking lot is similar. As those numbers do not differ much, it is possible to continue with the evaluation.

One interesting fact is that slightly more vehicles park in the preferred parking lots with the Level 3 approach. Other levels have similar results but are different from Level 3 output.

The number of unsuccessful drivers is predictably decreasing with an increasing level of information. Level 0 allows all drivers to freely search for spaces in the parking lot, even if there is no free space. In Level 1, the drivers enter the parking lot when there is at least a free stall, but multiple drivers could select the same stall. Level 2 is very similar to Level 1, but as the drivers who select the general stalls have a faster search time than the drivers who select the same category of stalls in Level 1. Level 3 does not have unsuccessful drivers, as the parking space selection is made even before entering the parking lot.

Search time is one of the most crucial information obtained from the simulation. It shows the actual effectiveness of each approach experienced by the drivers. Level 0 has 52.4 seconds of average search time, which is a few seconds more than Level 1 and Level 2. The average search time of Level 3 is more than 11 seconds faster than Level 0.

The total time lost for 54.2 unsuccessful searches is 8212.31 seconds for Level 0. The total time lost for the Levels 1, 2, and 3 controls depends on the number of unsuccessful drivers. Level 2 sends drivers to the general stall areas earlier than Level 1. As a result, average drivers find their space faster. On the other hand, Level 3 does not have lost time in the parking lot as it chooses the stall for vehicles right at the entrance.

6 CASE STUDY IN PRAGUE

6.1 PRAGUE PARKING

Prague uses a zoning system as a tool for parking regulation. The primary purpose of zoning in Prague is to ensure that residents in busy locations can find a parking stall near their homes, properties, or businesses. Another purpose is to motivate visitors to stay in selected locations only for the necessary time and free up the parking spaces for other drivers ("Parkuj v Klidu", 2022)

The list below shows and describes Prague parking zones:

a) Blue zones for residents' parking

- Marked with blue horizontal and vertical traffic signs. Permits for these zones are issued based on the permanent residential address or property ownership. Other vehicles can be parked only for a maximum of three hours after paying the parking fee.

b) Purple zones for mixed parking

- Purple zones are marked with a purple stripe on the vertical traffic signs. Permits for these zones are also issued based on the permanent residential address or property ownership. However, other vehicles can park in that zone for a maximum of 24 hours (The maximum time can differ).

c) Orange zones for visitors

- Orange zones are marked with an orange stripe on the vertical traffic signs. That parking lot is intended for short-term parking of visitors. The maximum time spent in the orange zone parking space is two hours. ("Parkuj v klidu" 2022)

An alternative to parking in zones in Prague are P+R parking lots. These parking lots should be located in areas with access to public transit. In addition, P+R parking lots should persuade out-of-town drivers to drive into the city in their vehicles and then use public transport to move around the city. ("Parkuj v Klidu", 2022).

6.2 Study Site

The second case study in this thesis is based on the P+R Holešovice parking lot in Prague, Czech Republic. GREEN Center s.r.o. company provided the data for the P+R Holešovice parking lot.

The P+R Holešovice parking lot is situated in district Holešovice, in the north part of Prague. It is located near the Prague Ring, which is a motorway that, after its completion, should create an outer bypass of Prague. There is also a train station about 200 meters (656 feet) away and a metro station that is 100 meters away (328 feet). Another point of interest near the parking lot is the soccer stadium of Loko Vltavín, which is approximately 500 meters away. Charles University is about 18 minutes by walking. The location of the parking lot is shown in Figure 6.1.

