Airport Landside Vehicle Modelling and Pedestrian Behaviour Modelling for the Connected and Automated Era

by

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Abstract

This research examines the current state of the airport landside operations using microsimulation models to help understand how these areas will change with the introduction of connected and automated vehicles. Data collection from an existing North American commuter airport curbside was conducted to support this research. The curbside models provide comparisons of capacity and estimates of level of delay to travellers based on the different uses of space for the curbside. The analysis of the travellers' journey is explored further by following their path through the pedestrian access corridor between the curbside and the airport security. Data of pedestrian movement speeds and total travel time within the corridor were collected. This was modelled to understand the impact of dynamic changes to desired walking speeds. The combination of the collected data and models gives a complete overview of the airport travellers' journey between the curbside and airport security.

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This research would not be possible without the support and help of individuals and organizations who provided necessary support and guidance.

Thank you to the airport authority for providing access to the data allowing this thesis to be completed using real-world data. Without this access this thesis would not have the same practical scope.

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List of Acronyms

4G: 4th Generation wireless communication technology

5G: 5th Generation wireless communication technology

AWTQ: Average Waiting Time in Queue

BRT: Bus Rapid Transit

CAV: Connected and Automated Vehicle

COM: Component Object Model

CSD: Curb Space Demand

CSS: Curb Space Supply

GNSS: Global Navigation Satellite System

IT: Information Technology

LOS: Level of Service

SAV: Shared Autonomous Vehicle

TNC Transportation Network Company

V2I: Vehicle to Infrastruction communication

V2X: Vehicle to everything communication

VBA: Visual Basic for Applications

VKT: Vehicle Kilometers Travelled

VMT: Vehicle Miles Travelled

VOT: Value of Time

Chapter 1: Introduction

Today, the airport traveller is faced with as many options on how to get to the airport as they have in options for their actual flight, if not often more. As transportation becomes automated this number of options will only increase, but if introduced properly, the experience for the traveller could become more inviting, simpler to understand, and more affordable. The airport curbside will need to know how to adapt if it is to accept the changes.

1.1 Disclaimer of North American Transportation Culture to Case-Study Application

The author and data collected from the case-study airport are both located in North America. Transportation is a global phenomenon that the author acknowledges changes in nuance depending on local culture. The findings reported in this thesis rely heavily on the observed and perceived behaviours of travellers in North America, which may be, and are likely to be, different than other locations in the world. Declarations of average travel speed, traveller demographic, available technology, and future trends are all, unless otherwise stated, from the North American perspective. By this nature, the author admits there is bias in how applicable this research is to the global scene. As a reader, this should be taken into account.

1.2 Private Transportation – The Modern Invention

Private transportation is a modern invention. The progression of both the automobile and commercial flight happened quickly after their invention and are closer in history to each other than to other forms of transportation. The invention of the automobile is often accredited to the Karl Benz 1886 patent of the Motorwagen (Mercedes-Benz 2022), a much different machine from the automated vehicles that are being developed today. However, the time it took to go from the Motorwagen to the popular use of the car was not long. Cars became available to more people with the creation of the Model T in 1908 by the Ford Motor Company (Ford 2022), only 22 years after the invention of the Motorwagen. 1915 and 1926 models of the Ford Model T pictured below in Figure 1.1.

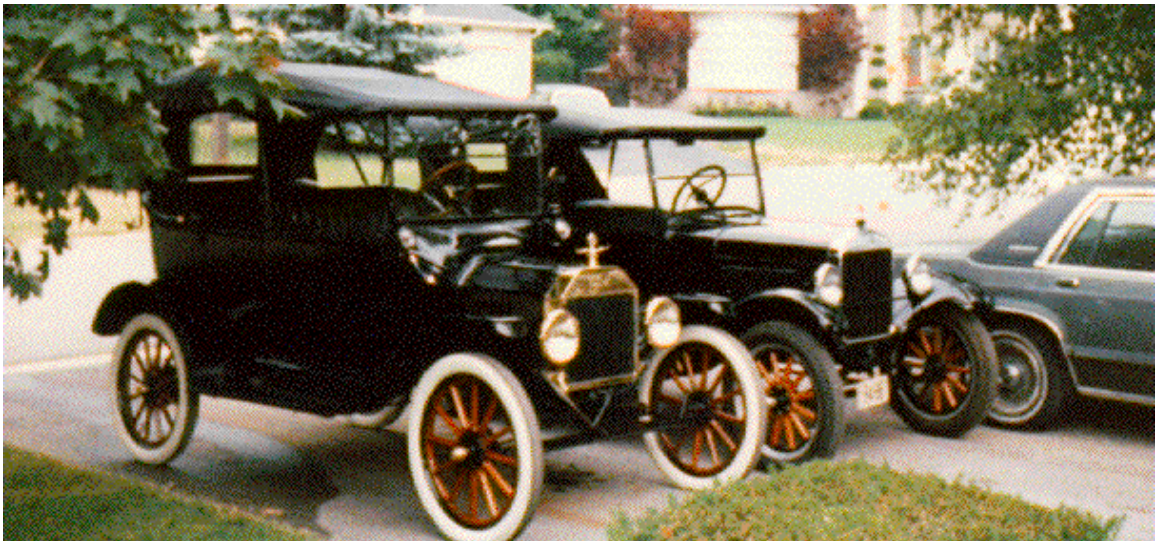


Figure 1.1: 1915 and 1926 Ford Model T by J. B. Gales (J. B. Gales n.d.)

During this development of the vehicle, as a popular mode of transportation, the invention of powered flight was also being pushed further. The Wright brothers took their first flight in 1903 (National Park Service 2015), 5 years prior to production of the Model T. Commercial flight soon followed with the first operating in 1914 between St. Petersburg and Tampa, Florida (Sharp and Hickok 2022). It was a 20 minute flight in comparison to the 2 hour boat ride, 12 hour train ride, or 20 hour drive. This was humble in comparison to the flights of today but shows how quickly innovation becomes used in transportation scenes of both automobiles and airplanes. In a span of less than 30 years the ideas of travelling over large distances by motorized vehicles and air had gone from developing ideas to established modes of transportation.

Large technological advancements are quickly embraced, as shown above, as they allow more people to be connected. It increases the distance people can travel in the same amount of time and gives people more independence and flexibility in their choices of travel. Today, we are being faced with the new inventions of electrified vehicles and automated wayfinding. These technologies are in active development and have been for some time. Electric vehicles were being developed as a scientific curiosity in the early 19th century (Department of Energy 2014), their development was halted by not having access to rechargeable batteries and the competing cheap petroleum costs, until now that fast charging battery technology is available and alternative fueling methods are being explored to offset environmental concerns. While this technology allows for cheaper operating costs, it does rely on other areas providing the necessary infrastructure to

support recharging the vehicles. Automated wayfinding makes driverless vehicles possible, turning everyone in the vehicle into a passenger. Connecting these vehicles to a larger network could also allow them to act as a taxi like service picking people up, even letting strangers easily share a vehicle, however, this also allows vehicles to travel while empty.

1.3 Problem Definition

Airports are faced with keeping up with changing mobility modes without a large level of control over which mobility modes are used at the airport, if they want to give their travellers options that reflect local transportation availability. Airports rely on the local transportation of their host cities to provide a way for travellers to get to and from the airport itself. If a transportation mode is dominant in a city, the traffic scene at the airport will reflect this. This makes airports dependent on transportation trends. Airports must then examine if they should adjust as the transportation scene changes to maintain or improve their service capabilities as transportation changes around it.

Today, airports rely heavily on third party stakeholders to maintain accessibility to the airport with their current business model. The personally owned vehicle, taxi company, and public transportation system are all major contributors to supplying travellers with access to and from the airport, using the curbside as the interface between the airport and the stakeholders. Complimentary services such as shuttles to nearby hotels and attractions are also in association with those businesses in which they service. Exercising their level

of control though, the transportation authority of the curbside and surrounding roads can generate revenue through charging the stakeholders a premium for the use of space. Taking this action allows the transportation authority to manage where these transportation modes are allowed to operate. This allows the transportation authority to organize and plan for the use of space of each transportation mode. However, the decision on which transportation mode to use is ultimately made by the individual traveller which in turn means the planning done by the transportation authority can be more reactive than regulating. Where transportation is concerned, airports allow the traveller and other parties at the curbside to have a heavy influence.

The business structure that this follows has made the curbside into an area where transportation modes fight over the use of space to offer the best options to the traveller while balancing their financial commitment to the premium for use of space. This is also in contest with the ability for the traveller to use their own personal vehicle and avoid the other stakeholders entirely, beyond traffic, in accessing the airport. Once there, the curbside further becomes an area for pedestrian activity, adding to its complexity and allowing for dynamic person movement, reaction, and behavioural effects. The behaviours of pedestrians at the airport needs to be known for proper design of the spaces and interaction with each of the transportation modes found at the curbside.

Furthering the potential complexity of the curbside is the coming introduction of connected and automated vehicles (CAVs). CAVs present a new way in which vehicles can operate, both for the personal traveller and for the fleet owner. For the personal

traveller CAVs present a travel mode that lets them be dropped off or picked up at the airport without requiring hiring a taxi service or being driven by someone else. For fleet owners this allows them to offer their services at a price that does not need to include a wage for a driver eliminating a large portion of their service cost. The application of CAVs also extends past the driver of small vehicles as it can replace all driver types. The new technology and capabilities of CAVs are beneficial enough that they could be seen as the dominant transportation mode in the future. For these reasons, the airport curbside with CAVs and pedestrian behaviours have been identified as the area of study and scope for this thesis.

1.4 Objectives

Airports will need a way to understand what changes they should take to prepare for CAVs. Airports are a critical part of the global transportation network which should not be put at risk during a time of innovation and need guidance. They provide timely connections between the world's major cities for both goods and persons. The guidance they need is in the form of predicting future impact of potential changes to transportation, which can be done through modelling. Such tools will allow the airport to compare its current level of service with today's traffic conditions to that of potential future conditions involving CAVs. This, however, requires a framework that can evaluate driver-based vehicles and CAVs with the same criteria while still accounting for their

differences giving airports information that is relevant to their future operations. This need prompted the main objective of this thesis.

To best accomplish this objective though, transportation authorities and companies supplying services using CAVs will need to take human behaviours into account. The type of transportation that will become dominant in the new era of autonomous vehicles will depend on the preferences of people and how those options best meet their travel behaviours. CAVs present a way to make current trends more efficient. However, they also present the potential for new trends to develop and to expose latent demand. Those currently barred from transportation due to today's limitation of accessibility could use CAVs as a mode of transportation. Including human behaviours into the discussion will help guide transportation authorities with decision making.

Further, the airport's service model will have to be profitable if they hope to continue to be competitive in the growing environment. Airports are not an exclusive service; they compete with each other and other forms of long-distance travel. Even CAVs themselves present an alternative to city-to-city travel by air as the passenger is not limited by driving fatigue and is free to work or partake in leisure activities during the trip. While comparing types of city-to-city travel is outside the scope of this thesis, the subject of cost-benefit analysis is discussed for the airport so transportation authorities can use the information for their own purposes. Without proper information suitable planning and budgeting will not be possible.

These identified needs of airports and related transportation authorities resulted in the following main and supporting objectives.

> **Main Objective**: Develop a Model to Evaluate the Service Capacity and Demand Impacts of Connected and Autonomous Vehicles to the Airport Curbside.
>
> **Supporting Objectives**: Human Behaviours, Cost-Benefit Analysis (for the airport)

Modelling was chosen to accomplish these goals due to its ability to both depict the traffic of today and project to future cases. This allows the base case scenario of today to be compared to the various future cases as well as being able to compare the future cases to each other. Microsimulation is used for the modelling space as the study area is small and the subject of interest is the impacts to individuals.

A visual representation of what this thesis aims to accomplish and how it connects the concepts of the existing airport operations and CAVs is presented below in Figure 1.2. This figure presents the key aspects that are considered in what was done or in the future work that will be required towards an academic understanding of the airport operations in the automated era. Today, we have the existing airport operations, the development of automated vehicles, and the connected network. We are seeing the connection of the automated vehicles and the connected network to produce the connected and automated

vehicle. For the airport, we have access to the data to collect for use in modelling and predicting future cases.

Connected and automated vehicles, however, are not present in public use enough for proper data to be collected, so instead literature review is used. This allows for prediction of future cases and their modelling towards the automated scene. This gives an updated visual abstract shown in Figure 1.3 where the contributions from this thesis are highlighted in red.

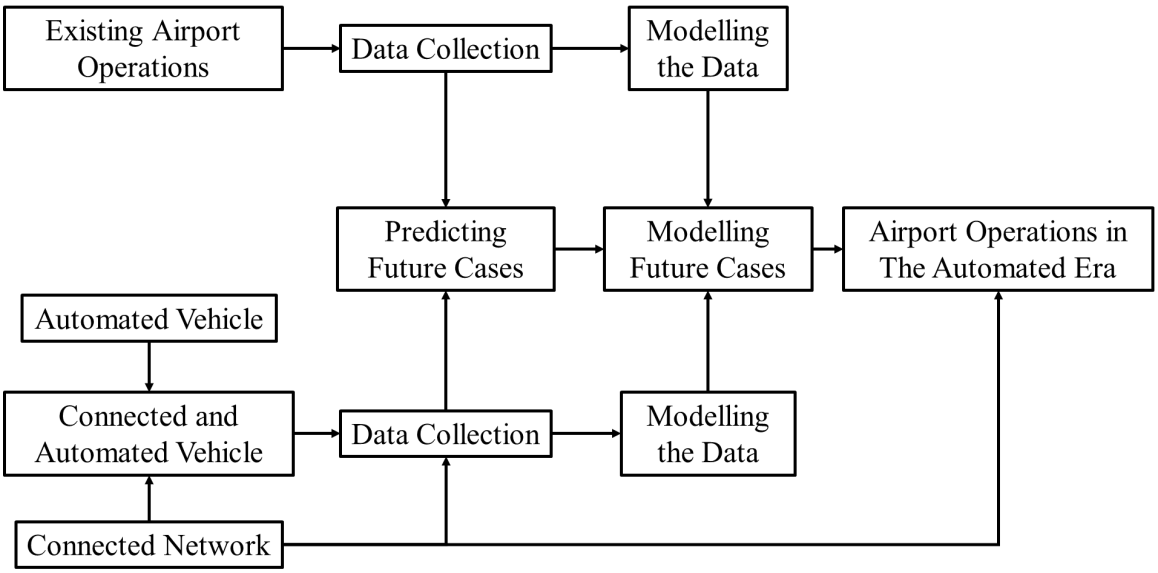


Figure 1.2: Visual abstract

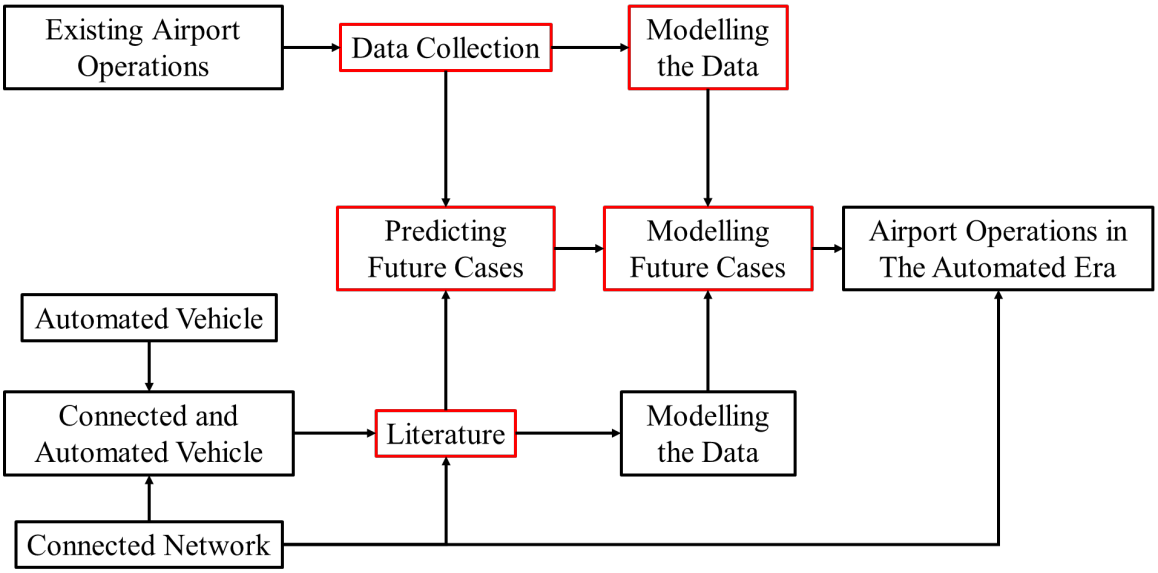


Figure 1.3: Thesis contributions

1.5 Thesis Outline

Chapter 1: Introduction

Chapter 1 has been an introduction to the thesis. It presented the information about how technology has progressed quickly in the past giving precedence for the need to quickly react to the new introduction of automated vehicles. The problem statement was detailed to inform the reader what this thesis is concerned about and to better outline the scope of issues that it is addressing. To more specifically address part of the problem statement, a specific objective was given. The following sections will contain supporting information for the problem statement and objectives along with work done to present a completed objective.

Chapter 2: Literature Review

Chapter 2 is the literature review for the thesis. While references to literature and their relevance to the thesis subjects can be found throughout, this chapter holds the bulk of the review introducing the background information for the research. The literature review covers the topics of the progression of the autonomous vehicle, autonomous public transportation, shared mobility, airport growth, the current state of airports, studies relevant to airports in the autonomous era, connected and autonomous local transportation, electric vehicles, and modelling among other supporting topics.

Chapter 3: Research Framework and Methodology

Chapter 3 details the research framework and general methodology of the thesis. How data was collected, how it will be used, and where it is applicable is detailed in this chapter. The chapter also includes a description of the different model types and scenarios that were constructed for the thesis. The modelling software used for the thesis is also detailed in this chapter. Reasonings for using the model types is found here as well.

Chapter 4: Airport Curbside

Chapter 4 contains the first study of the data collection done to address the objectives of the thesis. This chapter focuses on the airport curbside. Here, the study airport is outlined, and the motivation for the study of the curbside is discussed. The collected data that was used in the modelling is presented along with a statistical analysis to provide an understanding of the relationship between occupancy and vehicle dwell time at the curbside. Chapter 4 serves as the introduction for Chapters 5, 6, and 7 which cover modelling of the airport curbside.

Chapter 5: Monte Carlo Based Model of Curbside Queue

Chapter 5 presents the first modelling work for the airport curbside. It shows how a Monte Carlo based model of the airport curbside can be used to predict the probability of a curb space being available when a vehicle arrives. The base case, 50% increased demand, and 100% increased demand are all modelled. This probability is used to

estimate a delay before using the curbside. A level of service index is constructed using these levels of delay.

Chapter 6: Microsimulation Based Model of Local Shuttle

Chapter 6 presents how autonomous vehicles could be used at the airport to provide solutions to the demand issues currently at the airport along with potential future issues. A model of a local shuttle is used to redirect arriving vehicles away from the airport curbside by transferring travellers into shuttles first. The impact to the delay experienced by travellers is analysed between different amounts of arriving vehicles being redirected towards the shuttles. Results from theoretical simulations are also presented to provide a relationship between total demand and the needed local autonomous vehicle fleet to service all travellers.

Chapter 7: Microsimulation Based Model of City Shuttle

Chapter 7 models the use of a shuttle route connecting travellers to a city location. The shuttle acts as a direct route between the airport curbside and a hotel within the city. The route and schedule for the shuttle is fixed. The base case, 50% increase in demand, and 100% increase in demand are all modelled. The results and discussion explore how this increase effects the success of the shuttle keeping its schedule and the impact to the travellers waiting for a shuttle.

Chapter 8: Airport Corridor

Chapter 8 covers the pedestrian movements within the airport corridor. The data collection and modelling are discussed in this chapter in their relation to safety and impact to understanding travel for the scope of the whole airport. Pedestrian movement speeds while on the moving walkways (people movers) were collected and results are presented in this chapter. The modelling shows how state-of-the art microsimulation models can be improved to account for dynamic movement behaviours on these facilities and the results are compared to both the observed total travel times and the model results from both the custom case made for this study and out-of-box case.

Chapter 9: Conclusions, Contributions, and Recommendations

Chapter 9 gives the conclusions of the thesis. This is a summary of the major findings of Chapters 4, 5, 6, 7, and 8 supported by the literature review in the previous chapters. Recommendations on how the findings can be applied are also presented. Further, this chapter explains which parts of the problem statement were not addressed for others to build on this work with future research.

Appendix A: Knowledge Gained from Participation as an Intern in NSERC Program for Building Trust in CAV

Appendix A presents the knowledge gained from participating in the NSERC TrustCAV program. This program allowed the author to attend workshops over the summer of 2021 and a part-time work position over the summer of 2022. This appendix details the

knowledge that was gained in the area of connected and automated vehicles from this internship.

Appendix B: VISSIM Python Code

Appendix B presents the Python code that was written to support the modelling work done for Chapters 6 and 7. This code interfaces with the VISSIM model to make the modelling work and results possible. The code is presented in its working state as-is, as it is in active development and meant to be used specifically with each associated VISSIM model.

Appendix C: MassMotion C# Code

Appendix C presents the C# code that was written to support the modelling work done for Chapter 8. This code interfaces with the MassMotion model to make the modelling work and results possible. The code is presented in its working state as-is, as it is in active development and meant to be used specifically with the associated MassMotion model.

Chapter 2: Literature Review

This literature review was completed to support the modelling and simulation work discussed later in the thesis. It reviews the areas of automated vehicles, 5G wireless communications, computer vision, V2X, electrification, levels of automation, changes to parking facilities, shared mobility, urban sprawl, study results found in literature, and policy impacts. Further, it looks at the airports, the mode shares currently at airports, transportation within the airport, airport operations, and processors and logistics. Modelling of the airport operations, CAVs with VISSIM, and pedestrians with MassMotion is also covered. Finally, the methods and technology that can be used to collect data is discussed. These areas review those relevant to the thesis topic, with a focus on recent developments.

Additional specific supporting and background information can be found in each relevant chapter. Chapters 4 to 8 contain more supporting literature review specific to the chapter topics.

2.1 The Automated Vehicle

The connected and automated vehicle operates as a unit of a transportation system. This system relies on multiple levels of technology all cooperating to create a safe driving environment for connected and automated vehicles. These systems and the potential changes to how people travel is discussed next.

2.1.1 5th Generation Wireless Communications (5G)

New technologies are being introduced to many aspects of our cities that are being used to allow a future of connected and automated vehicles (CAVs). Canada is making efforts to bring 5G, the fifth generation of wireless technologies, to the country (Government of Canada 2017). 5G is providing the foundation required for CAVs to operate within. Connectivity will be increased, allowing for more devices to communicate to each other which allows many vehicles and supporting devices to build a connected transportation network. The latency of 5G is reduced compared to 4G which will allow for more real-time communication between vehicles addressing areas of efficiency and safety. Further, the bandwidth of 5G is increased allowing more detailed information to be transmitted, which is critical for computer vision technologies that produce large amounts of data used by automated vehicles for safety and wayfinding. This new generation of wireless technology has allowed connected and automated vehicle systems to be more feasible.

5G communication comes with additional security improvements but also new challenges (Dutta and Hammad 2020). The expanding network use cases require new security requirements to keep private information safe. Considering CAVs will be taking advantage of the new 5G features these security considerations will need to be implemented within the vehicle network.

2.1.2 Computer Vision

One of the major systems that enable CAVs to operate is computer vision. Computer vision is a full topic of research on its own, so it will not be fully discussed herein.

However, the required topics of computer vision for CAVs include the following, included from a more complete review for automated vehicles in a survey of the state of the art (Janai, et al. 2020): Sensors and sensing, Feature detection and selection, Tracking, and Motion estimation.

Sensors and sensing are required for the vehicle to react to the world around it. CAVs use a combination of different types of sensors. While companies like Tesla are trying to produce automated vehicles that only rely on camera vision most companies use a combination of sensors (Gilbert 2021). These sensors include cameras, radar, LiDAR, and thermal cameras. Cameras and thermal cameras allow the vehicle to see shapes and identify objects. These sensors allow for feature detection and selection which is a critical component allowing the vehicle to recognize other vehicles, the road, and persons to operate safely. Radar and LiDAR identify the distance to objects. Combined, these sensors, with the cameras and thermal cameras allow for tracking and motion estimation which helps the vehicle know where objects, other vehicles, or pedestrians are going and lets them be avoided to ensure safety.

The different types of cameras are capable of overlapping abilities. Multiple cameras or thermal cameras can be used to find distance using techniques similar to that of the human eye. If a camera or thermal camera is stationary, such as when found on infrastructure, it can be programmed to know where the objects are that it detects by referencing its own position. Radar and LiDAR can also find the edges of objects if their data points are dense enough. This can provide the general shape of an object for

identification purposes. However, using sensors in complex ways increases computing time. This computing time needs to be weighed against the benefits or practicality of using a better fitting sensor.