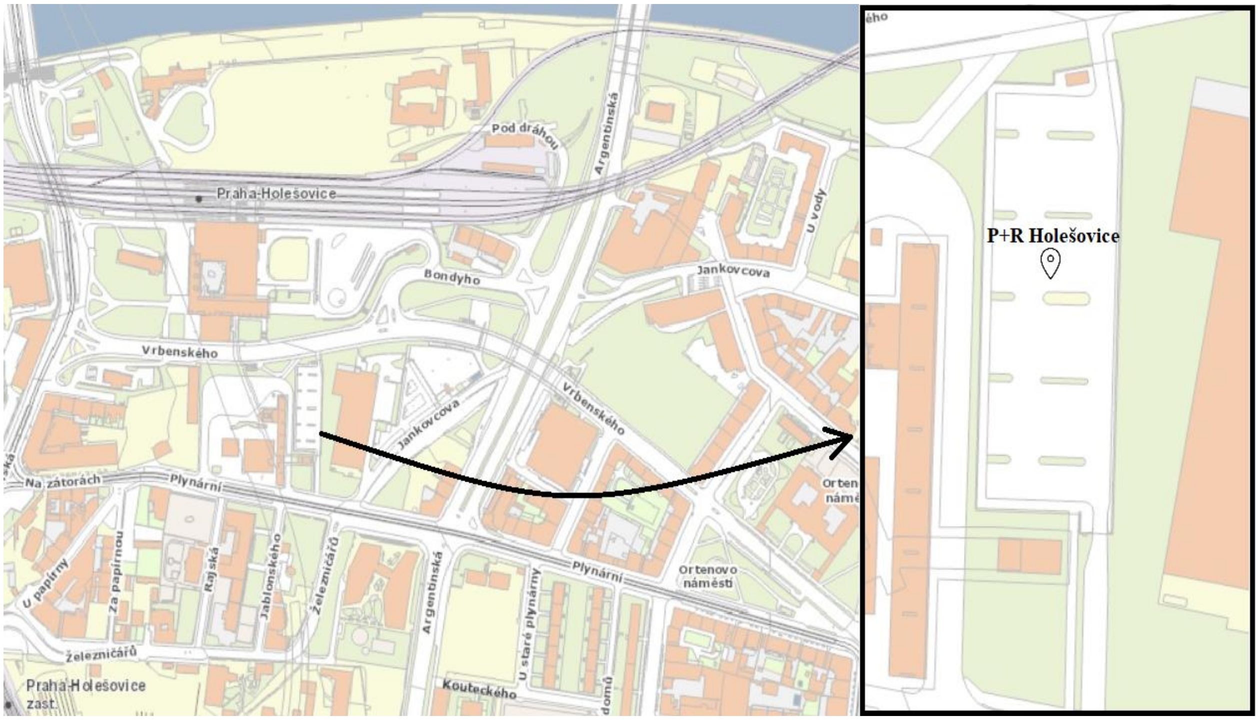

Figure 6.1: P+R Holešovice parking lot – location map.

The physical layout of the parking lot did not change over the years and has stayed the same. It has one exit, one entrance, and 76 parking spaces of which two parking spaces are reserved for disabled drivers. Two parallel two-way aisles run in the north-south direction, with the stalls arranged for 90-degree parking. The entrance is from Plynární Street that has a tram belt with a nearby tram stop, Nádraží Holešovice. The exit leads to Vrbenského Street. The physical layout of the parking lot is shown in Figure 6.2. The photo was taken in 2006, and the reason for using that photo is because the trees and bushes have grown over the years, obstructing the layout from the bird's view.

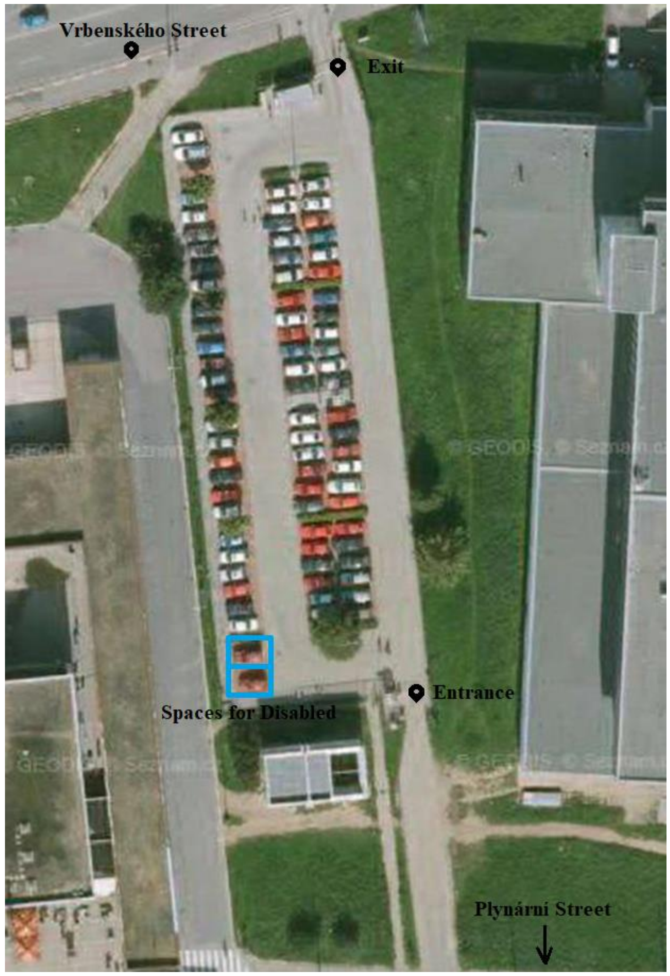

Figure 6.2: P+R Holešovice parking lot – physical layout. (“Mapy.cz” 2022)

6.3 DATA PROCESSING

The data for this parking lot was provided by the GREEN Center s.r.o., a company that provides technologies to the P+R Holešovice parking lot. The solution allows automatic counting of vehicles present in the parking lot and automatic barriers at the entrance and exit. All the data were collected automatically by the entrance and exit sensors installed by the barriers. The data were updated every ten minutes unless there was no entering or exiting vehicle.

The provided data is from February 2022, from the 1st of February, a Tuesday, to the 27th of February, a Sunday. The data from the 1st to 27th of February, 2022 can be found in Figure 6.3.