2.1.3 Vehicle to Everything (V2X)

All of the information generated by sensors is shared to and from the vehicle using the onboard computer that connects the systems. The autonomous vehicle can receive multiple signals from different sensors at the same time. The onboard computer analyses these signals to determine if they concur or conflict. Conflicting information will need to be handled by analysing the current conditions of the vehicle and the nature of what is being decided to determine which sensor to take as the trusted input (Gatien 2021).

As vehicles process information and make decisions they can then communicate this to other vehicles. By sharing the information vehicles can react to each other's decisions to maintain a safe driving environment. This is further shared to and from infrastructure. Infrastructure can also be equipped with similar sensors to that of the vehicles allowing the infrastructure to analyse the information and then communicate to vehicles. This is known as V2I (vehicle to infrastructure) communications. Connecting vehicles to all other vehicles, the entire infrastructure, and anything interacting with the autonomous vehicle is known as V2X (vehicle to everything). V2X allows the vehicles to operate within a safe and efficient network. A complete V2X environment will include connecting to the airport and its related areas.

V2X infrastructure, however, is currently not realized on the roads. Communication is one of the largest challenges to introducing CAVs to the roadways (Johnson 2017). While communication devices could be introduced at major intersections to supplement vehicle sensors and relay communication messages, urban side streets and rural areas will not see these devices without considerable financial commitments. This leaves areas where V2X is still limited and an area of continued development.

2.1.4 Electrification

The automation of vehicles is assumed to coincide with the electrification of vehicles as well. Currently, the internal combustion engine has promoted refueling stations to be located on-route on city block corners. These locations do not need to be preserved in the electric era as the automated electric vehicle can find a charging station on its own. The dangerous fumes and required delivery of fuel, for current gas-powered vehicles, are also eliminated allowing for charging stations to be in areas currently unreachable from safety and logistics perspectives. This has started investigations to know if new optimal locations for charging stations could be found. One study looked at the current parking locations and durations for finding locations for electric vehicle charging stations (Chen, Kockelman and Khan 2013). It was able to create a model that found the zones, not specific locations, for charging facilities based on these factors. This approach, though, appears to assume a continued behaviour of vehicles being mostly idle in the same locations for the same durations as current traffic distributions, which would fit a mostly personally owned automated vehicle scenario. Additionally, other studies looked at

placing the charging stations to minimize loss when travelling to the station (Ge, Feng and Liu 2011) or adapting the current approach of being able to service vehicles through the day as they operate (Lam, Leung and Chu 2014). These models would fit the scenario of mostly shared mobility or fleet owned automated vehicles. From these alternative models we can see that the topic of vehicles switching from fueling to charging is not a simple replacement of infrastructure. It will require an understanding of which future alternative of automated vehicle ownership structure is taken and an adaption to the available technology. Airports will have the opportunity to offer charging stations depending on the idle time of vehicles on location.

2.1.5 Levels of Automation

Automated vehicles will be able to replace the human-driver and allow for different mobility options. Communicating over the 5G network connected automated vehicles will be able to operate fully independently of the human-driver and create a mobility network across the entire city. This lack of reliance of the human-driver makes new mobility options available. To accommodate the new mobility options, though, the use of space currently used to service human-driven vehicles may undergo adaption to service the new needs. All these possibilities mean potential changes in human behaviour and land use design concepts for best providing access to the mobility offered by automated vehicles.

These advancements will not all come at once though, and SAE International has defined different levels of driving automation for use of comparison. Level 0 features are limited

and require driver interaction while at Level 5 the vehicle can operate fully independent of a driver (SAE International 2021). These levels can be seen more clearly in Figure 2.1 below showing the graphic provided by SAE International. For the purposes herein, unless otherwise stated, connected and automated vehicles will be assumed to be operating at Level 5. A discussion of the efforts needed to make Level 5 operations realized on the road is outside the scope of this thesis.

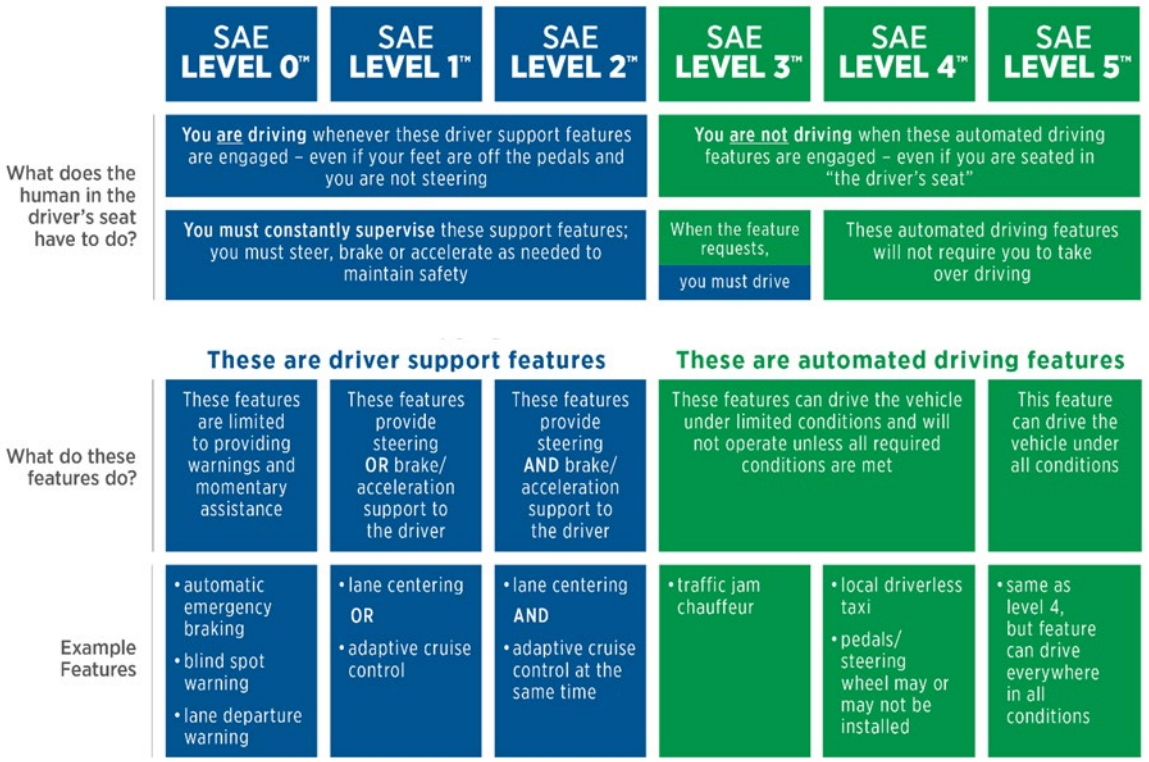


Figure 2.1: SAE J3016 levels of driving automation. Adapted from (SAE International 2021)

2.1.6 Changes to Parking Facilities

The automated vehicle can not only replace the every-day driver, but also the parking valet or the need to park at all. Currently, parking takes up a large mount of the usable space in our urban cities, up to 30% in some urban centers (Buro Happold 2018). This demand for parking spaces has developed in our cities due to our reliance on the private vehicle and the need to service demand within walking distance to attractions. The private vehicle also requires at a minimum two parking spaces to service a person's needs, one at the origin and the other at the destination. Our current use of urban space heavily prioritizes serving private vehicle parking in this way. Valuable land is taken up by parking garages and a full lane on a busy street can be sacrificed to service on-street parking to accommodate quick access to local shops. The impact of providing parking is widespread. Airports dedicate large sections of land to service parking and long sections of curb space are often reserved for waiting taxi services to allow passengers quick access. Connected and automated vehicles present an opportunity for this parking behaviour to change. The perspective of the traveller, parking space provider, and planner should all be looked at to get the best understanding of the different ways parking may change in the automated era.

From the traveller's perspective parking may become obsolete when planning their trip. They do not need to park at their destination and can instead be picked up or dropped off by their vehicle. This could heavily reduce the need for parking garages at the airport. However, this does not mean the space taken up by parking at the airport will no longer

be needed as it could be repurposed to best serve people being dropped off or picked up. The demand of space to easily access a vehicle on location or replace conventional parking may be comparable to the space currently used by some smaller local parking facilities. Curbside waiting areas may also be simply repurposed to on-demand pick-up and drop-off areas, which would require a revamping of the space currently used so the new mobility model can be serviced.

A modelling study was done to investigate these factors, using cost to an individual as the model input (Millard-Ball 2019). This study found that connected and automated vehicles operating in a city with parking as is found it cheaper to park away from downtown areas as they could either return home or find free parking spaces located in less dense urban areas throughout the city. The study also found the vehicles could seek out congested areas to operate at slow cruising speeds instead of parking, which was often cheaper than paying for a premium parking spot or resulted in less distance travelled than finding a cheaper or free parking space. This showed that the behaviours automated vehicles are capable of can change the need to park, but it may result in the vehicles adding congestion to the roads. Another study further supports the idea of the vehicles travelling further distances to find cheaper parking instead of eliminating the parking (Harper, Hendrickson and Samaras 2018). This study looked at travel behaviours in the Seattle, Washington area and the model found it favourable for vehicles to take advantage of the further but cheaper parking locations.

While both studies showed that home parking spots, if a person's home is close enough, could be utilized they did show that the use of personal automated vehicles do not show a favourable change in parking behaviour. While the downtown areas of parking could be repurposed from lack of demand, the need for parking is not always reduced with automated vehicles, the location is only reassigned. Ultimately, because there is still the need to find space to park and the space to drop-off the passenger more space is needed in total, except in the cases the vehicle was able to return home, but this results in the largest increase in vehicle kilometers travelled. These behaviours would change though between scenarios where there were more company fleet owned vehicles instead of personal vehicles. The issue that was found is that the automated vehicle is only servicing one individual much like the personal human-driven car of today. A scenario where there are more fleet owned vehicles, operating as shared autonomous vehicles (SAVs) may still repurpose more local parking for on-demand service; however, it would not suffer from vehicles still requiring a parking spot between use for a single individual. The vehicle can be used to service more people throughout the day and avoid parking. A modelling study in Austin, Texas found that each SAV could free up eight parking spaces in the core of the city (Fagnant, Kockelman and Bansal 2019).

The parking provider will also be able to change their service model to make their spaces more attractive, in this case the airport acts as the parking provider. Parking garages today use a variety of techniques to let people know if spaces are available and to get people to an available space within a timely manner. However, they are still limited to

providing enough space for people, or valets, to navigate through the spaces quickly and safely. The automated vehicle could instead park in the space by itself and make a better use of the space. A study was done showing how automated vehicles can park in a denser pattern by parking as if lane queuing while still providing quick access to each vehicle when needed (Nourinejad, Bahrami and Roorda 2018). This tighter parking ability could allow premium locations to become more competitive. This would affect the results of the modelling studies mentioned above, since they assumed the pricing and parking density properties of existing garages to remain similar. If the downtown parking facilities can change their pricing model due to higher service capacity, they could remain the most attractive parking option. This includes major transportation hubs like airports who may try to keep their existing parking facility profitable over repurposing the space. This would result in a reduction of total space required for parking in dense urban areas while keeping the locations close to major destinations, which could be a favourable situation for a future scenario with a large market penetration of personally owned automated vehicles.

From a city planner's perspective, the potential change to parking due to the automated vehicle presents an opportunity to address many challenges. With the growing population there is an increased demand for livable and commercial space within the urban area. The ability to move parking for vehicles out of these areas and replace them with facilities that service the needs of the population could be a major benefit. However, as previously mentioned, this relocation or reduction of parking may not occur unless under the right

circumstances. For planners to take advantage of the opportunity, they will need policy changes that address this area. The privately owned automated vehicle will act in a way to best reduce the costs to the vehicle owner while remaining close enough to the vehicle owner to serve their preferences of availability. This means they may prefer the further parking space if it remains cheaper lowering the need for downtown land use as parking for regular work trips as the vehicle can know when to leave their parking location and pick them up at the correct time without delay. Company fleets, however, will act in a way that gives the best cost benefit ratio for servicing customers which could change how much local parking is needed depending on their service model. This means the impact to land use will depend on the pricing model of the service and the price of parking. Fleets may also have less of a need for parking spaces as the vehicles could remain in use throughout the day going directly from one person to the next without parking. Airports will need to be aware of changes to parking around them as a reduction in parking options throughout the city may make their parking facility more attractive or reduce the ability for shared fleets to quickly respond to demand at the airport.

2.1.7 Shared Mobility and Transportation Network Company (TNC) Services

The concept of shared mobility and the services offered by TNCs are not new to be introduced alongside vehicle automation. Car sharing services and TNCs, such as Uber and Lyft, already operate within the urban scene. They operate much like a taxi service picking people up and dropping them off wherever needed. What automation offers is a reduction in the operating costs and increased service capacity from these services (NBC

2019). Shared mobility is also seeing growth with the introduction of mobility options such as bicycles, scooters, and other options connecting people with last-mile solutions where vehicles cannot be used. These services are expected to see growth in the connected and autonomous era due to these reasons.

Shared mobility and TNC services can impact the airport from the space these services need to operate in and how it can change mobility patterns. The need for operating and staging space relates with the previous topic of parking. Parking facilities could be repurposed for shared mobility and TNC services as a location for people to easily access a vehicle or for the company fleets to wait and charge between trips. Shared mobility and TNCs benefit from the ability to wait at local areas to provide adequate levels-of-service much like current taxi services. This suggests that different operating models of shared mobility and TNC services will affect the airport in different ways. Those operating with a larger fleet for shorter customer waiting times may require larger staging areas but others that operate to maximise vehicle usage to reduce costs may require smaller staging areas but will want quick and guaranteed curb access when they arrive at the airport.

The reduction in personally owned vehicles from an increased use in these services could also reduce the need to provide parking spaces. However, the current use of shared mobility services does not show an impact of changing vehicle ownership rates, according to a Seattle, Washington study (Harper, Hendrickson and Samaras 2018). This is an interesting claim that needs to be further understood for the future of shared mobility and TNC adoption in cities. Because these services are new, the vehicle

ownership rates could not be currently affected as people have not changed their main habits for transportation justifying their decision to own a vehicle. However, this could also be showing that there are additional reasons to owning a personal vehicle outside of urban transportation that current shared mobility and TNC services do not meet. Automated vehicles, though, could meet these requirements.

A further impact is from the change in behaviours that could come from an increase in accessibility and reduction in cost of these services. The service is capable of quickly and affordably transporting populations that currently struggle in our transportation network due to mobility barriers (Koen Faber 2020). Connected and automated vehicles can service someone by providing the means to access further transportation and could increase the number of trips being made overall. Furthermore, households will no longer be limited due to a vehicle being used all day by a primary worker of said household. Airports could see growth in demand from these factors.

This conversion from the ridesharing model of services like Uber and Lyft to a dedicated automated vehicle providing the same service could also mean an introduction of many empty vehicle kilometers (Soteropoulos, Berger and Ciari 2018) (Shaver 2019). To combat this, policy encouraging business models that are closer to the current UberPool or other methods that benefit the rider to share their vehicle should be introduced to make sure this new technology does not cause a higher level of traffic on the road. This has the potential to be beneficial to the airport by increasing vehicle occupancy rates at the

curbside. However, ridesharing does not guarantee trips to the airport will be grouped and would need an in-depth study for a proper understanding of the extents of the benefits.

As a final discussion on shared mobility, it is important to note that it comes in more forms than the automobile and that these different forms will have different impacts. Shared mobility can include bicycles, scooters, accelerated moving walkways (people movers), and other services aimed at providing mobility in a way that is easily accessed and shared by the public while maximizing the usage of the mode (Machado, et al. 2018). An increase in these types of shared mobility would result in a direct reduction in demand for vehicles within dense urban areas. However, these all require staging areas or a repurposing of existing space within the urban scene. Services like bicycles and scooters need easy access docking ports throughout the city that are large enough to meet peak demands and are in convenient locations to encourage people to properly return the borrowed bicycle or scooter. Accelerated moving walkways could make their appearance in areas that already see large foot traffic or areas that could use the service to try to replace current short vehicle trips. Advancements in connected and automated technology could make the payment or subscription to all these services convenient to further encourage their use over other transportation modes. However, this type of service is less adaptable to an individual's travel pattern and would require a good understanding of demand for travel where installed. Further, many airports are isolated from other parts of their associated cities and short distance travel options may not apply. The accelerated nature of the moving walkway, though, allows the service to compete with other mobility

modes while being space efficient, reduce road congestion, and encourage better physical habits of the city population (Kusumaningtyas and Lodewijks 2008).

2.1.8 Vehicle Kilometers Travelled (VKT) and Urban Sprawl Impacts of Automated Transportation

As discussed in the previous sections, the introduction of autonomous technologies could be changing the way people navigate our cities which could in turn influence the total VKT. VKT has an indirect effect on urban land use, as it can increase without the need to expand the road network if vehicles travel more efficiently or could require an expansion of the road network to avoid congestion. In the current driving environment, a personally owned vehicle that is manually driven can be assumed to take a route that is somewhat optimized for time, costs, and distance, among other factors. This operating style, by nature, does not always need to be followed by the autonomous vehicle. The automation of driving may change how people view the time and distance spent in a vehicle. A person may be willing to take a longer trip, measured by time, through congested traffic if they are a passenger and can save on mileage costs. A study found that without ridesharing the introduction of autonomous vehicles as a mobility service increased congestion and travel times (Levin, et al. 2017). Further, the connected and autonomous vehicle provides access to transportation to those currently faced with mobility barriers. Shared mobility and TNCs provide a way for elderly and those facing mobility barriers to travel. This would increase the volume of people using the roads which will increase VKT.

The autonomous vehicle's largest threat to increasing VKT is empty trips. The previous studies mentioned for parking (Harper, Hendrickson and Samaras 2018) (Millard-Ball 2019) present an issue of autonomous vehicles reducing the cost for the owner by travelling further distances to find cheap parking. This would increase the VKT compared to what is seen today. This is additionally supported by a modelling study that found private autonomous vehicles increase VKT and reduced the use of public transportation (Soteropoulos, Berger and Ciari 2018). However, it showed a more shared autonomous vehicle use would give positive impacts. A study of replacing personal vehicles with SAVs in a grid-based urban area showed each SAV could replace up to 11 personal vehicles but still resulted in an increase of VKT by 10% (Fagnant and Kockelman 2014).

Further research in this area resulted in a study on travellers using SAVs, at low market penetration, serving travellers in the core of Austin, Texas (Fagnant, Kockelman and Bansal 2019). Each SAV was found to be able to replace nine conventional vehicles, but it still resulted in an increase of VKT by 8%. These studies show that while SAVs work well at reducing the total number of vehicles on the road, they still operate in a way that creates empty kilometers travelled and increase the total VKT. This increase in VKT will have to be studied by urban planners to understand if there will be needed action to avoid congestion. If automated vehicles can move more efficiently in currently congested traffic conditions, or the additional VKT is found to travel in non-peak directions, the existing road network may be able to support the adoption of automated vehicles.

However, if there is a mix of human-operated and automated vehicles still within an urban area these efficiencies may not be realized and action may need to be taken that will have impacts to the land use, including a possible dedicated lane for automated vehicles to allow them to take advantage of their more efficient travel patterns.

Urban sprawl is a further concern that automated vehicles may cause and is related to the issue of VKT. Since the driving process is being done by the car, the person can now act as a passenger and could view the time as available to do other activities. This in turn could reduce the associated costs of travel time allowing people to live further from their regular destination. A study was done on the effects to a city due to the introduction of automated vehicles and found the direct effects always increased sprawl (Larson and Zhao 2020). However, when considering the indirect effects this urban sprawl was not always guaranteed. These indirect effects include those discussed earlier of change in required parking space freeing up land for housing which makes the city more compact.

This is supported further by the idea of travel time savings, which has been a large area of design considerations due to the value of time. A study done in the UK determined that, among other findings, time is scarce and will always have a value and that non-working time can share a similar value across modes (Mackie, Jara-Diaz and Fowkes 2001). With this reasoning, the time spent in the vehicle would need to be seen as productive by being able to spend the time earning money or for desirable leisure activity. Otherwise, long travel times and distances would result in both higher out-of-pocket expenses for the trip and higher costs from value of time. Since a shared vehicle model is expected to be more

affordable than a single occupancy or private automated vehicle trip this limits the work or leisure activities available to passengers and, as a result, reduces the likelihood the introduction of automated vehicles will have a major impact on causing urban sprawl. While the scenario of a person being able to work from an automated vehicle riding it solo is possible, travel costs also extend to non-work trips and the choice of living location depends on more factors than work related activities. The combination of the results of the city model and the value of time suggests that if city planners promote the changes from CAVs to allow for denser living spaces the issues of urban sprawl should be able to be avoided.

The airport should be aware of urban sprawl due to automated vehicles as this can influence the arrival modes of travellers to the airport. If more people are living further away from the city centre due to automated vehicles making longer trips, in distance, time, or both, more attractive then this could increase the number of trips arriving at the airport through this mode.

2.1.9 Study and Model Results from Literature

Provided within this section is Table 2.1, presented below, from literature summarizing many of the findings where automated vehicles were looked at for their future impacts. Three major trends can be seen in the results from these studies. The first is the reduction of total vehicles. Even a small CAV penetration rate saw relatively large reductions in total vehicles. The ability for CAVs to make multiple trips servicing multiple people allows them to greatly reduce the demand for individual vehicles. The second trend,

however, is related to the first in how the total distance traveled by vehicles increased in most results. This is due to empty kilometers where the CAV is travelling to pick someone up or returning home after dropping someone off. Finally, the third trend is the reduction in needed parking spaces. CAVs can either return home to avoid paying for parking or continue to service other travellers and never need to stay parked for extended durations throughout the day. This was seen to reduce the need for parking up to and over 90%.

Table 2.1: Summary of study characteristics and results on impacts of AVs on travel behaviour and land use. Adapted from (Soteropoulos, Berger and Ciari 2018)

Reference	Study Region	Methodology	Main Model Assumptions	Scenarios/Assumptions on transport supply	Main Results
(Burns, Jordan and Scarborough 2013)	Ann Arbor, USA	Queuing and simulation Models	Constant travel speed with peak hour factors; Grid network; avg. waiting time: 0.4 minutes	Replacement of all trips of vehicles driven less than 70 miles/day with SAVs	-85% vehicles
(Kornhauser 2013)	New Jersey, USA	Activity-based-Model	Constant travel speed Grid network	Replacement of all private vehicle trips with SAVs (ridesharing) with pick-up stations	-46% vehicles
(Burghout, Rigole and Andreasson 2014)	Stockholm, Sweden	Hybrid micro-mesoscopic traffic simulation model	Link speeds as 75% of free-flow speeds for trip assignment model	Replacement of all home-based work private vehicle trips with SAVs Replacement of all home-based work private vehicle trips with SAVs (ridesharing); acceptable travel time increase 30% to 50%	+24% VKT -92% vehicles -11% to -24% VKT; +13-25% VHT -95% vehicles
(Fagnant and Kockelman 2014)	Hypothetical city, USA	Agent-based-Model	Constant travel speed for peak/off-peak; Grid network; avg. waiting time: 0.3 minutes	3.5% of trips served by SAVs	+11% VMT -91% vehicles
(Spieser, et al. 2014)	Singapore, Singapore	Design-oriented approach	Avg. travel speed is periodically time-varying	Replacement of all private vehicle trips with SAVs	-66% vehicles

Reference	Study Region	Methodology	Main Model Assumptions	Scenarios/Assumptions on transport supply	Main Results
(Childress, et al. 2015)	Seattle, USA	Activity-based-Model	Mode and Trip Choice Model Capacity changes for freeways and major arterials	+30% road capacity +30% road capacity, -35% VOT (household trips_ for private AVs +30% road capacity, -35% VOT, -50% parking cost for private AVs SAVs with cost of $1.65/mile (no private vehicle trips possible)	+4% VMT; -4% VHT +5% VMT; -2% VHT +20% VMT; +17% VHT -0.3 and -1.6 percentage points in PT and walk share +35% VMT; -41% in VHT +4 and +5 percentage points in PT and walk share
(Fagnant, Kockelman and Bansal 2015)	Austin, USA	Agent-based-Model	Hourly varying link-level travel speeds	1.3% of regional trips served by SAVs	+8% VMT -89% vehicles
(ITF (International Transport Forum) 2015)	Lisbon, Portugal	Agent-based-Model	Link travel speed based on trip assignment Rule-based Mode-Choice Model based on existence/non-existence of PT Three different sizes of SAVs	Replacement of all motorised trips by SAVs Replacement of all motorised trips by SAVs (ridesharing)	+44% to +89 VKT; -84% to -89% parking spaces -77% to -83% vehicles +6% to +22% VKT; -93% to -94% in parking spaces -87% to -90% vehicles
(Kim, et al. 2015a)	Atlanta, USA	Activity-based-Model	Mode and Trip-Choice Model	+50% road capacity +50% road capacity, -50% VOT for private AVs +50% road capacity, -50% VOT, -71% operating and -100% parking cost for private AVs	+4% VMT +13% VMT +24% VMT; +12% VHT; -0.8 percentage points in PT share
(Kim, et al.	Seoul, South	Agent-based-	Travel behaviour and	Increase in road capacity, 100% market	More dispersed

Reference	Study Region	Methodology	Main Model Assumptions	Scenarios/Assumptions on transport supply	Main Results
2015b)	Korea	model	residential location choices including locational preference factors	share of private AVs Preference for road and city centre accessibility and low-price regions	development of urban space
(Zhang, Guhathakurta and Fang, Exploring the impact of shared autonomous vehicles on urban parking demand: An agent-based simulation approach 2015)	Hypothetical city, USA	Agent-based-Model	Constant travel speed for peak/off-peak; Grid network; Average Waiting Time: 2 min	2% of trips served by SAVs	-90% parking spaces
(Bischoff and Maciejewski 2016)	Berlin, Germany	Agent-based-Model	Time-varying link travel times Demand-supply balancing dispatching strategy Max waiting time: 15 minutes	Replacement of all private vehicle trips by SAVs	-91% vehicles
(Boesch, Ciari and Axhausen 2016)	Zurich, Switzerland	Agent-based-Model	Travel times form MATSim for actual trips Max waiting time: 10 minutes	Replacement of all private vehicle trips by SAVs	-90% vehicles
(Chen, Hanna	Hypothetical	Discrete-time	Constant travel speed	10% of trips served by SAVs	+7% empty VMT; -87%

Reference	Study Region	Methodology	Main Model Assumptions	Scenarios/Assumptions on transport supply	Main Results
and Kockelman 2016)	city, USA	Agent-based-Model	for peak/off-peak; Grid network Avg waiting time: 7 to 9 minutes	10% of trips served by electric SAVs (with recharge time and vehicle range)	vehicles +7% to +14% empty VMT; -85% to -73% vehicles
(Chen and Kockelman 2016)	Hypothetical city, USA	Discrete-time Agent-based-Model	Constant travel speed for peak/off-peak; Multinomial logit Mode-Choice Model Grid network; average waiting time: 3 minutes	-65% VOT, $0.85/mile operating cost for SAVs (with battery recharge time and vehicle range)	-25 percentage points in car share -3 percentage points in PT share
(Correia and van Arem 2016)	Delft, Netherlands	Assigning private AV trips to road network	Mode-Choice Model Travel times change after trip assignment	Replacement of private vehicles with private AVs in households Replacement of private vehicles with private AVs in households, -50% VOT for private AVs	+17% VMT; +3 percentage points in car share -49 % VMT; +9 percentage points in car share
(Fagnant and Kockelman 2016)	Austin, USA	Agent-based-Model	Hourly varying link-level travel speeds Avg. waiting time carsharing: 1,9 min Avg. waiting time ridesharing: 1,2 to 1,4 min	1,3% of regional trips served by SAVs 1,3% of regional trips served by SAVs (ridesharing) Acceptable travel time increase for ridesharing 20% to 40%	+9% VMT; −90% vehicles +2% to +5% VMT −90% to −91% vehicles
(Friedrich and & Hartl 2016)	Stuttgart, Germany	Macroscopic and microscopic travel demand Model	Link travel speed based on trip assignment Rule-based Mode-Choice Model based on existence/non-existence of PT	Replacement of all motorised trips by SAVs	+18% to +39% VMT; −77% to −81% vehicles −77% to −83% parking spaces

Reference	Study Region	Methodology	Main Model Assumptions	Scenarios/Assumptions on transport supply	Main Results
			Two different sizes of SAVs	Replacement of all motorised trips by SAVs (ridesharing)	−20% to +36% VMT; −90% to −93% vehicles −90% to −93% parking spaces
(Hörl, Erath and Axhausen 2016)	Sioux Falls, USA	Agent-based-Model	Time-varying link travel times Demand-supply balancing dispatching strategy Mode-Choice Model; max. waiting time: 17 min	−65% VOT, $0.85/mile cost for SAVs	+60% VMT; −20 percentage points in private car share −10 and −8 percentage points in PT and walk share
(Thakur, Kinghorn and & Grace 2016)	Melbourne, Australia	Land Use and Transport Interaction Model	Travel behaviour and residential location choices with accessibility to employment as explanatory variable	−50% VOT for private AVs Replacement of private vehicles with SAVs (ridesharing) with 0.49 €/km operating cost	+4% population in inner parts of the city −3% population in the far outer suburbs −4% population in inner parts of the city +3% population in the far outer suburbs
(Auld, Sokolov and Stephens, Analysis of the effects of	Chicago, USA	Activity-based travel demand Model	Mode and Trip-Choice Model Link travel speed based on trip assignments	+12% to 77% road capacity −25% to −75% VOT, 20% market share of private AVs	+1% to +4% VMT +2% to +18% VMT

Reference	Study Region	Methodology	Main Model Assumptions	Scenarios/Assumptions on transport supply	Main Results
connected-automated vehicle technologies on travel demand. 2017)				−25% to −75% VOT, 75% market share of private AVs +77% road capacity, −25% to −75% VOT, 100% market share of private AVs	+10% to +59% VMT +21% to +79% in VMT
(Bangemann 2017)	Munich, Germany	Microscopic travel demand Model	SAVs with two seats	Replacement of all private vehicle trips with electric SAVs (with recharge time and vehicle range)	+14% VMT −91% vehicles
(Heilig, et al. 2017)	Stuttgart, Germany	Agent-based travel demand Model	Combined Destination and Mode-Choice Model Avg. waiting time: 7,5 min	−45% cost/mile compared to private car for SAVs (ridesharing), −70% cost/mile with occupation rate >=1,64	−20% VMT; −85% vehicles; +4 percentage points in PT share; +8 and +5 percentage points walk and cycle share
(Levin, et al. 2017)	Austin, USA	Cell transmission model based dynamic network loading simulator	Link travel speed based on traffic flow simulator; Waiting time: 10 min	Replacement of all private vehicle trips with SAVs	−72% vehicles
(Martinez and Viegas 2017)	Lisbon, Portugal	Agent-based Model	Link travel speed based on trip assignment Rule-based Mode-Choice Model Max. waiting and travel	Replacement of all motorised trips by SAVs (ridesharing) Replacement of all motorised trips by SAVs (ridesharing) and taxi buses (8–16 seats, boarding at	−25% VKT; −95% vehicles −29% VKT −97% cars, +568% buses

Reference	Study Region	Methodology	Main Model Assumptions	Scenarios/Assumptions on transport supply	Main Results
			time increase: 15 min	specific points)	
(Liu, et al. 2017)	Austin, USA	Agent-based-Model	Time-varying link travel times Mode-Choice Model Avg. waiting time: 3 min	−50% VOT, $0.5/mile operating costs for SAVs −50% VOT, $0.75/mile operating costs for SAVs −50% VOT, $1/mile operating costs for SAVs −50% VOT, $1.25/mile operating costs for SAVs	+9,8% empty VMT; SAV fleet = 17% of travellers +13,2% empty VMT; SAV fleet = 15% of travellers +15,7% empty VMT; SAV fleet = 13% of travellers +15,1% empty VMT; SAV fleet = 13% of travellers
(Llorca, Moreno and Moechel 2017)	Munich, Germany	Agent-based-Model	Time-varying link travel times Demand-supply balancing dispatching strategy Average waiting time: 8 min	Replacement of 20% of private vehicle trips with SAVs Replacement of 40% of private vehicle trips with SAVs	+5% VMT; −14% vehicles (overall) +7% VMT; −28% vehicles (overall)
(Zhang and Guhathakurta 2017)	Atlanta, USA	Agent-based travel demand Model	Constant travel speed for different day periods; Avg. Waiting Time: 3,8 min	5% of trips served by SAVs (car- and ridesharing); −100% parking cost $0.5/minute operating costs (carsharing) and $0.3/minute (ridesharing)	−4,5% in parking land
(Zhao and Kocckelman 2017)	Austin, USA	Travel demand Model	Hourly varying link travel speeds (congested time	−25% to −75% VOT for private AVs and SAVs 1$/mile operating cost (private AVs)	+18% to +41% VMT

Reference	Study Region	Methodology	Main Model Assumptions	Scenarios/Assumptions on transport supply	Main Results
		(traditional trip-based four-step Model)	information) Mode-Choice Model	and 1.5$/mile (SAVs) −50% in VOT, −50% to −100% parking cost for private AVs and SAVs 1$/mile operating cost (private AVs) and 1.5$/mile (SAVs) −50% in VOT for private AVs and SAVs 1$/mile operating cost (private AVs) and 1$/mile (SAVs) −50% in VOT for private AVs and SAVs 1.5$/mile operating cost (private AVs) and 1.5$/mile (SAVs)	+26% VMT +28% VMT +29% VMT
(Auld, Verbas, et al. 2018)	Chicago, USA	Activity-based travel demand Model	Mode and Trip-Choice Model Fleet penetration based on model (AV cost) Link level travel speed based on trip assignments	47.8% to 100% fleet penetration of private AVs −30% VOT, 13.4% to 100% fleet penetration of private AVs −50% VOT, 13.4% to 100% fleet penetration of private AVs	+6% to +8% VMT +15% to +24% VMT +21% to +43% VMT
(Boesch, Ciari and Axhausen 2018)	Zug, Switzerland	Agent-based-Model	Time-varying link travel times Mode-Choice Model	−38% VOT for private AVs, −54% VOT for SAVs +25% operating cost for private AVs (0,22CHF/km); −50% operating cost for automated PT (0,13CHF/km); 0,46 CHF/km operating cost for SAVs	+16% VMT −12 percentage points in private car share −4 and −16 percentage points in PT and slow modes share
(Kröger,	Germany	Aspatial	Travel speeds constant	−25% VOT for private AVs, 7,5%	+3,4% in VKT; +1,3 and

Reference	Study Region	Methodology	Main Model Assumptions	Scenarios/Assumptions on transport supply	Main Results
Kuhnimhof and Trommer 2019)	and USA	travel demand Model	to today Combined mode and distance choice (No traffic assignment) AV market share based on diffusion model AV availability for teenagers, adults without driver license and mobility-impaired people	market share −25% VOT for private AVs, 29,3% market share −25% VOT for private AVs, 10,1% market share −25% VOT for private AVs, 37,6% market share	−0.2 percentage points in car and PT share +8,6% in VKT; +3,8 and −0.4 percentage points in car and PT share +2,4% in VKT; +1 and −0.3 percentage point in car and PT share +8,6% in VKT; +3,7 and −0.9 percentage points in car and PT share
(Zhang, Guhathakurta and Khalil 2018)	Atlanta, USA	Activity-based travel Model	Varying link travel speeds (congested time information); no trip delay	Replacement of private vehicles with private AVs in households determined by min. number of AVs to satisfy travel demand of household members	+13.3% empty VMT −9.5% vehicles

2.1.10 Potential Policy Impacts and Needed Changes

From examining all the previous topics, it can be seen that the changes caused by automated vehicles depends on their use case. This means policy changes will be needed from developers to guide the changes towards positive impacts. A study in 2019 found that there is still a lack of knowledge for planners to truly address automated vehicles because they do not know how communities will use automated technologies (Yigitcanlar, Wilson and Kamruzzaman 2019). They suggest that planners should be proactive with guiding the changes and engage with communities since it is the social aspect that is uncertain. Studies that show us what policy changes may be needed should be examined to get a better understanding of the actions that should be taken in preparation for automated vehicles.

Airports should be aware of the direction automated vehicles are taking in their implementation. Depending on people's comfort level or desired use-case the future scene for automated vehicles could be different.

A case study on the policy impacts towards restricting the individual use of a car in the urban area of Rome was found (Coppola and Silvestri 2019), comparing individual to shared transportation. This study was not focused on automated vehicles but was concerned with how policy changes could be used to change travel behaviours of current modes. The model found that introducing policy that restricted car use alongside improving public transit services showed a mode shift towards the more sustainable transportation modes. It also resulted in limiting urban sprawl. These effects can be

extended to automated vehicles and transportation modes showing that with the right policy urban areas can influence the direction of change.

A further study was found that reviewed multiple surveys on people's perception and acceptance of CAVs which revealed some of the potential ways people could prefer to use the new technology without policy intervention (Zmud and Sener 2017). One survey found that younger people stated they were more favorable of self-driving vehicles, but mostly people were scared of automated driving. Other surveys found that the introduction of CAVs was likely to introduce an increase of VKT due to those who do not regularly drive, or are limited by the current mobility options, stating an interest in using the automated vehicle for transportation. They also found people stated a slightly higher interest in owning their own automated vehicle over using car-sharing companies. While this is a future interest study instead of one that reviews actual behaviours and cannot be fully trusted, it does show that the risks of increased VKT and urban sprawl due to the introduction of automated vehicles could be realized if policy is not introduced to limit it.

It was seen that while automated vehicles will most likely be changing the parking structure of urban areas as they stand today, the exact changes depend on more factors of how automated vehicles are used. Shared mobility and TNC services will also be adapting to the automated era making use of automated vehicles which could change their service models requiring a change to the curbside use or the introduction of staging areas. The automated vehicle was also seen to increase VKT in many studies even with a

reduction in total vehicles which will require an understanding of the travel patterns to know if current urban and facility service roads can handle the increased load. Urban sprawl was found to be directly increased by automated vehicles, but the indirect impacts of automated vehicles could reverse this. The change of fueling locations to charging locations for the electric autonomous vehicle could also change what services are expected at the airport. Since the automated vehicle can recharge itself when not in use these locations may change compared to the traditional corner gas, being located either at parking facilities, something that airports may be able to take advantage of, or throughout the city depending on travel patterns. Finally, policy makers and planners will need to take proactive action if they want to see positive impacts from the introduction of automated vehicles on the roads. automated vehicles come with both positive and negative impacts to urban land use, and appropriate policy will be required for airports to see benefits.

2.2 Airports

2.2.1 Mode Shares of Current Airports

The airport of today is a vehicle focused scene. The private car is used by the majority of travellers in many of the cases. Table 2.2 below displays the mode shares found at select airports from data that was found in literature. We can see that direct transportation options are the favoured mode of transportation. Where private cars see smaller shares, the areas that increase are shuttles or taxis, again bringing travellers to and from their

destination directly. This translates to a need for vehicle curb space at the airport. The curbside and the curb spaces are an important factor in today's airport in meeting the demand and providing a good level of service to travellers.

Table 2.2: Distribution of arrival mode shares at airports

Study Purpose	Year	Airport	Private Car (%)	Rental Car (%)	Public Transit (%)	Taxi (%)	Shuttle like Service (%)
Modelling passenger choice between competing airports in San Francisco Bay Area (Pels, Nijkamp and Rietveld 2003).	2003, data from 1995	San Francisco	64	2	2	6	25
		San Jose	88	2	1	5	4
		Oakland	84	1	6	1	8
Special Generators Survey (R.A. Malatest & Associates Ltd. 2016)	2013	Ottawa International Airport	67 (36 driver, 31 passenger)	6	5	21	2

The transportation trends of today influence the desired use of new technologies. We further need to understand how the current demand of mostly private vehicles is affecting the airport curbside to have a proper understanding of the change to automated vehicles will make. Up to date data from more airports is needed for this to be possible and why a data collection effort was done at the study airport for the thesis.

2.2.2 Transportation Within the Airport

Airports offer passengers ways to get around the airport and these could expand in the autonomous era. Connected and automated vehicles act as a way of providing mobility as a service. The aging population and raised awareness for mobility issues of the population can be addressed by automated systems. Connected systems can also allow passengers to request services ahead of time, even on ticket purchase, reserving the service so they know it will be available to them for when they arrive. This also allows airports to seamlessly share information on passenger needs so that services can be ready or made available for passengers coming from other airports. These services are already automated for luggage transfer (Greater Toronto Airports Authority 2018) so connecting that process to mobility services in a connected facility is the next logical step. A pilot project in Winnipeg's Richardson airport has started providing automated wheelchair services to passengers (Cash 2019). The project provides access to this essential service to passengers with mobility concerns without needing to involve staff. This both reduces the operational costs of providing the service while providing it in a way that increases the independence provided to passengers. The service has also already been tested in airports in Tokyo, Amsterdam, Abu Dhabi, and Dallas. The goals of projects like these are to develop services that will be waiting for passengers as they arrive at the airport so their time at the airport is free of any mobility barriers.

2.2.3 Airport Operations

Beyond the changes to facilities for arriving and departing passengers are those to the airport operations themselves. Maintaining an airport currently requires a significant staff, this can change with CAVs and connected systems. Many of the operations at airports are being looked into for replacement by CAVs, one in particular that is relevant for Canadian and other Northern airports is snow clearing. A group of researchers developed an algorithm that can be used by a snow clearing fleet to plan out an efficient path (Saska, Hess and Schilling 2008). The algorithm finds the path that clears all the runways and service paths while maintaining snow clearing safety standards. Baggage transportation and other surface operations can also be made autonomous. A study investigated using GNSS to keep track of vehicle locations while they conducted their work in a modeled airport environment (Bijjahalli, Rmasamy and Sabatini 2017). The system was focused on safety and providing early warnings of danger. Furthermore, stations within the airport that are interacted with by passengers could also become autonomous and run by robots (Hornyak 2020). While less tested, this direction of progress is expected in the era of automation as a way to speed up passengers processing time at airports. All these changes have the potential of reducing the operating costs of airports from the reduced labour costs. Airports will need to analyze the development costs compared to the savings as these technologies become available for use to best take advantage of the cost savings that will be available from connected and autonomous systems.

2.2.4 Processors and Logistics in the Era of Automation

Connected and autonomous systems present opportunities to the changes that will be coming to the processors and logistics at airport landside management. A large portion of onboarding trips coming into airports originate within the city (R.A. Malatest & Associates Ltd. 2016). This means with study and integration of trip planning apps airports could anticipate more accurately when passengers will be arriving for flights. Staff, and focus on processors, can then be arranged to service the areas as needed. These changes could mean a difference in how check-ins are operated at an airport and how people pass through security. Preboarding activities can be completed online or by robots (Hornyak 2020) allowing more passengers to be serviced at once increasing the service level to customers. Automating stages in a passenger's time at an airport, such as baggage check, could also increase passenger processing time while reducing labour costs for the service.

The automation of security and its effectiveness is a current area of research for airports. Figure 2.2 shows a simplified example of the use that current autonomous security scanners have at security gates. They work to compliment regular procedures by baggage screeners to help identify objects that are harder to notice.

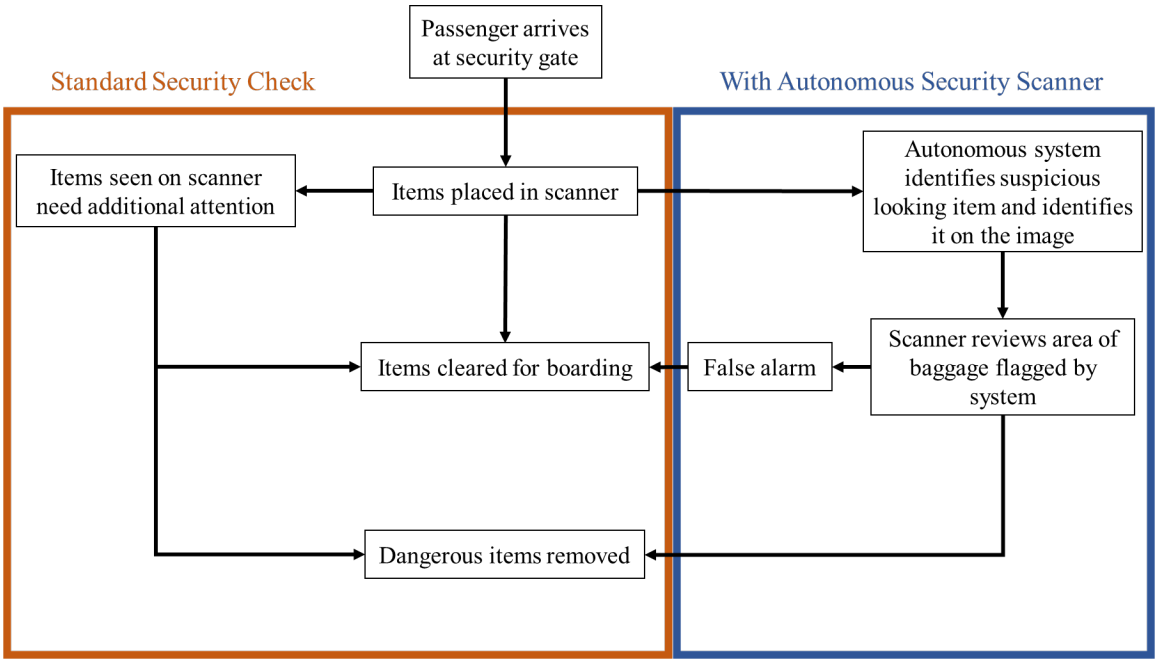


Figure 2.2: Comparing an example security check process with that aided by autonomous security scanner

The results of studies done on airport screeners aided by autonomous security scanners though show that the operation of these technologies should be focused more on reliability than accuracy (Hattenschwiler, et al. 2018) (Huegli, Merks and Schwaninger 2020). In these studies, the researchers tested different configurations of automation aided security screenings. The automated system was found to not make a noticeable difference in detection rates of objects that are already identified with high confidence by operators. Where it did make a difference was in objects like bare explosives that screeners currently have a low confidence rate in identifying (Huegli, Merks and Schwaninger 2020). This means that airport security can benefit from introducing these systems to aid their screeners. However, current automatic detection systems come with a

balance of detecting more dangers but at the cost of more false positives. They wanted to know the effects of having screeners aided by a system with a high hit rate but also high false alarm rate compared to that of a lower hit rate but reduced false alarm rate, see Table 2.3 below for two of the systems used in the study.

Table 2.3: Rates for automated explosives detection systems for cabin baggage screening (Huegli, Merks and Schwaninger 2020)

	Hit Rate	False Alarm Rate
System 1	80	20
System 2	61	5

What they found was that the high false alarm rate was resulting in screeners falsely clearing bags that should have been flagged. What was concluded was that a system with a high reliability, low false alarm rate compared to detection rate, is recommended if airports should start using automation in airport security. If a system is used with a high false alarm rate then protocols are recommended to be in place to keep screeners from ignoring them. From these studies we can see that automation is being adopted as an aid for security. Operators are not being replaced by these systems and security still relies on screeners to be present. Low reliability systems, even with high accuracy, are not recommended as the false alarms could either decrease the security or increase the inconvenience to passengers due to an increase in having to further investigate bags and this would increase the time required to process passengers through security.

Overall, the changes at airport processing gates should be directed at increasing the quality of service over speed alone. It was found that passengers rated their experience not on the actual processing time but instead on the concept of perceived time and quality (Correia and Wirasinghe 2007). Automation of processors then should not only be implemented for their efficiency but also should keep passengers informed and able to progress through an airport in how they are comfortable. Reducing human interaction in place of automation should not reduce the ability for passengers to act in a dynamic way that reflects their needs.

Additional to automation is the investment in Information Technology (IT) at airports as these systems work together to create a connected environment. Recently, airports have been spending more on IT to provide more services to passengers (SITA 2019). These systems allow airports to offer more mobile services to help passenger flow and have shown that these investments have increased customer satisfaction. This increased level of IT to create the connected environment means that airports will either need to house significant computational power and systems or use 3rd party providers. Additional research is needed to know the benefits of each, as housing their own technology lets airports provide their own services but 3rd party providers may be the better choice for making the process seamless for passengers.

2.3 Modelling and Simulation of Airport Operations, Processors, and Logistics

Modelling the spaces at airports requires multiple levels of modelling. Airports are generating trips to and from the rest of the city they are part of. This means that the modes of transportation that people use to come and go in will depend on the transportation available in the city and offered by the airport. The modelling of these city-wide transportation trends is currently handled by nodal networks (Katazawa and Batty 2004). The cities themselves handle these models and information from them can be gathered from city reports, like portions of the Ottawa Special Generators Study (R.A. Malatest & Associates Ltd. 2016) and the GTAA 2018 Annual Report (Greater Toronto Airports Authority 2018) mentioned in previous sections.

The study of the San Francisco Bay area modelling effort was to see the effects on choice between different airports (Pels, Nijkamp and Rietveld 2003); an important factor in many large cities with multiple airports competing for passengers or simply city design promoting access. This study modelled the choice of airport and arrival mode based off the total trip cost to the airport. They identified two ways of modelling this scenario. In the first, airport and mode choice are made independent of each other. A person has already chosen an airport to fly out of and are now choosing arrival mode. The alternative is to base the airport and mode choice on each other and choose them together. Neither option has been initially chosen and instead the choice of airport and mode depend on

each other, so the final decision is based on the combination of the two giving the most desired outcome. They used a nested logit model to account for the different types of choices people will make to give the modelling outcomes more realistic results. Using the data gathered from their survey sample to estimate traveller's value of time, the modelling efforts found that access time was the main factor for airport choice. This was in part due to them finding a high value of time, $2.90/min for August and $1.97/min for October for business travellers, over earlier studies. This information can also be applied to the general case of airport access modes though too. While not the focus of the study, the high value of time in air travellers identified by the researchers could be used elsewhere to explain mode choices of people when getting to an airport.