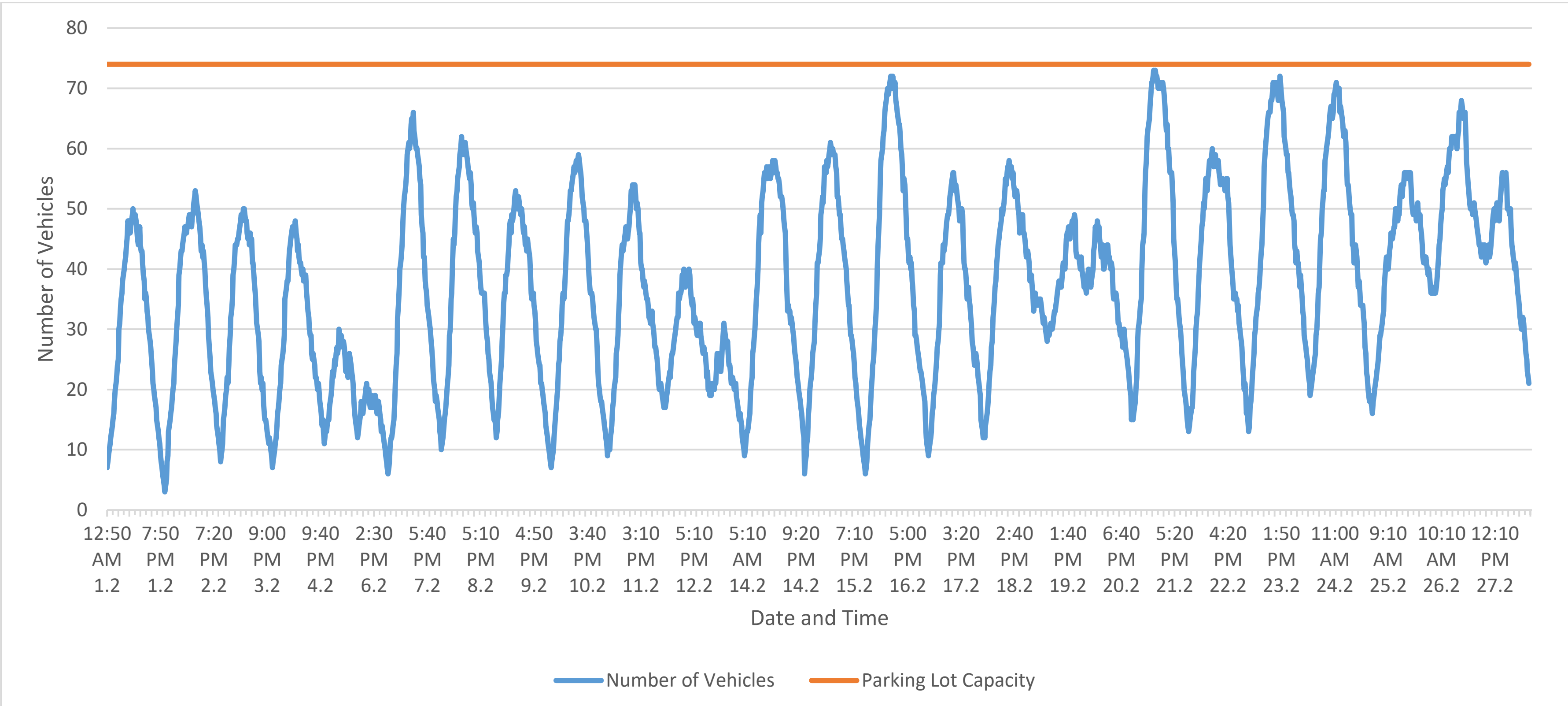

Figure 6.3: P+R Holešovice parking lot – observed number of parked vehicles in February 2022.

From the occupancy pattern in the data, it is clear that weekends had lower occupancy than weekdays, but more vehicles parked overnight. It is also visible that the first half of the month has lower usage than the second half. That could be caused by the start of the spring semester universities on the 14th of February, 2022.

It was found that most cars present in the parking lot were on Monday. As data did not contain the last day of the month (Monday, 28th February), the second-highest occupant day was chosen, therefore Wednesday. The occupancy of the parking lot on each Wednesday (2nd, 9th, 16th, and 23rd February) in the month is shown in the graph in Figure 6.4.