Another study wanted to model the effects of autonomous vehicles on vehicle kilometers travelled and average trip duration (Moreno, et al. 2018). In this study they modelled different levels of shared autonomous vehicle saturations of the total city car fleet and how the trip times for these vehicles compared. What they found was that with high saturation that the average trip time became like that of when using a personal car. However, total trip time for using a shared vehicle compared to using a personal car were longer as a user will almost always need to wait for the shared vehicle to come pick them up, a situation that gets worse with a lower saturation of shared vehicles. While not a direct study of the mode uses to airports, this information does give some insight into what could be expected of shared vehicle use to an airport. Combining this information with the high value of time from the San Francisco study for mode choice to an airport it

points towards a city needing a higher saturation of shared vehicles with quick service for shared autonomous vehicles to become prominent at an airport or replace the use of personal cars. This, however, is an area requiring further study before any conclusions can be made.

Once looking at the airport as an isolated system the modelling is no longer recommended to be nodal but instead a microsimulation process (Katazawa and Batty 2004) and instead of insights from arrival modes and travel patterns we get pedestrian movements and areas of congestion at the airport. The microsimulation approach used to be avoided due to its high computational demand, however, recent technological advances has made it available for use and allow models to be built to show the flow of people through airports (Jon Kerridge 2001). Microsimulation is currently considered the best option for modelling these spaces with social forces being the driving concept behind simulating person behaviour in many of the programs available (Seyfried, Steffen and Lippert 2006).

Modelling the internal facilities at an airport are important to understand the impacts changes to facilities and behaviours can have on the waiting times of passengers and where people may accumulate. With the potential changes coming to terminals at an airport it is important to know what factors influence the processing or waiting times of each activity or checkpoint. In an effort to display the modelling capabilities of a mesoscopic scaled model a group looked at the effects different scenarios would have on the Athens International Airport arrival patterns and passport control facility (Manataki

and Zografos 2009). Mesoscopic scaled models use components from both macroscopic and microscopic models. They were able to model the effect to waiting time from changes in behaviour while at the airport facility. An area that was found to increase the waiting time is the increased use of e-check-ins. The areas looked at are not typically directly connected and the increase in e-check-ins increasing passport check waiting times was not easily expected. They also found a decrease in use of auxiliary services at the airport, such as shops, also increased the waiting times when going through the passport checks.

Another modelling study looked at speeds of different boarding strategies (Van Landeghem and Beuselinck 2002). In this study they identified the importance that some airports have in functioning as hubs, taking in passengers from other airports from many different flights and boarding them onto a larger plane or the opposite of needing to dispatch to multiple different smaller planes. In these cases, boarding times can be a critical bottleneck to the service capabilities of these airports. These researchers stated that airlines have a ten-minute turnaround goal, but that time is not met and was not found to be a reasonable goal through the model. In fact, the modelled scenarios found that a random boarding order was faster than the current more widely used structure by about five minutes. The only boarding structure modelled that was able to approach the ten-minute goal was calling each passenger individually. They found that due to the arrangement of the cabin and the aisles not allowing for maneuverability it inhibits the flow of people and slows down the boarding process. By calling each passenger

individually it allowed the model to call passengers in a way that they would minimize the interference with each other. However, this type of boarding procedure was also identified as being potentially too confusing or complicated to be practical outside of a modelled environment. It could also separate groups or families from each other during the boarding process, something that would lower the quality of service of the airline.

Looking at these two modelling exercises we can identify the areas in them that could be present in a connected and automated environment. It has already been identified earlier that processes like e-check-ins could become more popular in a connected environment. These potentials for improvement in processing other areas of airports, though, as was seen in the model of the passport control facility, could have negative effects on other areas. For the boarding cases, today calling each passenger individually would be a complex undertaking. However, in a connected environment this undertaking could be less intimidating and easier to communicate to passengers. The issue of separating passengers could also be addressed in a connected environment as it could be already in the system that travellers are together and thus will want to board as a group. This though, is unfortunately a theoretical view of being able to improve the boarding procedure in a connected environment as the model did not account for people using this type of technology and instead assumed people were aware of the boarding strategy in other ways. Taking this into consideration then, continued modelling of the whole airport and its facilities will be important in the future to know how some of the areas that have already been identified as issues and areas of potential improvement could be addressed.

2.4 Modelling CAVs with VISSIM

The modelling of CAVs with microsimulation software is not standardized in its current state. A review of available literature was done by (Gora, et al. 2020) to help contribute towards summarizing the state-of-the-art for microsimulation models for CAVs. VISSIM was identified as a widely used tool for microscopic simulations and one that is used in cases with automated vehicles. They found that the underlying model used in VISSIM, Wiedemann, has been used to model CAVs before. Further, it was identified for its ability to extend its capabilities through the use of interfaces that allow custom adaptions in behaviours to be added.

However, the paper found that the lack of empirical data from CAVs has kept literature from agreeing on a universal method. Without this data precise calibration and validation of the models is not possible. They recommend a collection of real-world data is needed, combined with a modelling standard, for future modelling efforts to be able to compare results with confidence.

Further, more literature was found reviewing currently available modelling software capable of modelling CAVs (Ahmed, Huang and Lu 2021). This paper also identified VISSIM as a popular tool that allows users to model the expected behaviour of CAVs. By modifying the Wiedemann model parameters, if CAV behaviours are known, and user defined operations through the COM interface users can get results of CAV behaviours.

This identifies VISSIM as a good choice for modelling CAVs as its wide range of application to the future use of CAVs allow methodologies to be compared.

Looking at efforts using VISSIM itself to model CAVs, the paper by (Zeidler, et al. 2019) was found that deals with modelling the driving behaviour of automated vehicles. Within, it states that currently there is no common agreement for parameter settings when modelling automated vehicles in microsimulation software. Two major reasons are given. The first being the lack of data since manufacturers of automated vehicles are currently in tight competition and are not revealing information about their car following algorithms. The second is the current development of technical components is not uniform among all manufacturers so there is no general technical capability of a standard automated vehicle.

To combat the lack of a general algorithm the researchers of the paper collected data from three vehicles driven in a real-world scenario and applied this data to simulations based on the Wiedemann car following method, the method used by VISSIM. The setup of vehicles was one manual driven car in the front followed by two automated vehicles. This let them collect data on how the vehicles behave with and without communication to the lead vehicle. The data collected from this exercise was then compared to results found in VISSIM when modelling the same scenario.

The research showed that automated vehicles communicating with the leading vehicle are reproduced well in VISSIM while problems remain in the cases with no communication to a leading vehicle. When communicating with the lead vehicle, the parameters of the

automated vehicles could be adjusted to match the observed behaviours. However, when no communication with the lead vehicle occurred the behaviours are more varied which resulted in a difference between the observed and modelled results.

Modelling vehicle safety is an issue that has been explored using VISSIM. A study was done using VISSIM and Paramics to predict collisions based on traffic conflicts (Saleem, et al. 2014). The work in this study simulated peak hour conflict conditions for four legged signalized intersections in Toronto, Ontario. Non-microsimulation approaches use historic collision data to predict future collisions when evaluating safety. For CAVs historical data may not be applicable. While the study did not evaluate the intersections for CAVs it did show that VISSIM was capable of being used to evaluate the safety of the intersections currently using the areas of conflict and included suggestions on how to improve safety. This ability is useful when considering the future need of modelling new vehicle behaviour types with CAVs. Modelling safety was not a subject of this thesis; however, the ability for VISSIM to evaluate safety enables future work in this area to include safety in the analysis of the airport landside operations. This safety evaluation would include the safety to other CAVs, non autonomous vehicles, vulnerable road users (pedestrians, bicyclists, etc.), traffic control operators, and emergency personnel which VISSIM could be used for.

2.5 Modelling Pedestrians with MassMotion

MassMotion (Oasys 2022) uses a social forces model of pedestrian movement, which the state-of-the-art was summarized in a 2018 study (Chen, et al. 2018). While this study did mention the development of different pedestrian movement models, it considered the social force model to have become one of the most widely used models. The study by Chen considers the social force model to account for pedestrian shape, mass, walking speed, and group. It also considers human movement as being a combination of the movement categories of straight flow, rounding a corner, entering or exiting a confined space, bi-directional flow, crossing flows, random flows, avoiding, self-stopping, following, and overtaking. All these actions can occur in airport spaces.

The state-of-the-art review by Chen considers the version by Helbing and Molnar (Helbing and Molnar 1995) as the starting point for the social forces model. In this version, each pedestrian has a driving force towards their destination, repulsive forces due to obstacles or other unfamiliar pedestrians, and attraction forces due to friends or attractions. The sum of these forces results in a movement vector to move the pedestrian within the model, as shown in Figure 2.3 below.

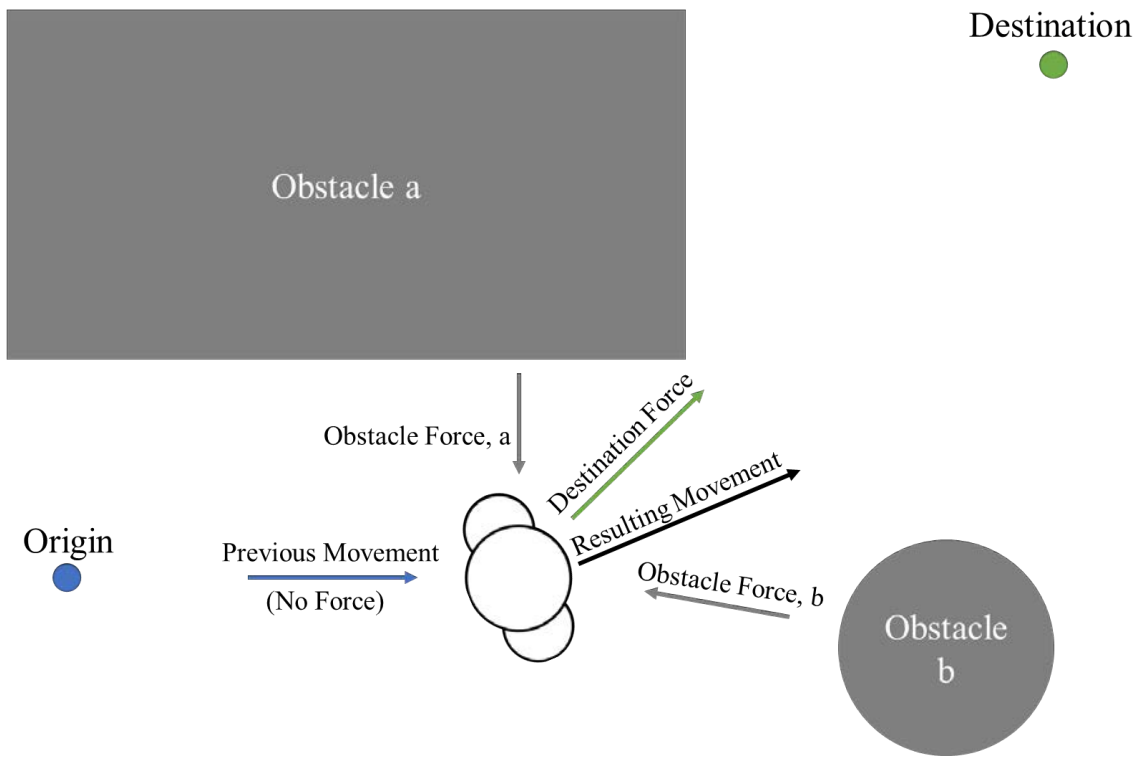


Figure 2.3: Social forces on a pedestrian between origin and destination

Since this version, the equations continue to be improved to produce more realistic movements. The social force model was first developed to consider low density environments but has since grown to include forces to react to high density environments where pedestrian come into contact (Helbing, Farkas and Vicsek 2000). These are expressed as normal forces and are shown along side repulsive forces due to other pedestrians in a crowd in Figure 2.4 below.

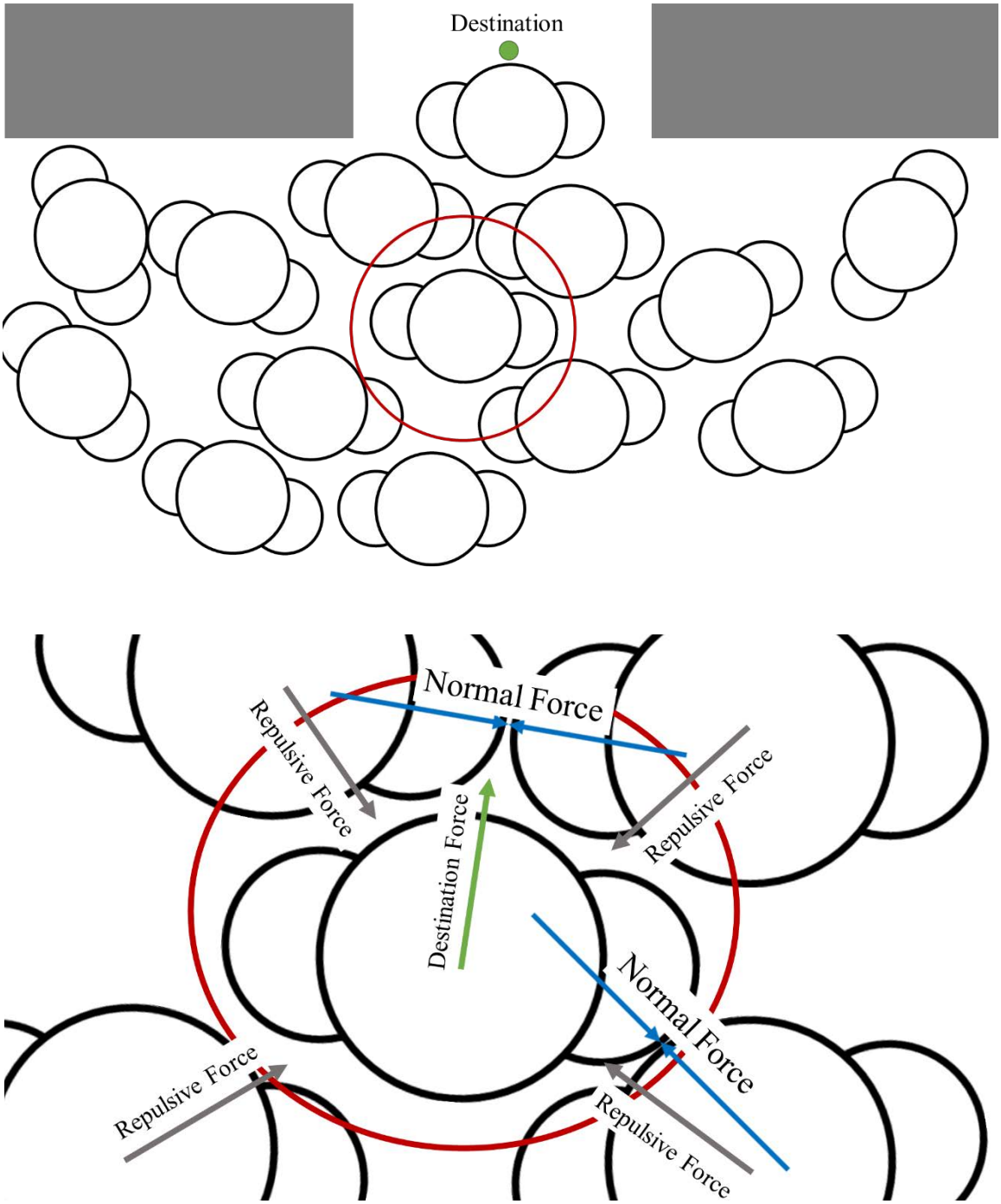


Figure 2.4: Social forces on a pedestrian due to contact in a crowd

Due to proximity and contact being a factor to the social force model the shape of the pedestrian within the model is also a consideration. Three shapes are used, a circle, an ellipse, or three circles as seen below in Figure 2.5. The simpler shape of the circle allows for faster calculation of large crowds, such as those in stadiums, while the more complex shapes allow for more accurate results. The choice for which shape to use depends on the size of the model and the required outputs. MassMotion allows for the choice of which shape to use. Including a shape portion for roller luggage is also necessary for application at the airport scene where this is common.

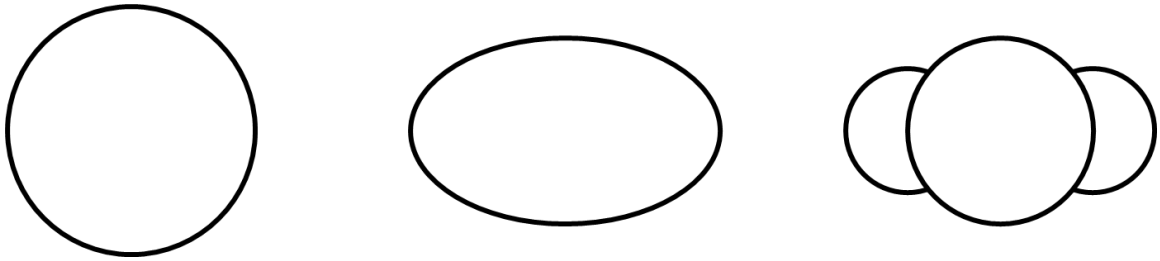


Figure 2.5: Social forces pedestrian shapes: circle, ellipse, three circles

Since this development researchers have looked to improve the areas of group movement, bidirectional flow, bottleneck flow, overtaking behaviour, self-stopping behaviour, self-organization phenomena, pedestrian movement on stairs, and emergency evacuation.

MassMotion itself has been validated for its use as a social forces model simulation software for evacuation modelling (Arup 2019). They have verified the following use cases for the software: corridor walking speeds, stair walking speeds, exit flow rates, pre-evacuation times, movement around corners, assignment of parameters, counter-flow,

crowd exit usage, exit allocation, stair congestion, movement disabilities, affiliation, and dynamic availability of exits. These were tested in accordance with the standard set of evacuation modelling verification tests by International Maritime Organization Circ. 1238 and the National Institute of Standards Technical Note 1822. Additionally, they verified for the behaviours of stair merging and stair flows which were not included in the verification tests.

Oasys, the publishers of MassMotion, have provided case studies where MassMotion was used in practice (Oasys 2022). In the areas of transportation, the case studies include uses for Sao Paulo Metro Line 6, a commercial lobby in South Korea, Champ de Mars in Montreal for a new park, Wilson Street in Toronto to increase accessibility for the Toronto subway network, and others such as museums, universities, and a stadium. MassMotion is capable of modelling diverse pedestrian environments as its inputs can be adjusted to fit the scenario in question. These case studies show how it has been used for transportation centres before making it a good choice for the airport. The use of MassMotion can also be found in literature, as discussed below.

MassMotion has been used to interface with other transportation simulators. In one study (Srikukenthiran and Shalaby 2017), MassMotion was used to create detailed crowd simulations at important locations while the transit network was modelled using Nexus. Nexus allows for multiple simulators to interact and MassMotion was the focus of this study showing it can be used in combination with other software to create a full picture of travel. This study highlighted how MassMotion can improve an existing model

framework of an area. The results from MassMotion can be actively used as inputs for other models.

MassMotion was also used in a study to evaluate its use for modelling building egress (Rivers, et al. 2014). The paper used observed evacuation drills to validate MassMotion over four buildings of different scales. They found the total evacuation times to be within 10% of the observed total egress times and noted that agent movements and behaviours on egress stairs to match that of the observations. Egress is an important area for pedestrian modelling. MassMotion provides a way for different safety measures to be compared between different layouts.

MassMotion can also be used to model the movements of groups not of the average general public. A study was found where the evacuation of elderly was examined using MassMotion (Li, et al. 2020). The study was interested in finding the impacts to evacuation times due to the distribution of dependent elderly in higher floors of a nursing home. MassMotion was able to show that the evacuation time was significantly prolonged when the proportion of dependent elderly was increased. These results highlight how MassMotion can be used to examine how different demographics effect the flow of pedestrians in an area. As the numbers and locations change it can have a noticeable effect on the results to the performance of the space and MassMotion is capable of showing this difference. This application of different demographics can be extended to the airport when using MassMotion.

2.6 Methods and Technology used for the Study of Human Factors at Airports

Studying human factors has been and will remain a large task for any transportation study. The data collected not only has to have a large enough sample, but that sample needs to be reliable and unbiased. Direct intervention to ask questions can also introduce a bias, but this is the only way available to discover the true motivations of people and their perceived experience. These forms of surveys are important in understanding the impact changes will have. Directly asking questions helps give answers that explains why people are making the choices that they are. What these surveys lack though is saturation and numbers thus it addresses the reliability of the data more than the sample size.

Another more general but larger scope survey can also be done to capture more data. These types of surveys can be done on their own or to compliment a questionnaire survey and are usually volume counts and speed studies. It is much easier to only observe the behaviours of people without major interference. Collecting this type of data shows how people are moving regardless of their desired path, instead showing the one that they ultimately chose due to the conditions at the time. The data can be collected by going to the site itself or by reviewing footage at a later date.

What has been explained above briefly are two of the major types of survey methods for collecting transportation data, including pedestrian movements. These two methods can be collected in person or with new technology. In person, surveys can be collected by

going to the site and asking questions or observing from a distance. This method is reliable but labour intensive to get any significant amount of data. Questionnaire surveys can also be conducted through phone after the trip by willing participants, these again though can be labour intensive. Additionally, emerging apps are being developed that let people complete the survey on their own. However, questions in app-based surveys need more attention or a better explanation as there is less availability of someone to guide someone through the survey and questions could be answered incorrectly.

The participation rates of each of these methods can vary. A study was done looking at the factors that impacted participation rates of surveys for epidemiology studies (Keeble, et al. 2016). Of the effects to survey structure itself they found that incentives or free gifts and prenotification helped with participation rates. Paper surveys were found to be more effective than electronic, web surveys, or telephone surveys. Telephone surveys were found to be useful though as participation rates were positively related to the number of calls made. Additionally, calling multiple times along with contacting through postal was also found to increase participation rates.

When using data collected at the airport it must be understood that the sample is not random. The data is collected from existing airport users. Further, data collected on the same day or within a short period of time within that day will be focused on travellers potentially sharing the same flights. This is expected to leave out individuals who may have chosen to avoid travelling during those times or at all. The reasons for those

decisions are not collected in the methods used for this thesis and should be taken into consideration.

Non-response bias can be present in any survey and can lead to incorrect conclusions from studies. These issues are explained in a paper (Berg 2010) and summarized here. Non-response can come in multiple forms, not answering one or more questions of the survey or not completing the survey at all. When an individual does not answer a question or the entire survey the reason why is lost. If the sampling for the survey was random, the characteristics of the individual giving the non-response are unknown. In this way, non-response introduces an unknown factor of bias to the study as the reasons for the lack of data points are unknown. As an example, when pulling over vehicles for a roadside survey some may refuse to participate. The reason for this refusal could also not be recorded. Reasons for refusal could be privacy or being late; however, since the surveyors do not know why the survey was refused these concerns or reasons are not represented in the survey data. This results in a non-response bias since there is no data on those that refused to find a correlation between the individual and refusing to participate.

Another form of bias that is introduced to surveys is that of response by proxy. A study was done looking at the impacts of proxy bias when conducting a survey through the telephone (Badoe and Steuart 2010). When a survey is conducted through the telephone often the trips for the entire household are asked for and is done through proxy by a single member of the household. However, the household member completing the survey

may be unaware of all the trips made by other members in the household. The study by Badoe and Steuart found that home-based discretionary trips and non-home-based trips were underreported through proxy. School and work-based trips were not underreported.

Another emerging technology for the use in collecting data for transportation and pedestrian movements that could be used in the airport scene is that of Big Data. Big Data is more of a concept of a collective of information than any actual data form itself. It has been made possible by the continued growth of how information can be collected and has generated an enormous amount of data (Chen, Mao and Liu 2014). This data, though, is not all useful to transportation and not all the transportation data is useful to airports. This means that a subset of data will need to be extracted from it to be used, which requires newer technologies.

Big Data, though, is a step towards a connected environment where everything is generating and has access to information. Data collected from smart phones are able to track people and, while not always over their whole trip, with enough data and time the aggregated results can show a multitude of trips patterns over their entire length, including where they used each travel mode (Zheng, et al. 2016). This can be useful in knowing how people are coming to and leaving an airport since it can capture the whole trip and not just the arrival mode of passengers. This type of data can even continue to keep track of passengers once they have arrived at the airport, keeping track of the location of their smart phone. This presents a way to know the details on a person's trip from home, to the airport, while in the airport, and their travel destination while being

able to repeat all of this for their return trips and have that data connected. It gives a full high-level picture of the actions of passengers that use the airport.