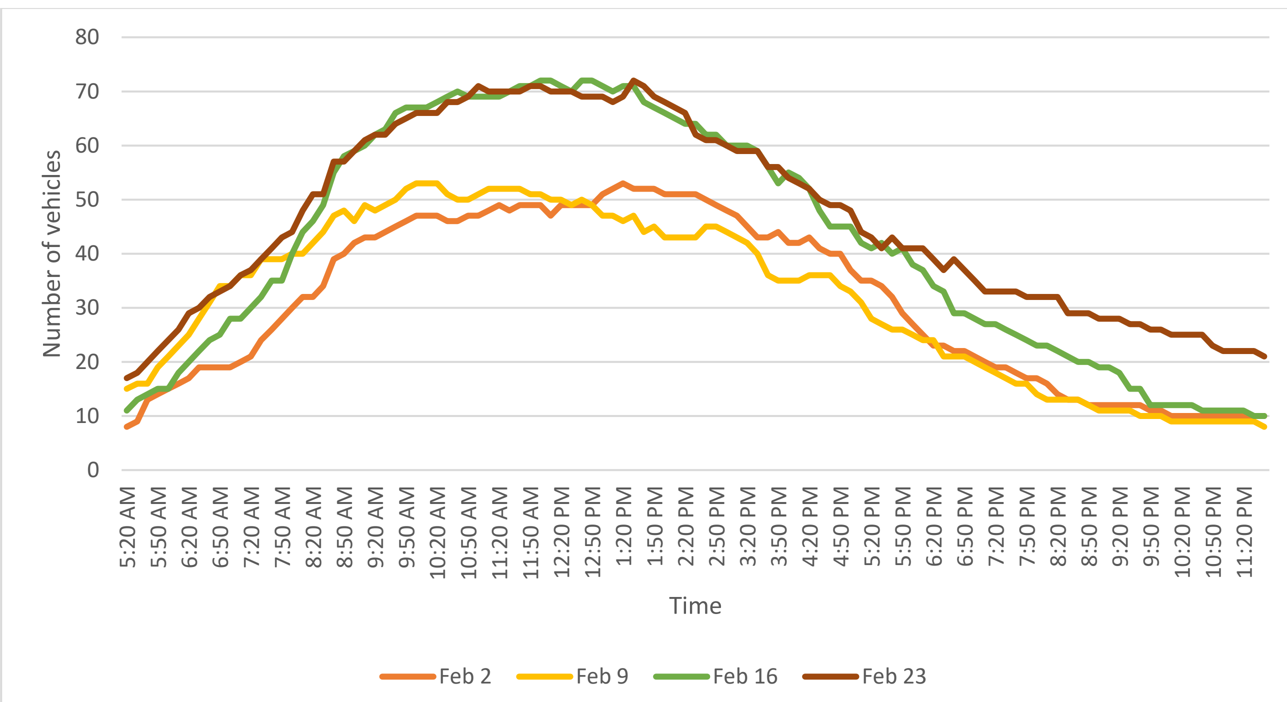

Figure 6.4: P+R Holešovice parking lot – observed number of parked vehicles on all Wednesdays in February 2022.

For simulations, three datasets were chosen. The first one with the low demand was the first Wednesday in the month, 2nd February. The second dataset contains high demand, which was taken from the last Wednesday of the month, 23rd February. Finally, the last dataset was an average of all four Wednesdays in February. Figure 6.5 shows a graph with low, average, and high demand each hour.

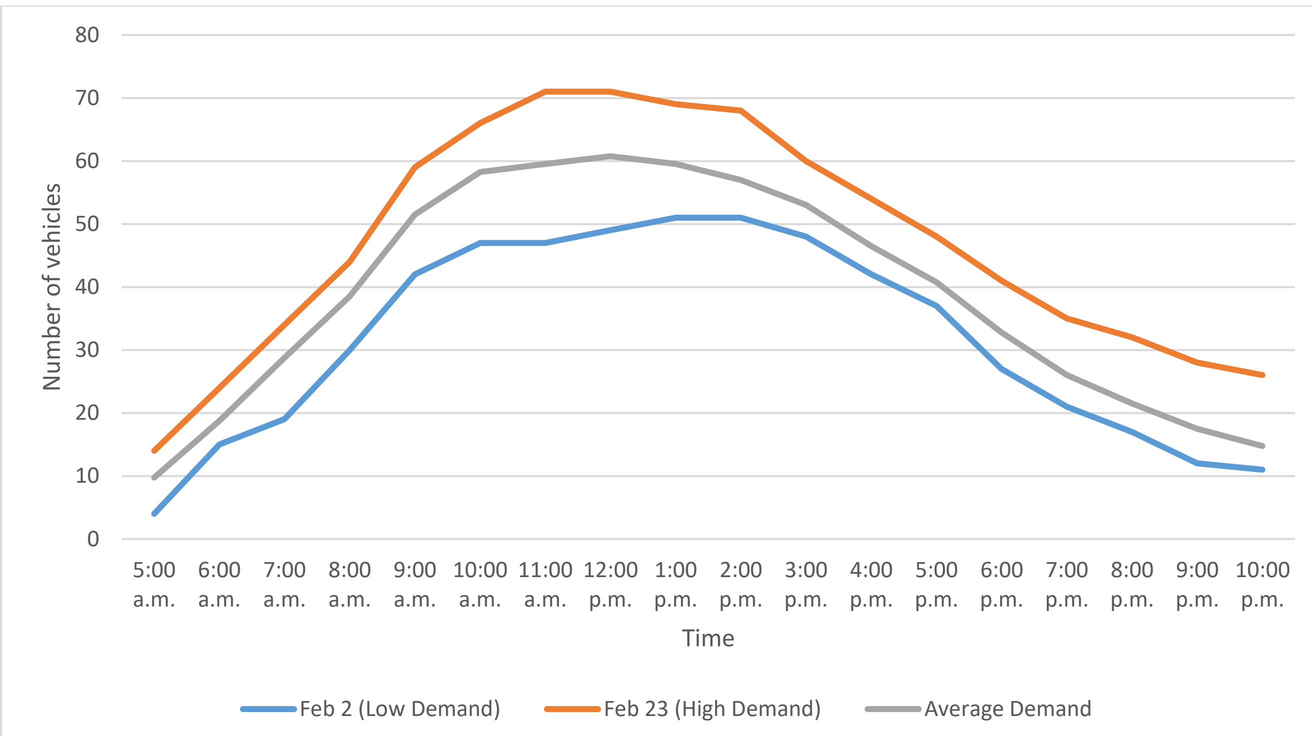

Figure 6.5: P+R Holešovice parking lot – low, average, and high parking demand curves.

From the graph, it is clear that the peak hours are the same and the only thing that changes is the number of vehicles present in the parking lot. The chosen minimum, maximum, and average occupancy datasets will be processed in the next subchapter with the P+R Holešovice parking lot AnyLogic parking model.

6.4 Simulation Experiments

The AnyLogic model for the P+R Holešovice parking lot is similar to the one for the UTEP SB2 parking lot. It also consists of three main parts, physical layout, logic model, and output data (graphs). The main difference will be in the physical layout of the parking lot. The physical layout of the P+R Holešovice parking lot in AnyLogic is shown in Figure 6.6.

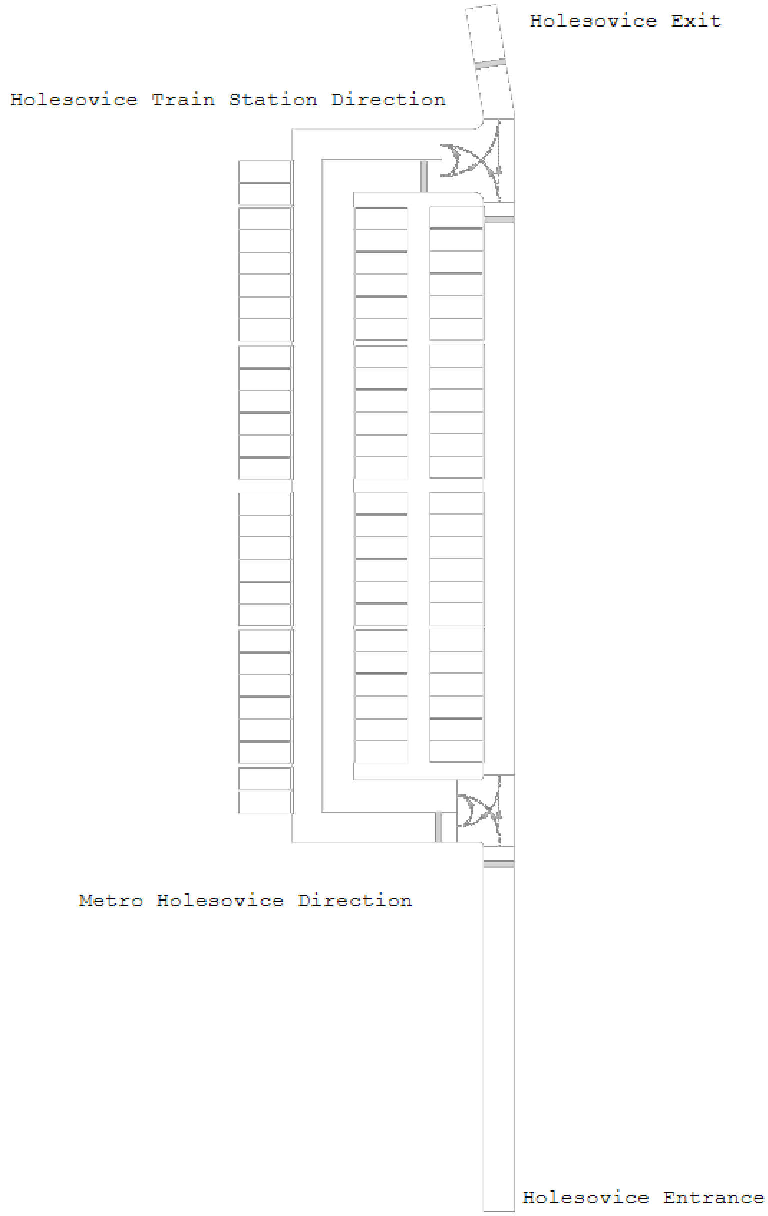

Figure 6.6: P+R Holešovice parking lot – layout of simulation model in AnyLogic.

Same as the UTEP SB2 parking lot model, the P+R Holešovice parking lot has three types of parking spaces, preferred, disabled, and general parking stalls. The distribution of preferred and general parking spaces in the UTEP model case was assumed for the P+R Holešovice parking lot, which means 40 preferred parking stalls and 34 general for the P+R Holešovice model. The two parking stalls for disabled drivers are located in the left corner of the parking lot near the entrance.