Chapter 3: Research Framework and Methodology

This research was conducted to examine the effects of connected and automated vehicles to the airport with a focus on the curbside and the areas of human behaviours and movement in the connected pedestrian corridor.

The airport curbside is the interface between the study airport and the surrounding city. It is here that passengers are dropped off or picked up at the airport, transitioning between being a pedestrian at the airport and their choice of travel mode getting to or from the airport. Incoming travellers to the airport access the curbside through an access road connected to an intersection with a public road. This access road acts as the queue to the curbside as well when all spaces are being used. When vehicles leave the curbside, they again use this road and exit using the same intersection they used to enter.

Between the curbside and the airport security is the pedestrian corridor. This corridor acts as the only access for pedestrians between these two points at the airport. From the perspective of someone dropped off at the curbside, a traveller will enter the airport building at the curbside, wait at the elevator bay for an elevator down into the corridor, travel through the corridor walking normally or using the people movers, walk up the stairs, escalators, or use the elevators at the other end of the corridor, and then enter the lobby containing the queue for the airport security. Travellers that are being picked up at the curbside would have gone through this process in reverse by starting at the lobby. Friends and family may accompany travellers at all points through the corridor.

Access to new efficient, quick, and affordable transportation can have an impact on how the world develops. Travel speeds have changed the size of cities and has connected cultures that were once isolated. To address this, research is needed on the current state of airports and how the demand of transportation may change in the coming automated era. This chapter introduces the research framework and methodology chosen to accomplish the research goals of this thesis.

The research required specific tasks to prepare for the study, analyse the data, and produce results. These can be seen visually as shown in Figure 3.1. The two major tasks for this research were data collection and microsimulation.

Data collection was done for both the airport curbside and the pedestrian corridor. These data sets were then analysed so they could be used in the microsimulations. At the airport curbside the data was focused per vehicle looking at the number of vehicles using the curb space within the hour and dwell times of each vehicle when using a curb space. The data collection for the pedestrian corridor collected data per individual, looking at each person's speed and overall travel time through the corridor. See the data collection section below for more information.

Microsimulation was also done for both the airport curbside and the pedestrian corridor. In parallel to the data collection, the microsimulation of the airport curbside focused on the vehicles while the microsimulation of the pedestrian corridor focused on the individual people. This work required producing scripts to capture the required elements

for this research. See the microsimulation section below for more information on each microsimulation and produced scripts.

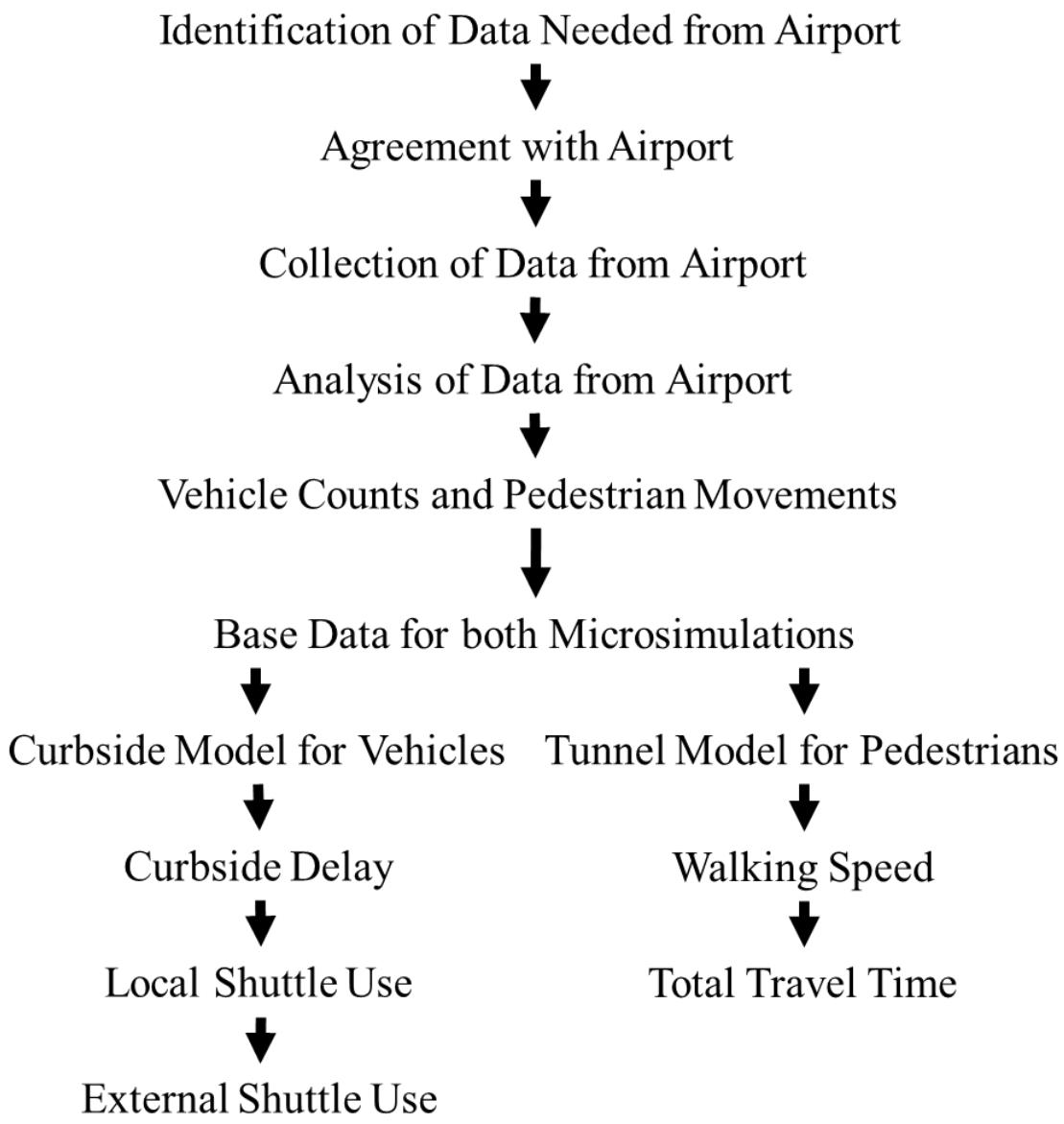


Figure 3.1: Research framework

Of note, the term model is used throughout while referring to multiple uses of the word, models of theory and models of space. The first case, models of theory, is to reference the theory that is being used to imitate the real-world. This can be understood as the mathematical equations used to decide the movement of vehicles or people. The second use, models of space, refers to the representation of a space within computer software. This can be understood as the roads of the curbside or the floor space and stairs of the pedestrian corridor. All models of the space case rely on using the models of theory to simulate human behaviour while models of theory can function without models of space. When models of theory operate without a model of space they instead use key properties of the space as inputs.

3.1 Data Collection

The data for this research was provided from existing airport security footage. This footage is collected every day by the airport authority and stored for their own security purposes. No adjustments to the location where footage was captured from or change to the airport layout was made. Only existing camera angles were used. This limited the data collection to what was already available. However, this also ensured that the traveller's experience at the airport was in no way affected by this study.

3.1.1 Airport Curbside Data Collection Methodology

As mentioned above, airport security footage was used to collect the data for the airport curbside. This was provided in raw video format and used video from a single camera.

No data collection tools or video processing was done on the footage. Data collection was done through visual inspection. Video playback software was used to navigate to desired sections of the video and to allow rewinding or pausing of the footage to properly identify and record information as needed.

A further description of the data collection methodology for the curbside can be found in Section 4.3.

3.1.2 Use of Collected Data of People Arriving at Study Airport

Data was collected for this research from the curbside of a North American commuter airport. This gave access to collecting data on mode shares at the curbside, vehicle arrival rates, and vehicle dwell times. For the purposes of this research the vehicle arrival rates and dwell times were used as critical inputs to the airport curbside model while the mode shares were to be used in comparison to other airport studies gathered through the literature review. Vehicle arrival rates and dwell times are critical as they provide the flow of vehicles and how long each vehicle needs to occupy the curbside to drop-off or pick-up a passenger. This time is not constant and depends on how prepared the passengers are to make the exchange when they arrive.

3.1.3 Airport Pedestrian Corridor Data Collection Methodology

The airport security footage from the airport corridor was used to collect the data. This footage was flattened before data was collected from it to correct for camera lens distortion as the location of each person on the image is important for accurate collection

of speeds. Data was collected from three different cameras. One camera provided spot speed measurements at a midpoint in the corridor. Footage from this camera was processed with the software Kinovea (Kinovea n.d.) to produce the spot speed measurements. The other two cameras were used to collect overall travel times through the corridor. This was collected through visual inspection using video playback software to allow for pausing and rewinding to properly identify individuals between the two videos.

A further description of the data collection methodology for the pedestrian corridor can be found in Section 8.3.

3.1.4 Use of Collected Data of People Moving Through Airport Pedestrian Access Corridor

The use of space that may be affected is not limited to the curbside and as such data was also collected on the immediate pedestrian areas after the curbside at the study airport. This area was a pedestrian access corridor that provided direct access from the curbside to the airport check-in and security. The corridor also featured a moving walkway (people mover) which effects how pedestrians move through the space. This led to the data collection of how many people were using the moving walkway feature, the speeds at which they were moving, and separated them based on classification of luggage. The luggage classifications were separated based on no luggage or light luggage that was able to be carried, and luggage in rolling cases that people in the corridor pulled behind them.

3.2 Microsimulation-Agent Based Modelling

This research chose to use microsimulation-agent based modelling since it is concerned with the changes to the demand and supply interaction of the individual at the airport. Microsimulation models allow the simulation to evaluate the use of space by each individual vehicle or person.

As the focus is on each individual vehicle or person, the microsimulation approach used in this research is agent-based. An agent in a microsimulation is a simulated entity that holds the same properties as the real-world entity that it represents, as shown below in Figure 3.2 and Figure 3.3. In this research both the vehicles and pedestrians acted as the agents for their respective models. Each agent does not have to share the exact properties of a real-world individual. Instead, the agent is given the properties as needed for the area in which they are being modelled. More than one agent type can be defined within the model allowing for multiple types of vehicles or pedestrian profiles to interact. The models move each agent individually based on the network and the presence of other agents within the model. At any time in the simulation there can be many agents, only one agent, or no agents. Agents enter or leave the model as defined by the scenario conditions.

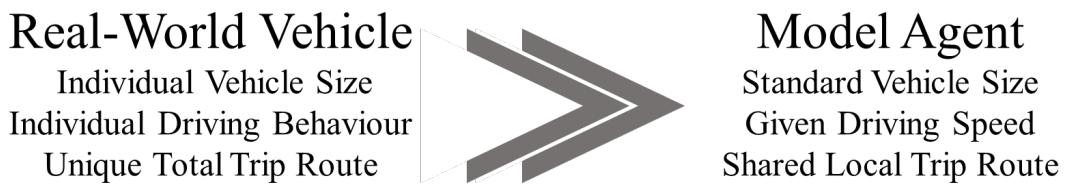


Figure 3.2: Vehicle characteristics to agent characteristics

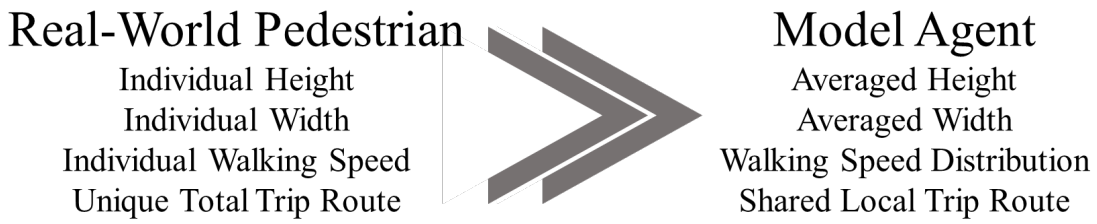


Figure 3.3: Pedestrian characteristics to agent characteristics

Both simulation software used for this research, VISSIM and MassMotion, operate on a time step basis for interacting with the agents. A time step in the software is the next point in time that the model needs to jump forward to. This allows it to have a finite point to calculate to when finding where to move the agents and how the agents interact. Microsimulation-Agent based modelling requires a small enough time step to produce results that allow the agents to react as expected but large enough so calculations do not take too long. By having a reasonable time step and a modern computer it allowed for running simulations faster than real time during this research. This allowed multiple hours of simulated results to be run within one hour of real time.

3.2.1 Airport Curbside Vehicles

VISSIM (PTV Group 2022) was chosen as the model space for the airport curbside. VISSIM allows for the modelling of the vehicles and pedestrians through a realistic road and pedestrian area representation. It further allows custom scripts which allowed the functionality of the simulations to be expanded to include the necessary components for this research through the COM interface. A model airport was built for the study. See Section 2.4 for a literature review on the applicability of VISSIM for modelling CAVs and Section 6.1 for the model used in this study.

The goal of this section of the research is to evaluate the effects to an airport due to automated vehicles. In the modelled scenarios there are two major assumptions that were made for the future cases when considering CAVs: electrification of automated vehicles and the full connection of automated vehicles to the network.

The first assumption means automated vehicles are relying on an electric grid network that can be provided at staging and parking locations instead of traditional gas stations. This provides an additional value to these locations for automated vehicles. On-site vehicles can use their staging locations to stay charged without the need for a trip to a fueling location. Further, the electrification allows the vehicle to support the systems of the second assumption.

The second assumption allows the automated vehicle to communicate with other vehicles, passengers, and infrastructure over the V2X network. This is needed to ensure

safety and efficiency of the network. This assumption is most critical when evaluating automated vehicles in the context of airport spaces. It has the potential to widely impact the travel behaviours of people within an urban area and that of the vehicles themselves. The connected aspect of the vehicle allows the vehicle to plan its movements based on data being given to it by other vehicles or the surrounding network. These abilities were accounted for when modelling them in the airport curbside.

These assumptions allowed for the model scenarios to be built where vehicles would react to the planned design of the space. If only self-driving behaviours were assumed, vehicles could not be relied upon to react to changes outside of their sensor range. However, the connected aspect of the vehicle allows them to be provided vehicle routing instructions at the local level.

A link-based network was used for the airport. Each road of the airport is represented by a link. This link is given the road properties, so the model knows the number of lanes and the direction of traffic on those lanes. All vehicles operating in the model as agents are input onto these links and travel from link to link. Changing lanes on the same link is possible and agents will do this on their own as needed.

Links are joined using other specialized links known as connectors. These connectors are defined by the two links they are connecting and the point on each link that they connect to. This allows links to have multiple connections and for these connections to be on mid-

points or ends of the links. Connectors can also be defined by which lane of the link they are connected to so only vehicles in the correct lane may travel to the other link.

Vehicles enter the model as agents through a vehicle input property on a link. This generates agents at the start of the link using a random distribution. The distribution is defined using an hourly volume. Multiple types of vehicles can be input on a single link through either multiple vehicle input properties or defining the relative spread of the different agents within the single input property. Once input to the model, the agents will navigate through the model on the links and connectors.

Agent routes in the model are defined using partial routes. These partial routes detail origin and destination links for the agent to travel from and to. Partial routes are placed on links and apply to agents as they pass through their starting locations. The partial routes can define which agent types follow them through their agent properties. This allows for agents to follow different routes while in the model from each other. Routing agents out of the model requires a partial route. Agents will leave when they reach the end of a link. However, agents will choose routes on their own to avoid reaching the end of a link. By placing a partial route an agent can be forced to leave the model where needed.

Parking spaces are special locations within the model that are placed on links. Agents access parking locations after being routed to do so through a parking route. Parking routes act in the same way as partial routes with the added effect of assigning vehicles to

park at provided locations within the parking route. Parking locations are used for drop-offs and pick-ups. Parking durations follow static times or random times from a given distribution. An agent will resume its partial route after completing the parking route and stopping at a parking location.

Changing agent properties within the model for the purposes of this research was not handled natively by VISSIM. To accomplish the required behaviours agent properties needed to be dynamically changed which required writing custom Python scripts. These scripts run at the start of each time step of the model simulation and remain active throughout the entire simulation run.

The first script handled the passenger properties of each agent. VISSIM generates arriving vehicles with different occupancies. These occupancies represent arriving or departing travellers. The script uses agents generated with existing occupancies for both drop-offs and pick-ups as it can use the number from the occupancy for both and agent behaviour does not change between these conditions. The script checks the state of the vehicle when it is on the curbside link. When the vehicle comes to a stop at a curbside location the traveller occupancy is recorded. This number is taken as the occupancy less one for agents representing human-driven vehicles and as the full occupancy for automated vehicles. When all passengers have used the curbside the agent type is changed. This allows it to follow one set of partial routes on its way to the curbside and another when leaving so it follows the correct route while the simulation is running.

Access to the curbside is also limited based on available curbside spaces. To keep the agents from progressing to the curbside link a script was written to handle stopping agents based on how many agents were already on the curbside link. This script enabled the agents within the model to follow the expected behaviour of vehicles while approaching the airport curbside.

A script to handle the local shuttle was written for this research. This script handled transferring travellers to and from their arriving vehicle and the local airport shuttle. When an agent representing a vehicle arriving at the airport enters the shuttle staging area the script takes over. To start, the number of travellers that the agent is either dropping off or picking up is recorded and stored as a group. The agent is then removed from the active model as it is now being handled by the script. The number of travellers being serviced by the agent is assigned to a local shuttle. When this is done, the capacity of the shuttle is checked against the number of travellers to ensure a shuttle is not used at over capacity. When a shuttle does not have enough available seats to service the next vehicle agent then a new agent is created within the active model representing the shuttle with the occupancy as recorded up to this point. Agents representing the vehicles arriving to the shuttle area are also put back into the active model after they have finished having their travellers assigned to a shuttle and are ready to leave. The shuttle agent then proceeds to move through the model and interact with the other scripts to successfully conduct the curbside trip and when it arrives back at the shuttle staging area the script handles removing it from the active model.

The departure time of a shuttle between the curbside and an off-site location needed to be handled by a custom script. The agent representing the shuttle is given a dwell time by VISSIM when it arrives to the stop. However, this dwell time is not dependent on the arrival time of the agent. The real-world scenario requires the shuttle to leave at its scheduled departure time regardless of its delay or early arrival time. A script was written to handle adjusting the dwell time of the shuttle to realize this condition. The script also allowed additional time to be added if the alighting and boarding passengers forced the shuttle to wait past the scheduled departure time.

City shuttle boardings scripts allowing the demand for the shuttle to take advantage of VISSIM providing non-static distributions/variations in demand over time was also written. The traveller input distribution was handled by VISSIM. However, each traveller was then immediately removed from the active model and added instead as a count to the script at both the airport and city locations. When the city shuttle is input into the model, the count from the city is added to the occupancy of the shuttle. When the shuttle arrives at the curbside the occupants are removed and then replaced with the count waiting at the airport. Maximum occupancy of the shuttle was checked each time to ensure it was not exceeded.

3.2.2 Airport Corridor Pedestrians

A supporting study was done for the pedestrian activity in the pedestrian access corridor at the case study airport. The software used to complete the modelling was MassMotion 10.6 (Oasys 2021). MassMotion is a state-of-the-art agent-based crowd simulation

software and is built as a pedestrian planning and evacuation modelling software. For this research it was used for its ability in looking at pedestrian planning. While evacuation of corridor spaces is of interest to airport design for instances of emergencies the model and scenarios created did not cover this area.

This portion of the research goal is to understand the human behaviours within the airport corridor. Looking at individual pedestrian speeds and interactions with features within the corridor are important.

MassMotion operates by modelling agents that represent each pedestrian within a built 3D environment. Each pedestrian is created as an agent within the model and is given an origin and destination. The agent is able to create a route through the model at all times from its current location to its desired destination, so if the agent is removed from its current path a new one is found. This allows for a microsimulation environment where agents can react to each other's presence within the model producing results closer to real world observations.

To simulate this reaction to other agents MassMotion uses the social forces model. Within any area of the model, the social forces model must reference a desired speed and surrounding obstacles to calculate the resulting acceleration and movement of each agent, pedestrian, within. This limits the behaviour of agents to follow this profile for the entire duration within the model. See Section 2.5 for more information on the social forces model.

Each agent within the MassMotion software moves along given surfaces. These surfaces construct a 3D model of the space. Each surface must be coded properly to what it represents in the real world. In this research, surfaces were coded as floors, doorways, ramps, stairs, escalators, and elevators. The surfaces need to be coded as such for MassMotion to navigate agents through the model. Agents are directed through doors to connect floor spaces on the same level and use ramps, stairs, escalators, and elevators to move agents to floors on different levels. The MassMotion software is programmed to treat agent movement behaviour differently on different surfaces. Agents walk their desired speed towards their destination on floors, unless blocked by objects or other agents, but they will adjust their behaviours when encountering other surfaces. This allows for speed adjustments based on ramp grade, when approaching and using stairs and escalators, and standing still while waiting for or in elevators.

Special surfaces exist to provide the origins and destinations for the agents. The origin points act as the area for the software to input agents into the model. Once created into the model the agent will then path find towards a destination surface that has been given to the agent. Agents will exit the model when they reach their target destination surface. Agents will not interact with origin or destination surfaces they have not been assigned to. Agents can be given more than one destination surface and MassMotion uses a distribution to decide which one to navigate the agent towards.

MassMotion supports features of importing geometry into the software so accurate existing 3D models of the space can be used to create the walking space within the

software. For the airport corridor, architectural drawings that were provided by the corridor authority were used to build a starting 3D model in Sketchup (Trimble n.d.). Sketchup allowed for simplifying the creation of the different floor, ramps, stairs, and escalator shapes for the corridor 3D model. This 3D model was then imported into MassMotion. Once imported, the different surfaces were modified within MassMotion so the software could identify them as each different feature properly. Small adjustments to the 3D model were made in MassMotion where needed for connectors between surfaces.

Further, the pedestrian inputs can be customized so that each agent, representing a pedestrian, can arrive according to observed distributions and behave with the correct movement behaviours. Agents can be created as part of different profiles. These profiles allow agents to have different desired walking speeds, size, and if they have luggage or not. All agents created under the same profile will have similar traits that they maintain throughout the model.

The 3D model layout and agent profiles are designed to be setup before a simulation is run and remain the same throughout the run. However, MassMotion provides a feature of allowing custom code to affect the model as it is run. This feature of adding custom code was used to expand the base functionality of the software to adjust agent behaviours to better match those observed in the corridor. The goal was to introduce dynamic desired speeds to the pedestrians during a simulation run based on their location within the 3D model. As the agent moved through the 3D model the desired speed value for the agent needed to be updated so MassMotion could move the agent correctly.

The efforts were focused on having the model use two movement speed profiles for the agents based on one separating condition. This condition was chosen as whether or not the agent was on the people movers. When an agent is first created and walking on floor space it uses a speed assigned to it from the provided speed profiles in MassMotion. When the agent first steps onto a people mover a new desired speed is generated for it by the custom code from a speed distribution. Once the agent returns to a floor space it resumes using the desired speed it was given by MassMotion as the custom code releases control of the agent. If the agent steps back onto a people mover it again uses the desired speed it did before on the previous people mover as the custom code once again takes over control of the agent. This use of speeds is illustrated in Figure 3.4 below.