The logic model of the P+R Holešovice parking lot has only one entrance and one exit. From the data provided, parking delay was set to a triangular distribution with a minimum of 45 minutes, a maximum of 720 minutes, and an average of 420 minutes. The P+R Holešovice parking lot's logic model is shown in Figure 6.7.

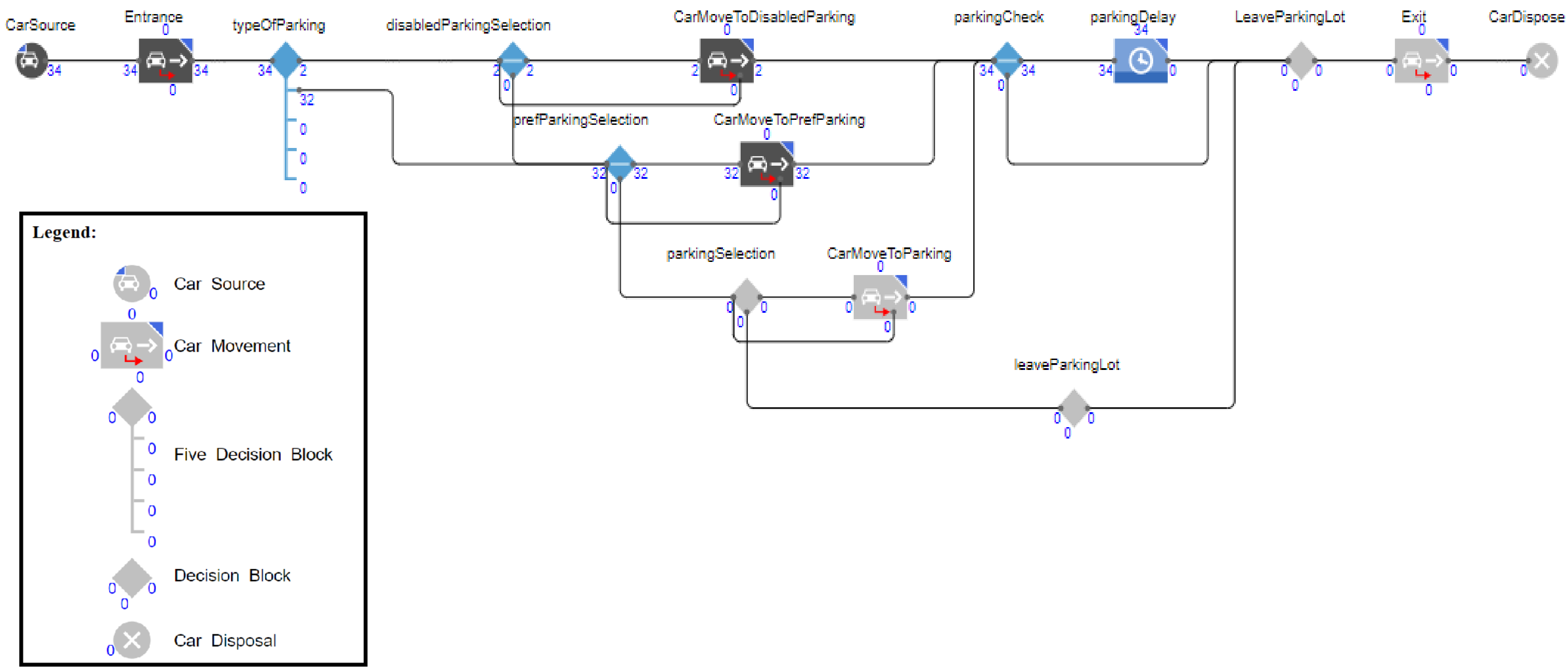

Figure 6.7: P+R Holešovice parking lot – logic model for existing operations.

As the physical layout and logic model has undergone some changes, the outputs of the simulation have changed. For example, there is no need to count the number of vehicles entering or exiting each exit as there is just one possibility for the drivers. However, the other counted outputs stayed the same as in the UTEP model.

6.4.1 Scenario 1 – 2022 Parking Demand

The number of vehicles at the parking lot was measured in the simulation from 5:00 a.m. to 10:00 p.m. These numbers of vehicles were checked against the observed data to validate the model. The number of vehicles present at the parking lot at each hour is shown in Table 6.1.

Table 6.1: P+R Holešovice parking lot – number of vehicles parked in Scenario 1.

Number of Vehicles parked in Scenario 1						
Scenario 1	1A		1B		1C	
Time	Model	Real	Model	Real	Model	Real
5:00 a.m.	3,9	4	10,4	9,75	14,1	14
6:00 a.m.	15,6	15	20,4	18,75	24,7	24
7:00 a.m.	21	19	30	28,75	37	34
8:00 a.m.	32,9	30	41,3	38,5	46,8	44
9:00 a.m.	41,5	42	53,4	51,5	58,9	59
10:00 a.m.	46,1	47	59,2	58,25	66,4	66
11:00 a.m.	44,9	47	61,7	59,5	71,8	71
12:00 p.m.	46,7	49	62	60,75	69,2	71
1:00 p.m.	48,4	51	59,9	59,5	66,9	69
2:00 p.m.	49,8	51	56,7	57	66,3	68
3:00 p.m.	48,3	48	50,1	53	59,4	60
4:00 p.m.	42,3	42	48,6	46,5	52,5	54
5:00 p.m.	37,3	37	40,3	40,75	45,2	48
6:00 p.m.	29,1	27	32,7	32,75	38	41
7:00 p.m.	22,2	21	26,3	26	32,9	35
8:00 p.m.	18	17	21,4	21,5	32,2	32
9:00 p.m.	13,2	12	17	17,5	29,5	28
10:00 p.m.	10,9	11	13,9	14,75	26,3	26