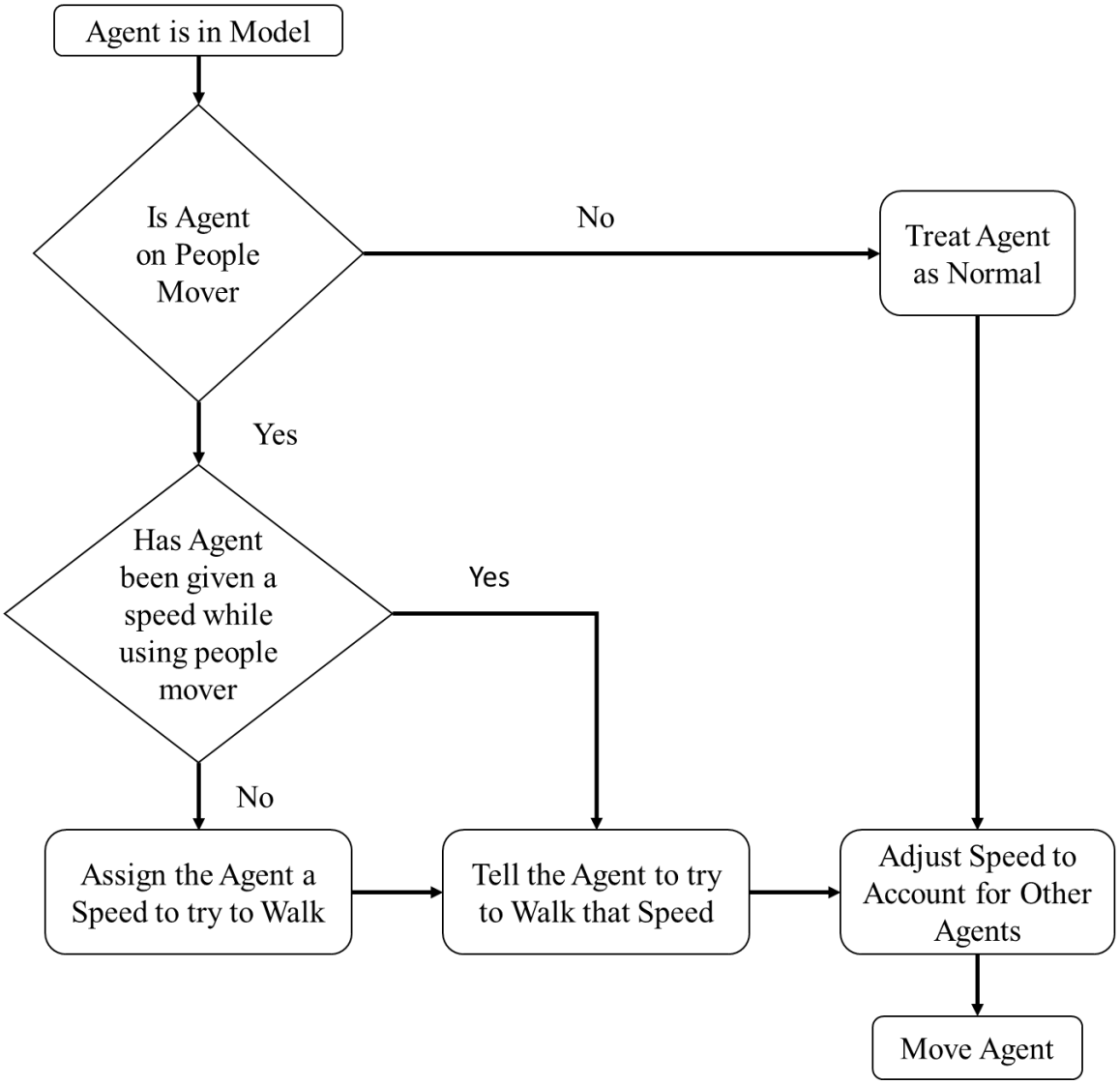


Figure 3.4: Speed profile conditions

See Chapter 8 for the model used and more methodology of modelling pedestrians in the corridor.

Chapter 4: Airport Curbside

This chapter directly addresses the major goal of the study by looking at the demand and capacity of the airport curbside. The airport curbside is an area that currently faces many service capacity issues as people arrive for flights. This area is a potential bottleneck for the airport without many options to improve without expanding infrastructure using the tools of today.

Automated vehicles present a challenge to the airport in that they will be changing the human behaviours of people using the airport curbside. Today, travellers that use the curbside are being dropped off or picked up by someone they know or through a taxi service. Others take public transportation options if a vehicle is not available to them or park their vehicle at the airport parking if no one can drop them off or pick them up. Finally, a dedicated shuttle can be taken to connect travellers to a city hotel. Instead, automated vehicles will be able to drop-off or pick-up travellers on their own and can way find through the airport to arrive at the most ideal location for the traveller. These automated vehicles can operate in the same manner as existing modes though. Some automated vehicles can service travellers as personal vehicles and taxis while others can be used as public transport or shuttles.

To support this research, data for the study was collected on site from existing security footage of the airport curbside over the holiday (winter) season of 2019, covered in Section 4.3 and 4.4. Vehicle and person counts were collected from observing the footage

through the peak hours. Vehicle dwell times were collected in the same way. The highest peak hour for the curb side saw a demand of 325 vehicles. Average vehicle dwell time was recorded at 96 seconds.

A Monte Carlo based model was used to look at the probability of an available curb space based on different levels of demand and total number of curb spaces. This work can be found in Chapter 5. Probability distributions were looked at for multiple different combinations of supply and demand for curb spaces. Future cases where more curb spaces were provided and with increased demand were looked at. This was used to estimate expected delay and level of service for the curbside.

The vehicle counts and dwell times were used in a microsimulation model built in VISSIM which can be found in Chapter 6. One base case scenario and four scenarios were built to explore the impacts from rerouting traffic to other areas of the airport. The base case scenario found the curbside does not have the capacity to meet the current demand, double parking and other actions need to be taken. In the four scenarios where traffic is rerouted, these travellers are then serviced by an automated shuttle that would bring them to the original curbside. The time spent transferring to the shuttle was considered as delay. Results showed that the scenario rerouting three quarters of the traffic to the other area gave the lowest delay due to the reduced time waiting in queue for a space at the curbside.

4.1 Introduction and Background

The curbside acts as the interface between the airport and the surrounding city providing travellers an area to transition from their inner-city transportation mode to access to the airport as a pedestrian. This area acts as a potential bottleneck for travellers as space is limited for each transportation mode. With the coming changes from automated vehicles demand for this space may increase but how it is used could also adapt.

Traffic at the airport curbside is critical in connecting travellers between the airport and the city. However, the mode of transportation chosen to arrive or depart from the airport is not always the ideal for capacity and traffic flow conditions. In North American, and many parts of the world, private vehicles make up a high portion of the transportation mode share which gets reflected on the mode shares scene at the airport. While public transportation options are available, travellers find the convenience of driving themselves or being dropped off or picked up high enough to continue to use a private vehicle. It offers travellers space for their luggage and could be seen as a more reliable option to arrive on time for their flight. However, vehicles at the curbside have a low economy of scale. The space taken per traveller is much higher for private vehicles and taxis at the curbside compared to the capacity in public transportation options.

Changing the vehicle traffic to automated vehicles could increase this convenience and as a result increase the demand for vehicles at the curbside without improving the use of space. This study looked to examine a potential future where automated vehicles are

commonplace and easily accessible to travellers. The connected and automated vehicle is expected to be introduced to the roads of cities and will be seen at the airport curbside. With its ability to drive autonomously it will also come with connections to deliver new mobility services that increase its availability to travellers. Two of these major changes that are expected are Shared Mobility and Last-Mile solutions.

Shared mobility solutions from automated vehicles could be a solution to many of the traffic issues of cities today. Connecting people to shared rides through automated vehicles allows automatic carpooling, cost savings, and a reduction in the need for vehicles. The connected and automated vehicle could connect to a ride sharing service and constantly maintain an updated view of the demand for trips in the city while planning each trip to optimize servicing people in a timely manner while sharing its occupancy. However, ride sharing does not guarantee shared destinations. Understanding this would require a model of the entire study, which is outside the scope of this research. Instead, the focus is put on the change to facilities within the airport grounds.

Airports function as a service to the public in providing a means for fast and convenient long-distance travel. The goals of the landside facilities at an airport are to provide all the services required by passengers while keeping their operating costs down. With the new technologies in automation being developed there are new opportunities for developing services and reducing costs. Figure 4.1 below showcases the most common landside facilities that are currently found at airports in an example of airport landside facilities layout. This layout is representative of what is found at the study airport location. As can

be seen, there are a variety of arrival modes to the airport and passengers can use almost any means of transportation in a city to get to and from an airport. With connected and automated vehicles entering the transportation network it is expected they will enter the airport space as well.

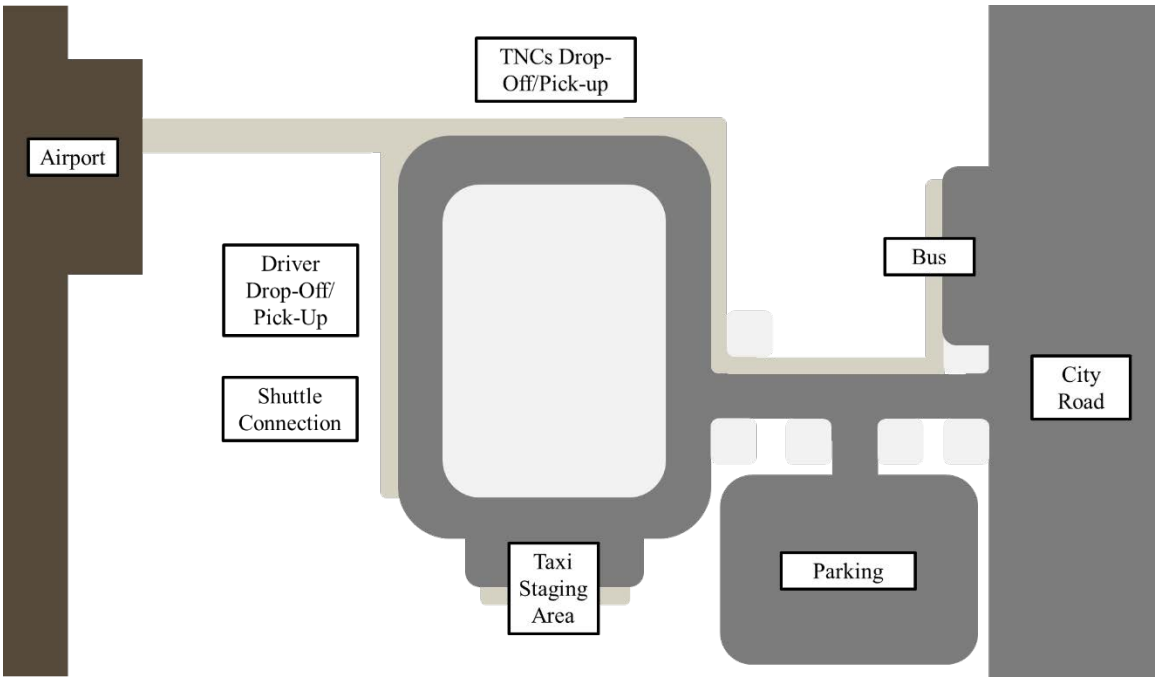


Figure 4.1: Example airport landside facilities

Connected and automated vehicles and systems will also introduce a new dynamic way of transportation, both within the airport grounds and trips coming to or leaving the airport. These systems are capable of new behaviours that have never been seen or used before in transportation and add a new complexity to the considerations that will need to be taken to accommodate them. These changes may also be large enough that significant changes may occur in the usage of some airport facilities, such as parking (Millard-Ball

2019). These changes will depend on the level of automation of vehicles, the mode share used by people getting to the airport, airport and city policy for automated and connected vehicle use, and the pricing of facilities. Automated systems can use creative approaches to problems. Depending on how policy and regulation develops, though, the solutions developed may be focused on reducing owner costs over transportation functioning better as a whole.

Studying these changes also requires modelling potential scenarios and observing the behaviours of people. As connected and automated systems have not been fully integrated into airport systems, we do not have a target facility to study how they will affect behaviours. Instead, we must rely on computational models to predict these changes. Models come in different structures, though, and some do better at modelling different aspects around an airport better than others. The different modelling software available now have been developed to either focus on the movement of pedestrians in a facility (Seyfried, Steffen and Lippert 2006) or model the traffic flow in a wider area, such as the surrounding city, showing the modal split, origin-destination patterns, and arrival patterns (Katazawa and Batty 2004). This means fully modelling an airport functioning in the era of connected and automated vehicles may require multiple approaches by different software to get a full appreciation of the changes due to these systems.

Modelling and forecasting require understanding the human factors involved. This means a proper collection of data and survey of behaviours of people at airports. There are

numerous ways in which data can be collected today; however, the data quality and integrity must be considered to collect information that is relevant and reliable to make decisions for the future. As connected and automated systems develop, more data collection methods will become more readily available. However, development will have to already be heading in the right direction by this point so these methods may be more appropriate for supplemental information when adapting plans.

One of the main services that an airport provides is connecting passengers with the surrounding city. Passengers are primarily arriving at airports as a return to home trip or to visit the city for business or recreational purposes (R.A. Malatest & Associates Ltd. 2016). This means passengers are looking for connections to local transportation options within the city. We can also infer from this finding that if travellers are landing at the airport looking for connections to local transportation they will also need the same service when coming to the airport from the city. With so many airport passengers needing to get to and from nearby destinations, connected and automated vehicles will primarily be working towards this purpose.

Figure 4.2 below summarizes the major landside transportation services that can be found at an airport and their expected development towards automation.

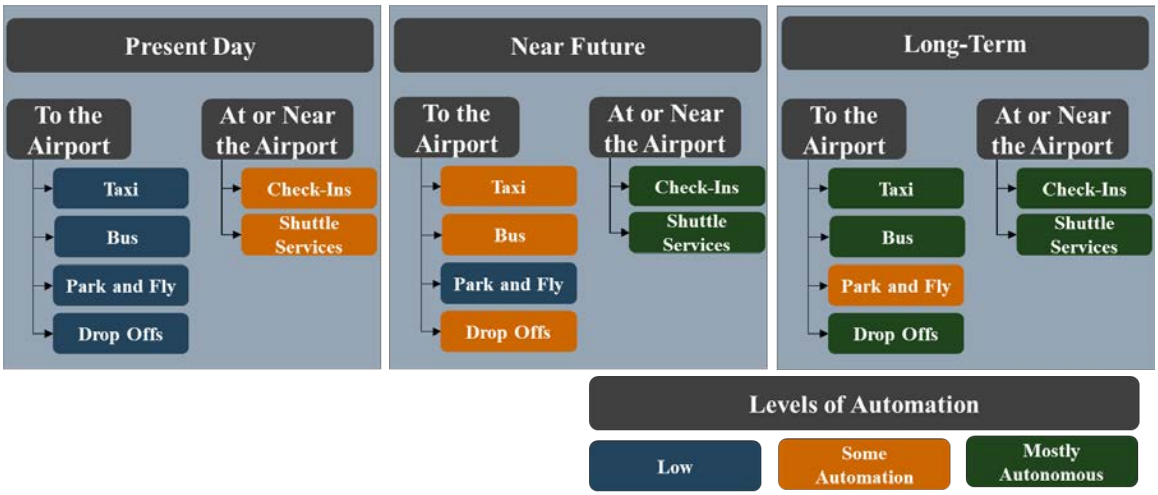


Figure 4.2: Services at an airport

The process of connecting passengers to local destinations is not novel to automated systems, though, with taxi, bus, car rental, and the recent addition of shared mobility already providing this service. A 2013 study in Ottawa of the city's transportation terminals showed the distributions of passengers at the international airport using each of the modes that are currently available (R.A. Malatest & Associates Ltd. 2016). This study found that the primary mode of arrival for air travel passengers was driving at 36% with the second highest mode being car passengers at 31%. The next highest arrival mode was taxi services at 21%. The use of urban transit was only 5% of the total, which was lower than the rental car usage of 6%. Rental car use was reported separate from driving a car or car passenger. No one was found to have walked to the airport. Departure from the airport shared similar usage of each mode.

Figure 4.3 summarizes the mode shares coming to and leaving the airport. While this study does not directly show what will happen in a connected and automated environment, it does show the type of services that people are using and will look for in the automated era. Of note for the Ottawa airport though is that its location does not promote walking or biking trips due to its location in the city, Figure 4.4 shows a map view of the airport location and facility layout. Many airports have similar geographical constraints to walking and biking. When surveyed, the dominant reason for the choice in mode that passengers travelled to and from the airport was convenience. These findings are further supported by an earlier study done in the San Francisco Bay area in 1995 that found the large majority used private vehicles and were more concerned with travel times to the airport for mode choice (Pels, Nijkamp and Rietveld 2003).

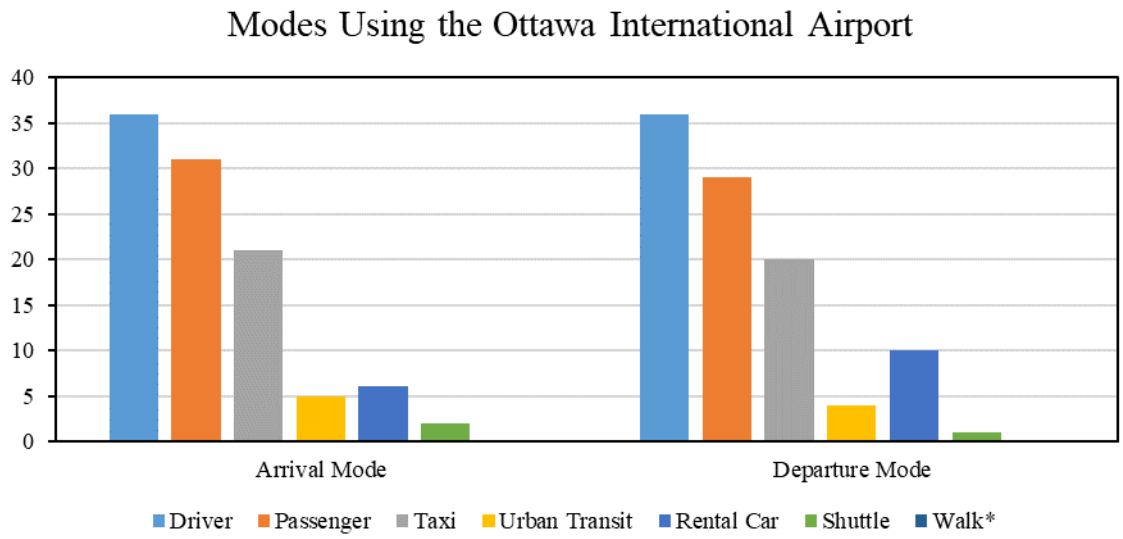


Figure 4.3: Modes using the Ottawa International Airport

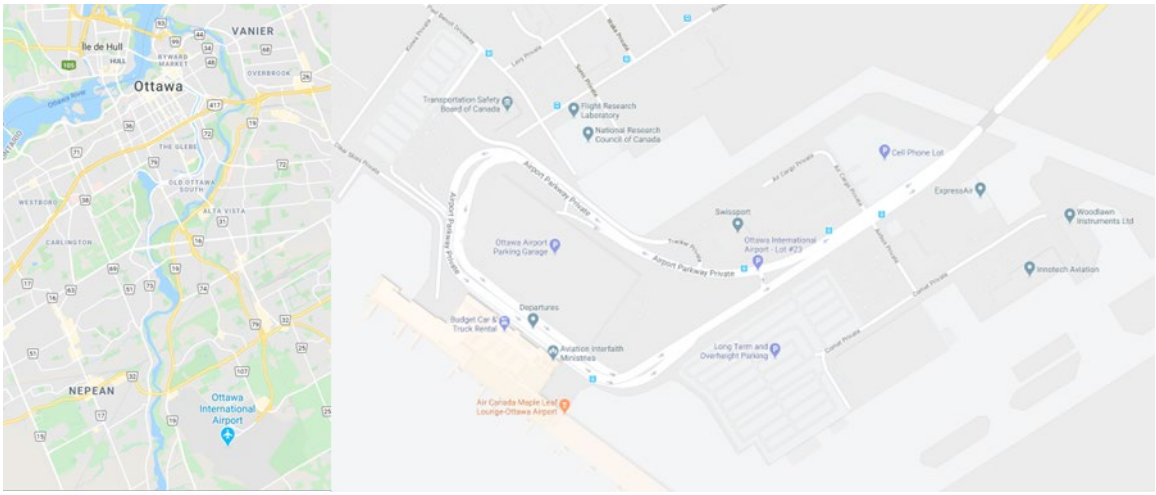


Figure 4.4: Map and area view of the Ottawa International Airport (Google Maps n.d.)

Convenience was a leading factor in choosing transportation options for getting to the Ottawa airport and one that could in the future be addressed by connected and automated systems. If airports want to cater their services towards passengers or impact the modes used to travel to and from the airport the focus should be on increasing the convenience offered by these services. As connected and automated vehicles are introduced into different transportation options, the distribution of mode uses may adapt to the potential change in service type and availability that each provides with the new technology.

Airport landside facilities will be going through changes to adapt to the introduction of new technology. Connected and automated vehicles (CAVs) will change how airports can accept passengers on the curbside. Vehicles will no longer need a driver waiting with it during a pick-up and drop-offs can be made with only requiring the air traveller in the car, however, others may still choose to share the ride to greet those arriving or say their

farewells to those departing. Each vehicle can be treated as fully operated in this new environment as if always attended by a driver. However, automated personal cars are not the only changes that will be present.

The growing industry of Transportation Network Companies (TNCs) have already become present at airports and are expected to only grow with the increase of automated vehicles (National Academies of Scences, Engineering, and Medicine 2020). Airports have already started changing their curbside to accommodate TNCs to allow passengers to use the service. TNCs are an effective way of connecting travellers to local transit by covering the last-mile connections. Connected technology can connect drivers to these options automatically with their transit trip making the process seamless (Self-Driving Vehicles and the Environment 2019). The alternative though, is that TNCs could have a negative effect on transit usage in cities by replacing the service and increase the vehicle kilometers travelled. If this is the case, congestion around airports could increase so airports should consider how TNCs are being used when adapting their curbside. Changes to the transit itself though could improve the attractiveness of TNCs operating to compliment transit.

Looking at the coming changes to transit we can see how they will be indirectly affecting the scene at airports. Cities are being encouraged to develop Bus Rapid Transit (BRT) systems to connect people to the major transit lines (Miebach 2019) and important destinations off the main transit lines. BRT allows commuters fast access to and from the transit lines of the city making the option more appealing. In the era of automation, these

busses also do not require a driver, a major cost of their current operation. They could also adapt their service level to different routes depending on requested trips by users to keep services throughout the day where they are needed. Airports will need to investigate how connected and automated vehicles are changing the transportation habits in the city around it. Whether their response should be a shuttle to the BRT, letting TNCs provide the last-mile connection, connecting the BRT to the airport directly, or other options is a topic for further investigation. Each option has its benefits and drawbacks that need to be studied.

A combination of the effects from TNCs, BRT, and automation of personal cars though will affect the revenue generating facilities such as car rentals and parking. Connected and automated vehicles are expected to improve the service capabilities of rental facilities (Greater Toronto Airports Authority 2018). The vehicles will be able to keep themselves charged in the rental lot by utilizing fast charging stations and organizing themselves to provide the correct vehicle with enough charge to customers. The amount of charging stations that should be installed to optimize the service of rental vehicles offered by the airport is a separate area of study. The automation also allows the rental cars to return on their own. This creates a different way in which rental cars can be used. Instead of customers needing to return vehicles to the airport, or to predefined locations, vehicles can return themselves to be made available once again for service. This would increase the amount of service each vehicle could provide, potentially reducing the fleet size companies would need to maintain at an airport. Further research is needed to confirm the

effects as changes in mode usage could also result in either a decrease in need for providing rental vehicles or an increase in the usage requiring more.

Another change that will come from connected and automated vehicles, similar to that of the rental services, is parking. Parking at airports acts as a source of revenue for airports. Approaches to sizing parking facilities on a cost-based development are available to show how parking can remain a profit source for airports in the coming changes (Massoud Javid and Kakimoto 2010). However, the changes to parking may not be straight forward. Parking is seen as a method for passengers to be able to conveniently arrive with luggage and quickly board. It is also suggested that the parking facility management and payment become automated for customers as airports develop to increase the service's convenience (Lohman 2016). Allowing passengers to pre-book a parking spot and guiding them through the parking facility towards an open parking spot would make the process faster for travellers. Vehicle charging services could also be offered at airport parking lots to let airport passengers know their vehicle will be fully charged and available to them when they return.

What also needs to be addressed, though, is the change in parking behaviours that could come due to automated vehicles. Automated vehicles do not need to park while not in use and two modelling studies found a significant reduction in premium parking uptake by automated vehicles (Lohman 2016) (Harper, Hendrickson and Samaras 2018). In these studies, they found that CAVs had new options that were not available to car owners before. CAVs can park at the driver's destination as they do now, travel after dropping

the person off to find cheaper or free parking, return home to avoid any parking costs, or cruise through the city. Parking at the destination for the passenger was one of the lowest options used by the CAVs as cities usually have areas not too far away where parking is much cheaper or free. Even when the free parking is only for limited durations CAVs can move themselves between these spots to take advantage of the free spaces with minimal distance travelled. The return home scenario was taken up when the home location was close enough or the duration of the parking justified the costs of the trip length to do so. The number of trips by car coming in from outside the city compared to locally would then potentially have an impact on parking at the airport. Finally, the cruising option involves seeking out congested areas in the city in an effort to drive as little distance as possible. If CAVs are allowed to coordinate this effort the results can be significant, essentially turning areas of road into parking lots. However, even if they cannot collectively work to create congestion, each CAV can simply move to the most congested area nearby on its own and, by seeking out other vehicles, will create the cruising parking lot. This type of behaviour was often modelled as cheaper than most parking options so unless policy and regulations against this behaviour or congestion charges are introduced in the cities airports operate in it must be considered in the future of parking at airports.

What all this means for airport parking is that costs of parking needs to be competitive with the options available to CAVs. If it is cheaper for vehicles to drop people off and seek out alternative parking services they will do so. This also means parking facilities may be able to be downsized though if their use reduces and the space used for other

revenue generating purposes. The more drop-off pick-up nature of CAVs means a higher use of the curbside areas for airports. Spaces that used to be a staple at an airport may have to be repurposed to serve shifts in passenger behaviour.

4.2 Motivation

The goal of this section of the study is to develop ways to consider the airport curbside when in use by automated vehicles. Due to the lack of existing automated vehicle activities at airports, designers need to rely on models and interpretation of the literature to make their plans. This work hopes to provide some insight into the activities at airports so proper considerations can be made.

Vehicle counts and dwell times for the commuter airport will provide usable data for expanding the understanding of the curbside activities at airports. Vehicle counts are important as the vehicles take up precious space at the airport curbside. This provides an understanding of the relationship between the actual number of vehicles that the curbside is servicing to the number of spaces available. This number may not always match what is expected as people are able to double park or find other ways of dropping people off or picking people up at the curbside without using a proper space. Additionally, the dwell time at each proper space should be understood so planners can know how long their spaces are being used. This allows planning for proper expansion or repurposing of areas to service the demand. Further, by analysing the dwell times of the vehicles by number of passengers and luggage type it allows the work herein to be applicable for other

modelling activities. A regression formula for dwell time by these parameters allows models to analyse future or alternative conditions with passenger count and luggage conditions that are different from the study airport. By providing the data in this format it is hoped that the work can be made applicable to further studies or used where a complete study of human behaviours in not possible.

4.3 Data Collection Methodology

All data collected for this study was done through airport security footage of the direct curbside area of an inter-city North American commuter airport. Vehicle counts, vehicle dwell times, passenger counts, and luggage types were all examined from this footage. Other areas used by vehicles were not available at the time of collecting data for the study. Traveller behaviour was not affected through the collection of this data. The security footage was provided as-is from stored recordings. These recordings and footage were already always collected by the airport.

The airport curbside in question acts as the service area for all passengers being dropped-off or picked-up at the airport making it an ideal area for study. The vehicle activity can be limited by traffic control that can limit vehicles to only proceed to the curbside area when there is available space.

Total vehicle counts for the Peak Hours were done separately from the dwell times. These counts identified the total volume of vehicles during the AM and PM Peak Hours

for two days that were provided in the late December 2019 (winter holiday season) and mid January 2020.

Data of the vehicle dwell time was collected at uncongested times. This allowed for easier tracking of each individual vehicle and ensured a proper tracking of each passenger associated with each vehicle. The uncongested conditions allowed the passenger count and luggage types to be recorded with accuracy and within a timely manner as the data was collected using manual inspection of the footage. The data was collected in this manner to correlate the vehicle dwell time with the number of passengers and the luggage type to explore how the dwell time is affected by these parameters. Luggage types were defined into two categories, no/light luggage or roller luggage, see Figure 4.5 below. Luggage type for the vehicle was assigned based on the heaviest class of luggage for any one passenger from the vehicle. Therefore, if only one passenger had a roller luggage the vehicle was classified to service passengers with roller luggage. Dwell time was defined as the time of the vehicle coming to a complete stop at the curbside space to when the vehicle started to move again.

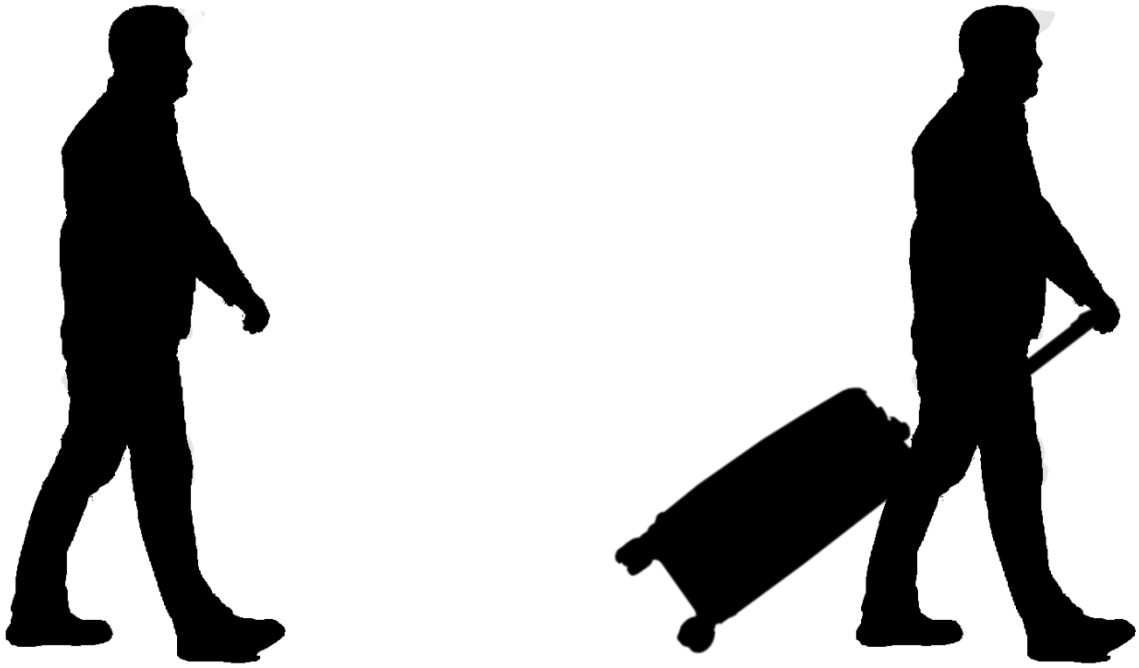


Figure 4.5: Graphic of demographics

Certain spots at the curbside were obstructed from view by the public transit shuttle as it waited at the curbside between running its service route. Data of vehicles at those spots were not included in the study because confidence in collecting all information was uncertain.

4.4 Data Collection Results

The following tables summarize the results from the data collection. The results represent the data for the two days that were provided for this research.

4.4.1 Total Vehicle Counts

Total vehicle counts have been presented for the AM and PM Peak Hours for both days in Table 4.1 below. The departures were the main source of traffic for the airport for all peak hours. The majority of the traffic being departures was not an expected result. Reasons for why the traffic was mainly departures is discussed in Section 4.5. These vehicle counts include all vehicle types arriving at the airport.

Table 4.1: Vehicle Counts

	Vehicles		
	Departures	Arrivals	Total
Day 1 – AM Peak Hour	195	8	203
Day 1 – PM Peak Hour	231	70	301
Day 2 – AM Peak Hour	154	10	164
Day 2 – PM Peak Hour	294	31	325

4.4.2 Vehicle Dwell Time

The average dwell time of each vehicle was collected from the vehicles properly using the temporary parking locations at the curbside. Results of these collected times can be found in Table 4.2 below. The average dwell time per vehicle was found to be 96 seconds. Regression of the dwell time when considering the heaviest luggage class of the passengers and the number of passengers was also done. This showed an increase in the dwell time of 25 seconds if the passenger had roller luggage and increase of 9 seconds per passenger. However, the variance of the data was not explained by each variable with small R^2 values found for each dependent variable when controlled for the other.

Table 4.2: Vehicle Dwell Times

Average Dwell Time (s)			
96			
Regression			
	Base Dwell Time	Roller Luggage	Passengers
Dwell Time (s)	68	25	9
R^2		<0.01	0.01

4.5 Data Collection Discussion

This data collection supports the work for the modelling as it provides real-world values. The vehicle counts provide the total peak hour demand for the airport so the model can compare performance of the scenarios under these conditions. Demand for curbside space was found to be primarily for departures, trips for people leaving the city. This could be for multiple reasons. Firstly, the airport is small and could be used by travellers to connect to international flights at larger airports. Secondly, the surrounding city has a student population that could be travelling home over the holiday season. Thirdly, in relation to the first point, the city houses another larger airport which could be attracting most of the arrivals from further destinations. However, the reason for this difference between arrivals and departures needs further study to be confirmed.

Considering the regression analysis of the collected data, the small R^2 for each dependent variable is to be expected as human behaviour in transportation is highly varied and dependent on the person, not just their circumstances. This shows that the understanding

of luggage type and occupancy only shows a difference in the average dwell time but does not explain why dwell times are different between vehicles.

4.5.1 Further Data Collection Work

Data collection could be expanded to more areas of the airport such as the parking area. This would expand the understanding of the flow of vehicles entering the airport. If usage of the parking garage changes in the automated era this would cause a change in the number of vehicles using the curbside so having these counts would help with modelling future case scenarios.

Data collection could be expanded to review a wider variety of luggage types. Currently, the data is only separated by heaviest luggage class of any one individual in the vehicle. Analysing the data with more disaggregate luggage type classifications and types from one vehicle may help explain the large variance in dwell times between vehicles.

Further, this data was collected pre-covid. It would be of interest to replicate the study in post-covid conditions to analyse if any changes in behaviour are observed. This is of specific interest to studies of group behaviour.

Chapter 5: Monte Carlo Based Model of Curbside Queue

This chapter covers the work of using a Monte Carlo based model to develop a level of service that is dependent on the expected delay to travellers. Chapter 4 serves as the introduction to this chapter. The Monte Carlo based model allows for future planning and predictions of delay using different levels of supply and demand for curbside spaces. The model provides a way to predict the probability of an available curb space for travellers. This in turn can be used to estimate the level of delay for a curb space if the probability is below 1. Different levels of delay can then be assigned to different levels of service.

5.1 Methodology

In the absence of detailed information on future demand for air travel at the study airport, conventional methods cannot be developed that could lead to sizing curb space for different users, such as passenger cars, shuttles, or public transit. Another important consideration is the need to treat both the demand for curb use and the availability, or supply, of curb space as uncertain. Under these planning conditions, a new approach is suggested that is based on Monte Carlo simulation method. This approach was used by (Khan 2022) to develop Monte Carlo simulation-based models to estimate the availability of a vehicle with required seats to a subscribing customer or a group of customers in the shared mobility context. Also, these models were used to study the balancing of demand and supply of fast chargers for electric vehicles under uncertainty.

In the present application of the Monte Carlo simulation-based method, the probability of demand for a time slot to occupy a curb space designated for unloading and loading tasks by a passenger vehicle is represented by the triangular probability distribution, shown below in Figure 5.1. Also, the probability of the availability of a curb space is represented by the triangular probability density function. The choice of this probability density function is based on demand and supply characteristics noted next.

The triangular probability density function is defined by three values: the minimum value *a*, the maximum value *b*, and the peak value *c* representing the mode or most likely value. This probability density function best meets the requirements for both the demand and supply factors and is widely used for the following reasons (Evans, Hastings and Peacock 2000)

- In real-life planning conditions under uncertainty, the planner can often estimate the maximum and minimum values, and the most likely value.
- The assignment of these values can be done without knowing the mean and standard deviation.
- It enables the analyst to avoid unnecessary extreme values due to definite upper and lower limit.
- Another desirable feature is that it is a good model for skewed distributions.

It is useful to note why other probability distributions were not selected for use in this study. The use of normal probability distribution requires the mean value and the standard deviation. Both cannot be specified in this application. Further, the normal

distribution cannot handle skewed demand as well as skewed supply distributions. The combination of Poisson and exponential distributions require knowledge of mean value and other factors that are not known at the planning stage. The uniform probability density function is easy to apply, given that only minimum and maximum values are required. However, this maximum entry probability density function assumes very high level of uncertainty and cannot handle peak demand and peak supply factors that also may exhibit skewed shapes.

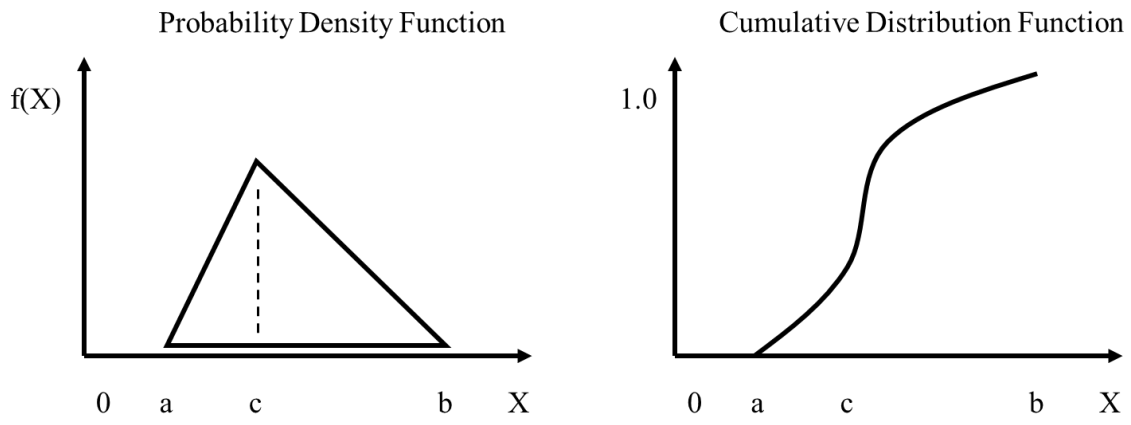


Figure 5.1: Triangular probability distribution function applied to demand and supply factors

The notable statistics for the triangular probability density function are shown below.

$$P(X) = \frac{2(X-a)}{(b-a)(c-a)} \; for \; a \leq X \leq c$$

And

$$P(X) = \frac{2(b-X)}{(b-a)(b-c)} \; for \; c \leq X \leq b$$

Also

$$P(X) = 0 \; for \; X < a \; and \; X > b$$

$$where \; c \in |a, b| is \; the \; mode.$$

$$The \; mean \; is \frac{1}{3(a+b+c)}$$

As noted earlier, a Monte Carlo simulation-based methodology can be adapted for evaluating the balance of available or planned supply of curb space with stochastic demand. This approach also has the capability to treat the unoccupied curb space as stochastic. The application of the adapted method enables the study of adequacy of curb space in meeting demand. That is, in the context of this research study, this method enables a comparison of demand for use of curb space with the availability of curb space and the outputs can be useful in advancing level of service (LOS) concepts. For realism, demand and supply are treated as stochastic. Given the theoretical base of the methodology it enables the demand and supply factors to be compared in each simulation as a part of 100 specified runs and adequacy or deficiency result is obtained. This method samples the probability density functions in a large number of simulation runs and the results include the distribution and probability of meeting the demand. For running

simulations, different random number streams can be defined. These random number streams are done through computer generated means.

The curbside models provide the basis for the estimation of the probability of the availability of a curbside time slot for the drop-off or pick-up operation. These probabilities are used to define the LOS experienced by the users of the airport curbside. The user is a human driver or in the future it will be an automated vehicle. A logical extension is to go beyond the qualitative description of LOS ranges, of LOS A to LOS F, by developing a delay index for each probability of accessing a curb slot. Further, for the delay index to be useful, it is necessary to define these so that these will be applicable to various curb use time slots that can differ from one processor to another. For example, a time slot for curbside unloading or loading operation of a passenger car or a taxi or a low occupancy van can be of 3 minutes duration. On the other hand, a shuttle vehicle that can serve about 8 to 15 passengers will require a time slot of about 6 minutes due to higher occupancy and such shuttle vehicles are expected to accommodate a wheelchair.

So, for airport curbside planning and operations, a method is required to define a delay index that corresponds to the probability of the availability of curb space. As an index, it should be applicable to time slots with specified time duration. If the index is defined as a multiple of a time slot, delay time can be found that corresponds to the probability of curb space availability. This capability will lead to the quantification of delay for various levels of service. For example, a delay index of 0.2 x a time slot of 3 minutes duration results in 0.6 minute or 36 seconds of expected delay while the vehicle is in a queue. For

this processor, a delay index of 1 x the time slot implies 3 minutes of waiting in a queue before a stall for the unloading or loading operation becomes available. If the delay index exceeds 1, the time spent in the queue will be more than one time slot.

5.2 Advancing Ideas on Level of Service

In cases when the P(Available curb space) goes below 0.5, this condition reflects disruption in the operation of the landside of the airport. In the practice of transportation, the subject of capacity and level of service has assumed much importance. From the perspective of stake holders interested in the smooth operations of the transportation facilities and system, it is highly unlikely that the conditions that result in P(Available curb space) < 0.5 will be acceptable and capacity improvements will be put in action on a priority basis.

Although attempts have been made in the past to define level of service (LOS) concepts for the various parts of an airports (e.g. curb for use by passenger cars, check-in, baggage collection, etc.), these do not take into account the stochastic nature of demand and supply. The following Table 5.1 shows an attempt to define level of service ranges for the use of curb space by passenger cars in drop-off and/or pick-up operations. The following comments are in order in defining the LOS ranges:

- The LOS and capacity designations should be regarded as probabilistic in nature (i.e. these cannot be regarded as deterministic).

- The LOS designation in transportation is based on a large number of factors that at times require subjective decisions in case of some factors (e.g. user comfort, convenience).
- The LOS E is commonly used to describe capacity level operations and can easily deteriorate to LOS F. Therefore, the onset of LOS E is commonly used to initiate measures to improve LOS. These measures can include intelligent technologies supported by advanced methods, and if necessary, infrastructure additions are considered.

Table 5.1: LOS Concepts

Level of service (LOS)	Probability (Availability of curb space when demanded)	Comments
A	0.9 – 1.0	Represents no delay condition; low demand periods.
B	0.8-0.89	Almost no delay; moderate demand periods.
C	0.7-0.79	Average demand periods; moderate delays can be expected.
D	0.6-0.69	Onset of peak demand condition and delays can be expected.
E	0.5-0.59	The LOS E reflects capacity level operations in order to accommodate peak demand condition. Due to demand surges, the LOS E can deteriorate to LOS F.
F	Below 0.5	At LOS F, the operations at the curb part of the airport breakdown. Due to high delays, double illegal parking may be attempted by some demand agents in the absence of traffic control.

NOTE: An attempt will be made to develop delay indicators for LOS.

5.3 Monte Carlo Based Model Results and Discussion

The methodology for computing the P(availability of curb space) as a function of the expected difference between supply and demand of time slots for curb space use by vehicles for their unloading or loading operation has already been described.

Figure 5.2 and Figure 5.3 are examples of results obtained from simulations. These figures show the plot of simulation results as well as the regression model. As can be appreciated from an examination of the figures, the regression models have logically very high R^2. Therefore, these models can be used with confidence for the study of level of service (LOS) and corresponding delay index.

The expected mean value of the available slots that corresponds to the P(availability of curb space) is the starting point for the development of the delay index methodology. The use of a regression model for a specified value of the P(availability of curb space) provides the expected available time slots. For example, for the case of 140 supply and demand time slots, the following values, shown in Table 5.2, of expected available time slots are obtained from the model, shown in Figure 5.2.

Table 5.2: Expected available time slots from model

P(availability of curb space)	Expected Available Time Slots (Mean Value)
1	58.65
0.9	46.88

The philosophical basis for estimating delay is as follows:

- When 58.65 slots are available, the probability is 1.0 that a vehicle will find an empty time slot for unloading or loading operation and therefore delay index is set at 0.
- When 46.88 slots are available, the probability is 0.9 that a vehicle will find an available slot. Since the probability is less than 1.0, a short delay can be expected. How to gauge the delay for this case (i.e. what is the value of the delay index?).
- Since 58.65 slots are associated with zero delay, we can set it as the base for estimating value of delay index for other probabilities of slot availability.
- At P=1.0, the proportion of available slot out of 58.65 time slots for zero delay = 58.65/58.65 =1.0. This becomes the base case for estimating the value of the delay index and in this case, the value of the delay index =0.
- At P=0.9, the proportion of available slots out of slots for zero delay = 46.88/58.65 = 0.8 (this can also be viewed as 80%). Since delay has a logical association with unavailability of slots, the unavailability proportion is 1-0.8=0.2 (20%). If we associate this delay index value with the duration of the time slot of 3 minutes, the multiplication of 0.2x3 minutes results in 0.6 minutes or 36 seconds of delay.

The application of the above method to the case of 140 supplied slots as well as 140 demanded slots results in answers shown in Table 5.3.

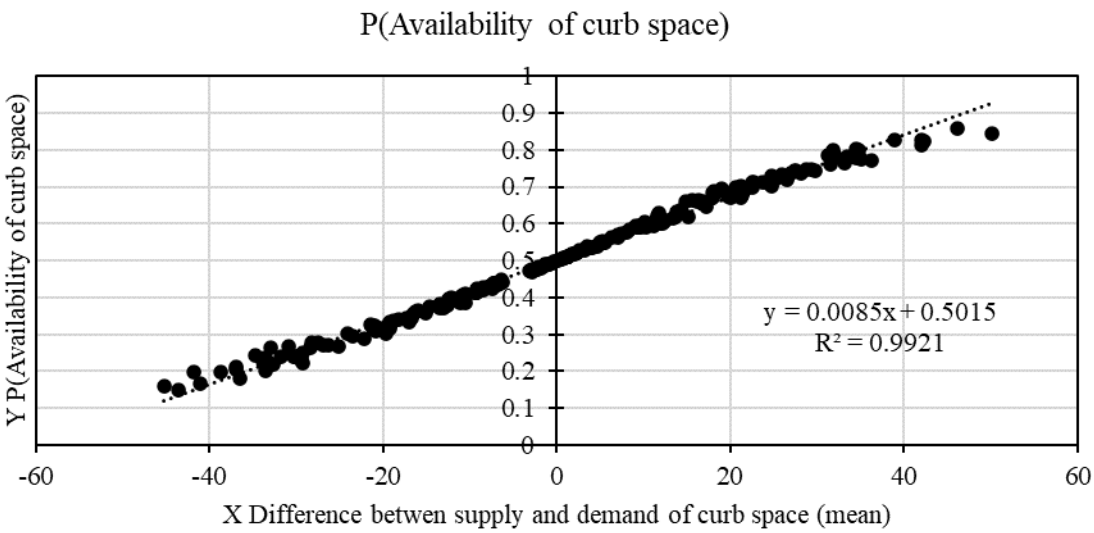


Figure 5.2: Results of 140 supply time slots and 140 demand time slots

Table 5.3: Delay Index for supply and demand equal to 140 time slots

Level of Service (LOS)	Probability of the availability of a time slot	Expected mean available slots	Slot unavailability index	Delay index (multiple of the time slot duration)
A	1.00	58.65	1 – (58.65/58.65) = 0	0
	0.90	46.88	1 – (46.88/58.65) = 0.20	0.20
B	0.89	45.71	1 – (45.71/58.65) = 0.22	0.22
	0.80	35.12	1 – (35.21/58.65) = 0.40	0.40
C	0.79	33.94	1 – (33.94/58.65) = 0.42	0.42
	0.70	23.32	1 – (23.32/58.65) = 0.60	0.60
D	0.69	22.18	1 – (22.18/58.65) = 0.62	0.62
	0.60	11.59	1 – (11.59/58.65) = 0.80	0.80
E	0.59	10.41	1 – (10.41/58.65) = 0.82	0.82
	0.50	0	1 – (0/58.65) = 1.00	1.00

5.3.1 Verification of the Delay Index Method

To check if the method gives reasonable results when applied to other cases of supply vs. demand for curb use time slots, the following case is used: 4 curb stall, 6 minutes duration for a single time slot. Therefore, the supply of time slots is equal to 40. Further, the demand for time stalls is also set equal to 40. The simulation results shown in Figure 5.3, suggest a model with very high R^2. This model is used to calculate expected available time slots that correspond to various probabilities of interest in the LOS study. Next, these expected mean values of available time slots are used as input to the delay index method. Table 5.4 presents inputs and the outputs of the delay index method. An examination of the delay index results for this case suggests that these are identical to those for case 1, see Table 5.5.

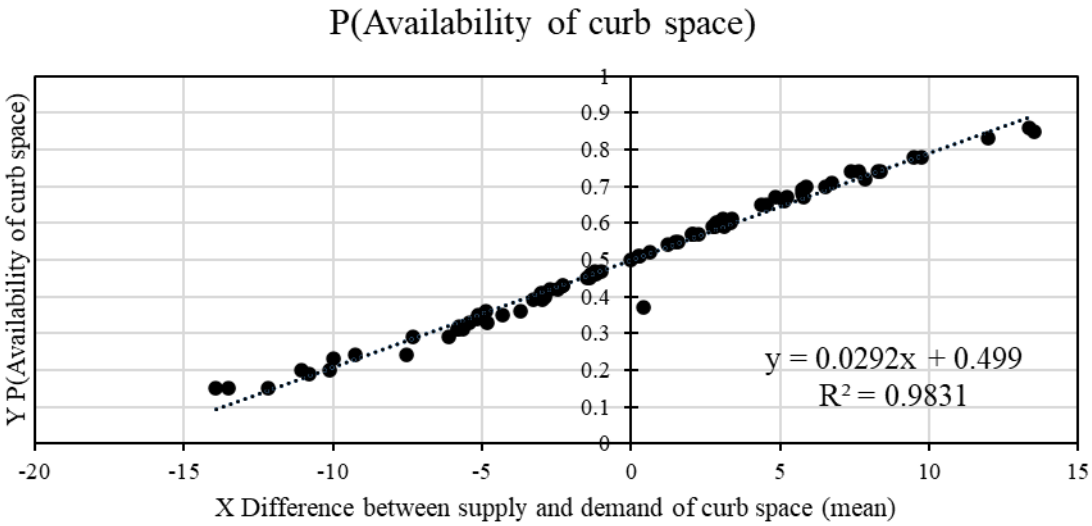


Figure 5.3: Results of 40 supply time slots and 40 demand time slots

Table 5.4: Delay Index for supply and demand equal to 40 time slots

Level of Service (LOS)	Probability of the availability of a time slot	Expected mean available slots	Slot unavailability index	Delay index (multiple of the time slot duration)
A	1.00	17.16	1 – (17.16/17.16) = 0.00	0
	0.90	13.73	1 – (13.73/17.16) = 0.20	0.20
B	0.89	13.39	1 – (13.39/17.16) = 0.22	0.22
	0.80	13.31	1 – 13.31/17.16) = 0.40	0.40
C	0.79	9.97	1 – (9.97/17.16) = 0.42	0.42
	0.70	6.88	1 – (6.88/17.16) = 0.60	0.60
D	0.69	6.54	1 – (6.54/17.16) = 0.62	0.62
	0.60	3.46	1 – (3.46/17.16) = 0.80	0.80
E	0.59	3.12	1 – (3.12/17.16) = 0.82	0.82
	0.50	0.03	1 – (0.03/17.16) = 1.00	1.00

Table 5.5: Verification of the method

Level of Service (LOS)	Probability of the availability of a time slot	Delay index for 140 time slot case (multiple of a time slot)	Delay index for 40 time slot case (multiple of a time slot)
A	1.00	0.0	0.0
	0.90	0.20	0.20
B	0.89	0.22	0.22
	0.80	0.40	0.40
C	0.79	0.42	0.42
	0.70	0.60	0.60
D	0.69	0.62	0.62
	0.60	0.80	0.80
E	0.59	0.82	0.82
	0.50	1.0	1.00

NOTE: For LOS F, the delay index will exceed 1.0.