The number of vehicles, number of disabled drivers, drivers that were able to park in the preferred parking stalls, search time, leaving time, and other simulation outputs describe the overall situation in the parking lot. are shown in Table 6.2.

Table 6.2: – P+R Holešovice parking lot – simulation outputs of Scenario 1.

Scenario 1	1A	1B	1C
Total Demand (vehicles/day)	92,3	116,7	144
Demand for Disabled stalls (vehicles)	1,2	1,6	2,2
Demand for Preferred parking stalls (vehicles)	73,3	82,8	96,6
Demand for General parking stalls (vehicles)	17,8	30,9	41,4
Unsuccessful search (vehicles)	0	1,4	3,8
Average Search Time (s)	32,3	33,0	33,3
Average Leaving Time (s)	26,6	26,8	26,9
Average Attempt	1,01	1,02	1,02
Total Time Lost (min)	0	0,63	1,92

The table shows that higher parking demand increases the number of unsuccessful attempts, average search time, average leaving time, the average number of attempts, and total lost time. However, the numbers and times increase only slightly. The first one is that the parking lot still does have space for more vehicles as the number of unsuccessful drivers is about four with the maximal occupancy. The second reason could be a simple physical layout of the parking lot that is not affected by the number of vehicles present in the parking lot. The third reason could be the small capacity of the parking lot that does not allow space for significant congestion. Finally, as there is just one entrance and one exit, drivers do not interfere with each other and move without any issues.

6.4.2 Scenario 2 – Smart Parking

The last part of the P+R Holešovice parking lot case study focused on smart parking. The four different parking navigation control strategies were tested in this parking lot. The four levels of control are Level 0 – no access control and no guidance, Level 1 – access control and no guidance, Level 2 – access control and zone occupancy guidance, and Level 3 – access control and destination stall guidance. The parking demand on Wednesday, 23rd of February, 2022 (high demand, as used in Scenario 1C) was used as the input in Scenario 2.

The number of vehicles at each hour in the parking lot at the four levels of control are compared in Table 6.3.

Table 6.3: P+R Holešovice parking lot – number of parked vehicles in Scenario 2.

Number of Vehicles parked in Scenario 2					
Time	Level 0	Level 1	Level 2	Level 3	Observed
5:00 a.m.	14,1	14	13,6	13,8	14
6:00 a.m.	24,7	23,2	25,5	25,2	24
7:00 a.m.	37	34,3	36,5	35,1	34
8:00 a.m.	46,8	43,6	45,2	44,2	44
9:00 a.m.	58,9	58,7	58,6	58,8	59
10:00 a.m.	66,4	68,2	65,2	66,4	66
11:00 a.m.	71,8	72,1	70,7	69,9	71
12:00 p.m.	69,2	71,1	70,1	70,4	71
1:00 p.m.	66,9	69,6	68,8	67,9	69
2:00 p.m.	66,3	68,7	67,1	68,9	68
3:00 p.m.	59,4	61,9	60,2	60,6	60
4:00 p.m.	52,5	52,1	53,3	52,3	54
5:00 p.m.	45,2	46	49,1	47,8	48
6:00 p.m.	38	38,4	39,9	39,7	41
7:00 p.m.	32,9	33	34	33,3	35
8:00 p.m.	32,2	32,1	32,2	32,2	32
9:00 p.m.	29,5	27,9	27,2	27,9	28
10:00 p.m.	26,3	24,4	24,1	24,7	26

In the P+R Holešovice parking lot are no significant differences between the model number and the actual number of vehicles present in the parking lot. That is caused by the generally smaller number of vehicles in the parking lot.

The simulation results will show the advantages and disadvantages of each approach. However, as the capacity is exceeded by a few vehicles, the differences will not be as general as in the UTEP technology parking model case. The other simulation outputs are shown in Table 6.4.

Table 6.4: P+R Holešovice parking lot – simulation outputs of Scenario 2.

Scenario 2	Level 0	Level 1	Level 2	Level 3
Total Demand (vehicles)/Day	144	144,1	142	141,5
Demand for Disabled stalls (vehicles)	2,2	1,4	2,1	1,2
Demand for Preferred parking stalls (vehicles)	96,6	95	94,2	94,6
Demand for General parking stalls (vehicles)	41,4	43	41,8	41,8
Unsuccessful search (vehicles)	3,8	2,3	0,1	0
Rejected Demand (vehicles)	0	2,3	3,8	3,9
Average Search Time (s)	33,3	33,2	32,9	32,2
Average Leaving Time (s)	26,9	27,0	26,8	26,6
Average Attempt	1,018	1,017	1,015	1
Total Time Lost (min)	1,91	1,25	0,04	0

The number of unsuccessful vehicles finding their parking stall combined with drivers that were not allowed to the parking lot is around 4 for all levels. That is probably the minimum to show the differences. Search time gradually decreases with a higher level of parking management, which is a good sign, but on the other hand, leaving time from the parking lot is highest with Level 1. Therefore, it is possible to say that the leaving time is almost independent of the parking management approach used.

Level 3 – access control and destination stall guidance provide the best results. The only thing that could be discussed is the number of vehicles that did not enter the parking lot. These drivers do not need to waste their time in the parking lot and continue to the next closest parking lot to park their vehicle.

In the P+R, Holešovice is entering and exiting the parking lot different from the UTEP one mainly because there is only one entrance and one exit, which leads to a different street. It means that with unsuccessful parking attempts, drivers waste their time in the parking lot and are forced to find their new target from a different place.

The use of smart technologies in the P+R Holešovice parking lot is not necessary according to the current parking demand, and because of the simple layout and small amount of parking stalls.

7 CONCLUSION

The thesis focuses on smart parking and the operational improvements of two parking lots with the provision of parking information. The selected parking lots were the UTEP SB2 parking lot in El Paso, Texas, and the P+R Holešovice parking lot in Prague. For the case studies, simulation models have been created in AnyLogic. The average search time, average leaving time, number of unsuccessful attempts, and lost time were analyzed.

7.1 Summary

The research shows that growing parking demand increases measured parameters such as search time, number of attempts needed to find a free parking space, and time lost because of the unsuccessful parking. On the other hand, the leaving time is minimally affected by the demand. These results were obtained from both case studies, which means that leaving time is probably not affected by parking demand in most parking lots.

The comparison of the operations using the parking demands in the years 2017 and 2022 was to evaluate as changes have been made to the UTEP SB2 parking lot's physical layout. Results show the demand difference between the years, as 2022 has significantly fewer total vehicles entering the parking lot. It also resulted in a search time decrease by five seconds and a minor decrease in the average number of attempts needed for successful parking in 2022.

Level 0 – no access control and no guidance have the biggest number of unsuccessful drivers who could not find an available parking space. Followed by Level 1 – access control and no guidance, which prevented the entry of vehicles whenever the capacity of the parking lot was reached. Level 2 – access control and zone occupancy guidance had slightly better results than previous Level 1. It provided better navigation in the parking lot, and more drivers could find an empty stall easier. The last level, Level 3 – access control and destination stall guidance, resulted in zero unsuccessful drivers as vehicles are assigned an available parking stall on entry. If there was no free parking space, drivers were not allowed to the parking lot. On the other hand, the decreasing number of drivers who were unsuccessful in finding their parking place increases the number of vehicles not allowed to the parking lot. There was no change in leaving time among the similarities, even with smart parking technologies, as there was no significant difference for each parking control management.

The different results were, for example, for search time. That was one of the main factors and for the case study in El Paso was a clear difference in results received. Level 0 with the worst results gradually continued with decreasing search time to Level 3, which provided noticeably better results than the other ones. However, it was not that clear in a case study in Prague. That could be due to a simple layout with one entrance and one exit and two rows with parking spaces, which does not allow the drivers a long search for a free space.

7.2 CONTRIBUTION

This section highlights the research contributions of this thesis as related to the three objectives.

This thesis provides an overview of the performance measures of parking facilities and intelligent parking technologies. Combining these two fields is important for the model creation and comparison of the advantages and disadvantages of each technology.

AnyLogic models for El Paso and Prague case studies show different scenarios with selected demand and parking technologies. They can find bottlenecks in the parking lots and identify the current operational issues. Moreover, created models provide very realistic outputs. This indicates that this modeling approach could be used for other parking lots.

7.3 LIMITATIONS

Parking is a complex topic with many factors that can affect drivers' behavior. This thesis attempts to consider as many factors as possible, yet AnyLogic does not support the option of different parking styles, and every vehicle parks with pulling in and backing out. Another limitation was with parking places placement as AnyLogic does not allow placing parking stalls in the intersection area.

7.4 FUTURE RESEARCH

Future research should include the simulation of technology usage, specifically the number of drivers who have different access to parking information. Another possible research is to simulate multiple parking lots in a system so that drivers with unsuccessful attempts and go to park in another parking lot may be simulated and their performance data collected for analysis. One other possible aim could be an implementation of nearby streets in the simulation to observe the effect of the congestion in peak hours on measured parameters. Another goal for future research could be an implementation of pedestrians as they also belong to every parking lot and change the behavior of vehicles.

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GLOSSARY

UTEP – the University of Texas at El Paso

P+R – Park and Ride

ITS – Intelligent Transport System

LPR – License Plate Recognition

U.S. – United States of America

LADOT – Los Angeles Department of Transportation

LA – Los Angeles

VITA

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