5.3.2 Comparison with Literature Source

Further checks can be made on the validity of the delay index method described earlier. A recent report from the US National Academy of Sciences provides information that can be used for comparison purposes. See Table 5.6 below.

Table 5.6: Delay corresponding to Level of Service (140 time slot case)

Level of Service (LOS)	Probability of the availability of a time slot	Delay index for 140 time slot case (multiple of a time slot)+	Delay (Seconds)	Comparison with literature (seconds) *
A	1.00 – 0.90	0.0 - 0.20	0 - 36	6 - 30
B	0.89 - 0.80	0.22 - 0.40	40 - 72	20 - 98
C	0.79 - 0.70	0.42 - 0.60	76 - 108	33 - 165
D	0.69 - 0.60	0.62 - 0.80	112 -144	47 - 233
E	0.59 - 0.50	0.82 - 1.0	148 - 180	60-300
F	< 0.50	>1.0	>180	

+ 3 minute time slots; 140 time slots per hour for 7 stalls.

* Small hub and smaller medium hub airports – time spent in queue for levels of service. (National Academies of Sciences, Engineering, and Medicine 2010)

Research was also found on a similarly sized airport where Dwell Time was compared to the modelled Average Waiting Time in Queue and the corresponding Level of Service. Here dwell time only accounts for the time stopped at the curbside whereas the 3 minute time used for the previous model also included the approach time of the vehicle. Here we can see the delay times producing similar Level of Service for the curbside. See Table 5.7 below.

Table 5.7: LOS Variation

Dwell Time (Minutes)	AWTQ (sec) and LOS
2	13.552 (A)
2.2	20.0115 (A)
2.4	30.5604 (B)
2.6	50.02 (B)
2.8	95.8291 (B)
3	316.022 (F)

(Pasindu and Udayanga 2015)

5.3.3 Base Case

In the base case, the supply of time slots is limited to 140 per hour, provided by 7 curb spaces. If all 140 slots/hour are assigned and there is zero available supply and the minimum value of $a = 0$. If all 140 time slots are available, the maximum value of $b = 140$. The highest frequency value c can take positions from a to b, no available spots to all spots available, depending upon usage pattern of curb space. The demand for curb space use can exhibit a similar pattern.

For characterizing the balance of demand for curb space within one hour with supply of curb space, the difference of modes (i.e. highest frequency value) of the supply and demand triangular probability density functions is used. The mode for supply function is called Curb Space Supply (CSS) and the mode of Curb Space Demand is named as (CSD). The conditions this produces is shown below in Table 5.8.

Table 5.8: Curbside supply and demand conditions

Difference in Supply and Demand	Resulting Curb Space Condition
CSS-CSD = 0	Balanced Condition
CSS-CSD < 0	Shortage of Curb Space
CSS – CSD > 0	Availability of Curb Space

Following the completion of the specified simulation runs, the methodology provides the following outputs:

- Expected value of available curb space windows (slots) (mean): this result can be a –ve number, 0, or a +ve number.
- Standard deviation.
- P(Availability of curb space) (the range is 0 to 1).

A large number of demand vs. supply conditions were simulated and each case was run 100 times. Figure 5.4 to Figure 5.6 show results for all cases. These cases cover the entire range of demand and supply conditions, based on 140 time slots. As expected, depending upon favourable supply conditions to serve demand, the probability values for the availability of curb space are at 0.5 or higher. The best fit models as well as R^2 values are shown.

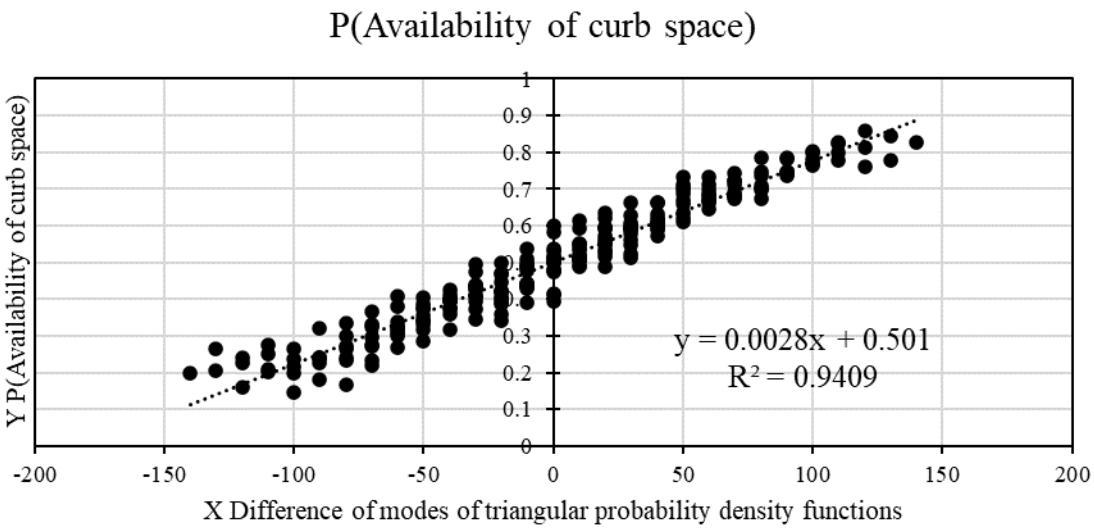


Figure 5.4: Results for demand and supply equal to 140 slots each

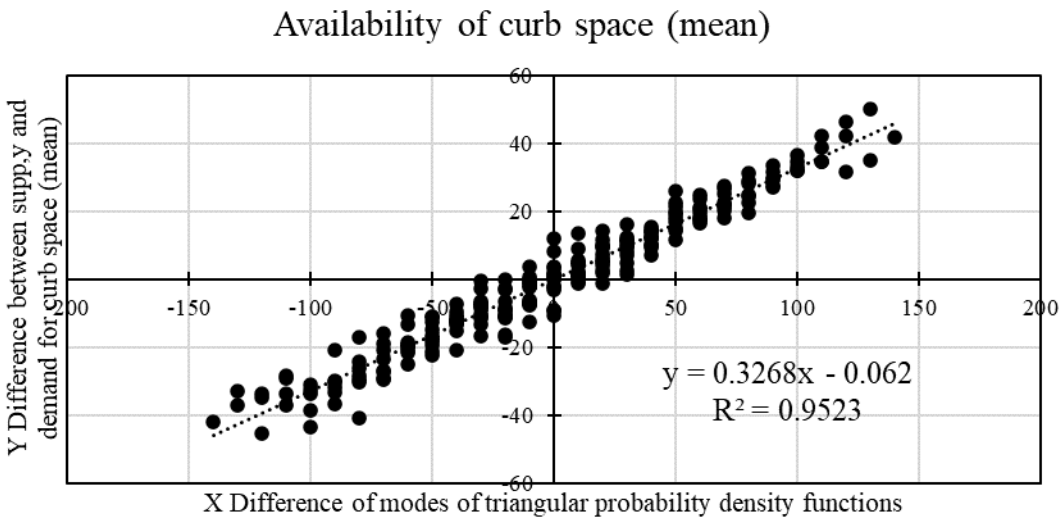


Figure 5.5: Results for demand and supply equal to 140 slots each

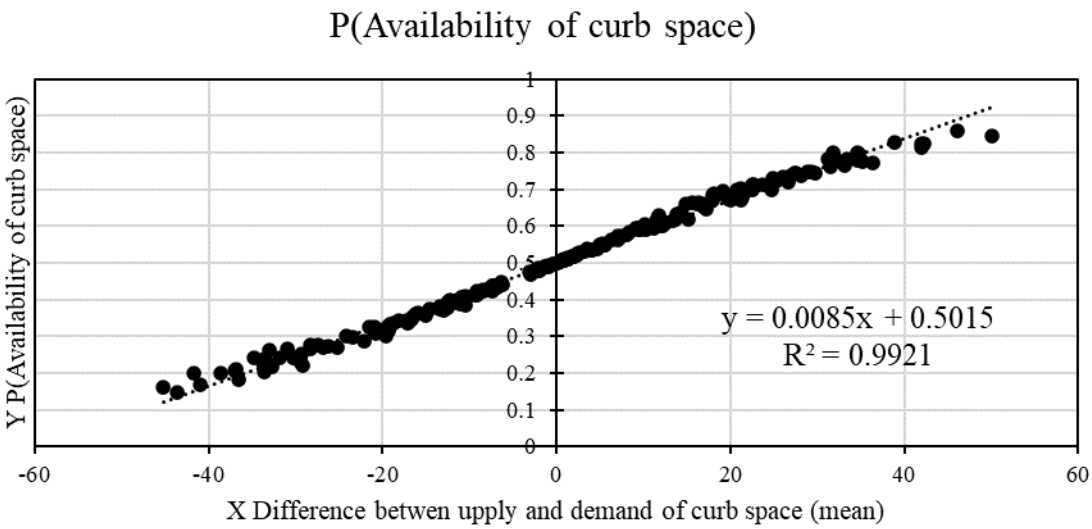


Figure 5.6: Results for demand and supply equal to 140 slots each

The cases with positive values of the difference of modes of the triangular probability distribution functions were studied as a separate group and the results are shown in Figure 5.7 and Figure 5.8.

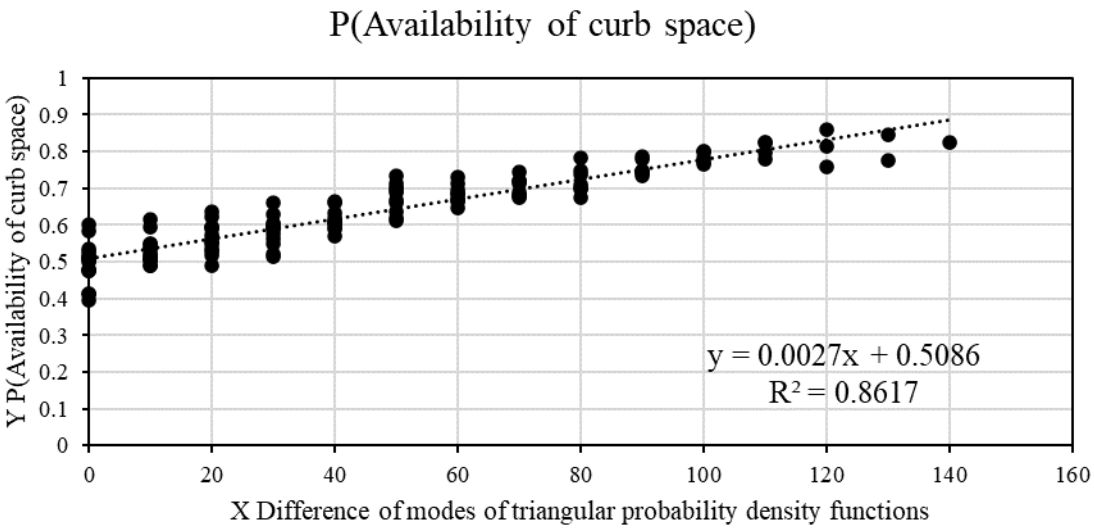


Figure 5.7: Results for demand and supply equal to 140 slots each

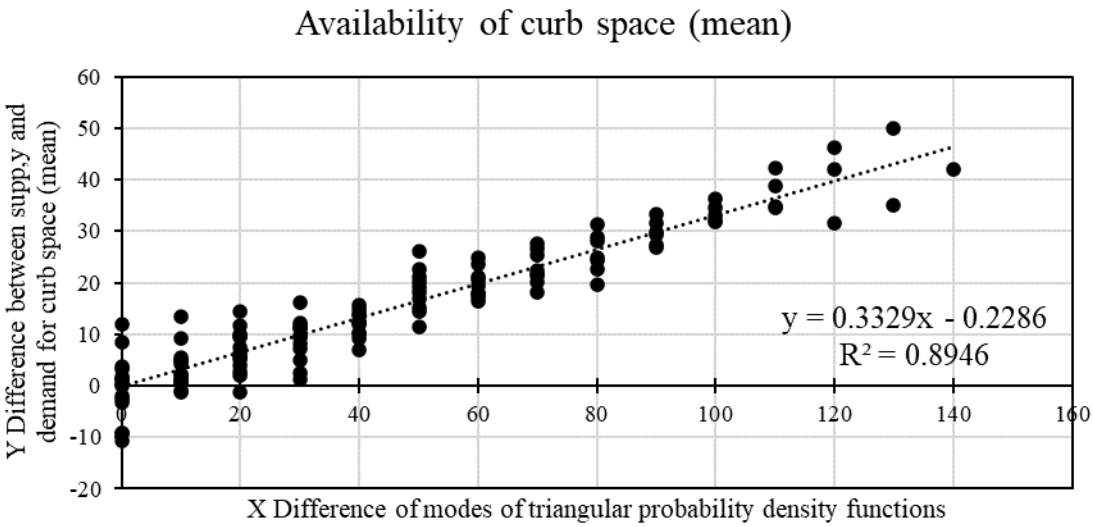


Figure 5.8: Results for demand and supply equal to 140 slots each

An examination of results illustrated in Figure 5.4 to Figure 5.8 show that when the highest values of demand for curb space and the supply of curb space are set equal, depending upon the pattern of demand for space and the availability of space, a wide range of demand vs. supply conditions can occur due to stochastic nature of these variables. These could span from most favourable to most unfavourable conditions.

5.3.4 Checking the Logic of the Methodology

The analyses and results noted above are based on 20 time slots of 3 minutes each per hour. For checking the logic of the methodology, one time slot of 3 minutes duration is studied and results are compared. Table 5.9 shows that the probabilities are comparable for similar demand vs. supply conditions for a single time lot of 3 minutes per curb space and 20 such time slots per curb space during an hour. Due to the random number-driven nature of the methodology, the probabilities need not match perfectly.

Table 5.9: Comparison of P(Availability of curb space) for one time slot per curb space vs. 20 time slots per hour per curb space*

Demand vs. supply conditions for 7 curb spaces designated for use of passenger cars	Simulations based on one time slot of 3 minutes per curb space (triangular probability density function)	Simulation of 140 time slots/hour of 3 minutes each (triangular probability density function)
Most favourable condition High supply, low demand	Supply: a =0, b= 7, c=7 Demand: a=0, b=7, c=0 P(Availability of curb space) = 0.84	Supply: a=0, b=140, c=140 Demand: a=0, b=140, c=0 P(Availability of curb space) = 0.83
Most unfavourable condition Low supply, high demand	Supply: a =0, b= 7, c=0 Demand: a=0, b=7, c=7 P(Availability of curb space) = 0.18	Supply: a=0, b=140, c=0 Demand: a=0, b=140, c=140 P(Availability of curb space) = 0.20

*For 7 curb spaces, the time slots are 7 per 3 minutes and 140 per hour.

5.3.5 Modelling LOS Improvements Resulting From Curb Extension

Results for a number of conditions shown in Figure 5.4 to Figure 5.6 suggest that LOS F can be encountered due to lack of availability of curb space. On the assumption that the airport authorities decide to extend the curb as a result 14 spaces become available for drop-off and pick-up operations of passenger cars. The extended curb now has 14 spaces, thus offering 280 windows of 3 minutes each. Given that demand will grow over time, at the outset, the highest demand is assumed to be the same as for the base case of 140 slots.

Conditions of demand vs. supply were defined and simulated. The results are shown in Figure 5.9 to Figure 5.11. Note that it found LOS A under all conditions.

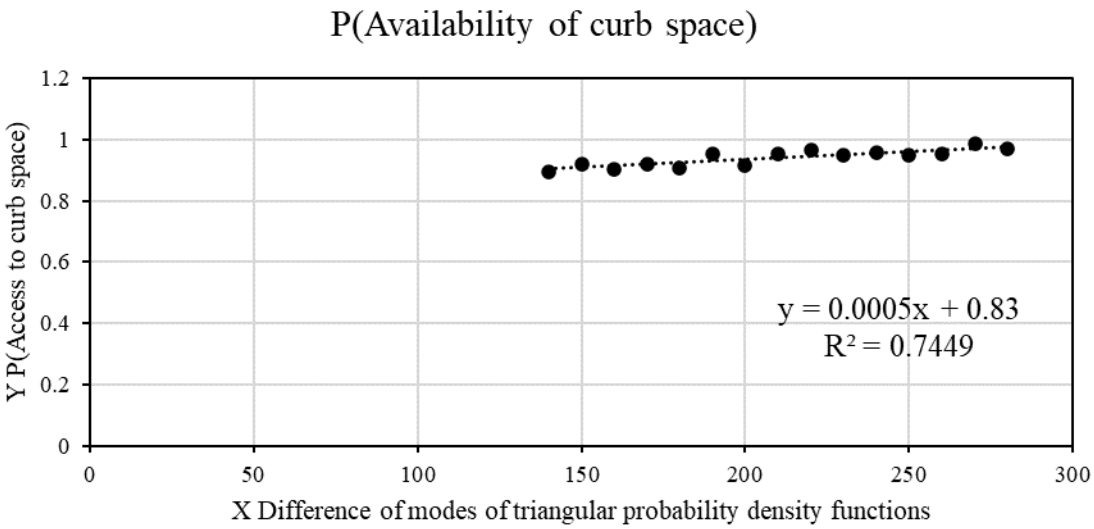


Figure 5.9: Results for 140 slots demand and 280 slot capacity

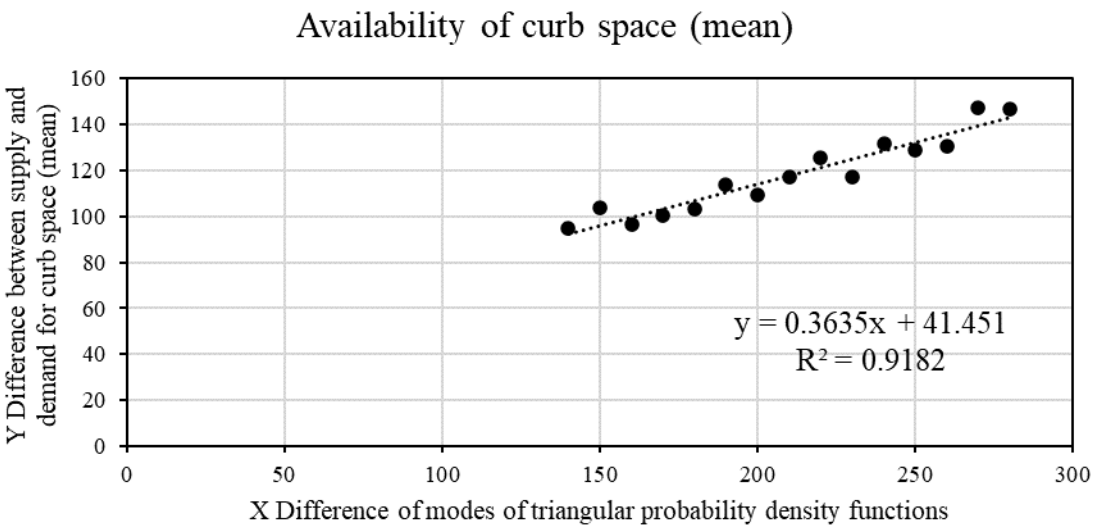


Figure 5.10: Results for 140 slots demand and 280 slot capacity

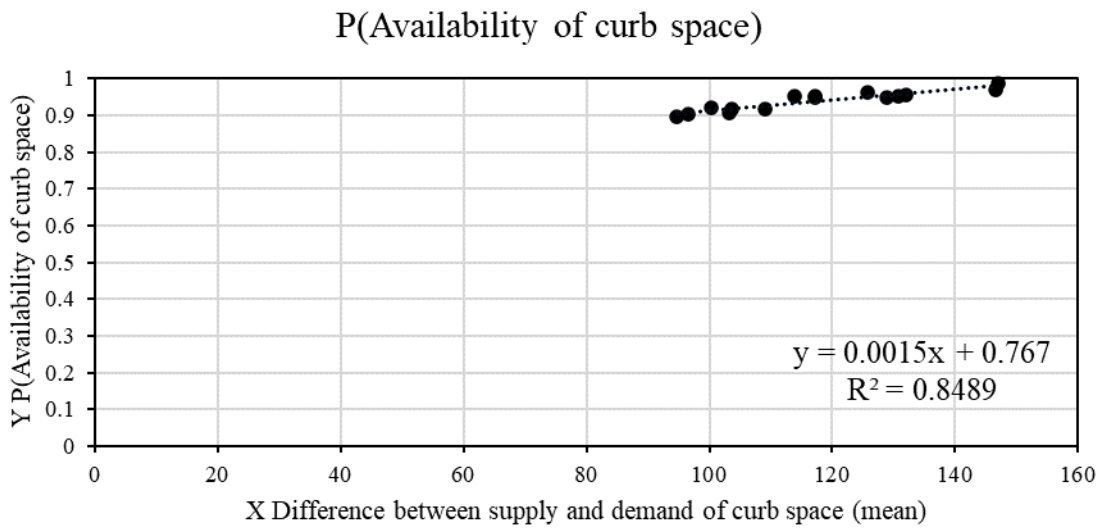


Figure 5.11: Results for 140 slots demand and 280 slot capacity

5.3.6 Modelling Effect of 50% Increase in Demand

Over time the demand will rise. Simulations were run for 210 time slot demand and 280 time slot supply. Results are shown in Figure 5.12 to Figure 5.14. As expected, LOS drops very slightly, but these are high enough for a highly favourable travel experience.

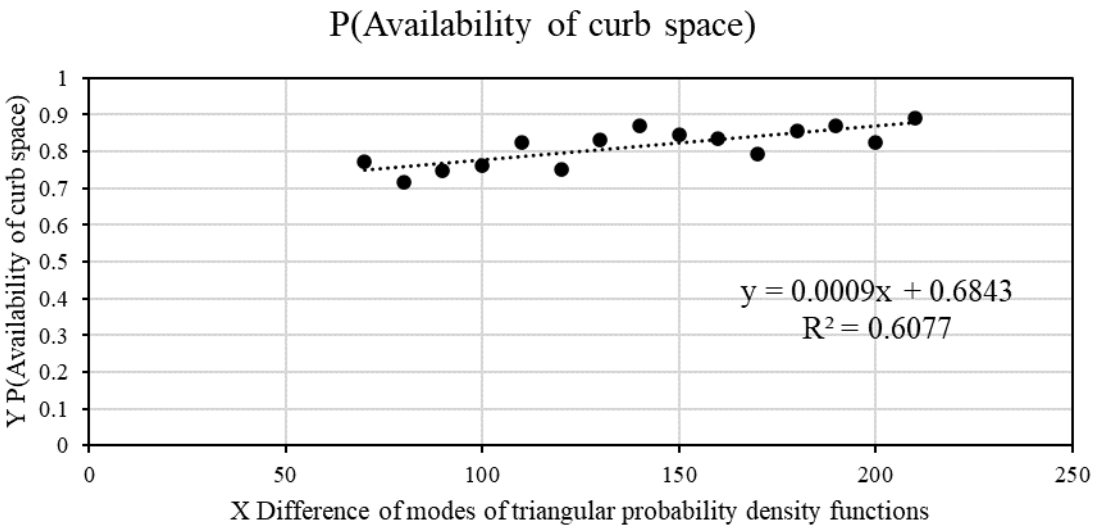


Figure 5.12: Results of 280 supply time slots and 210 demand time slots

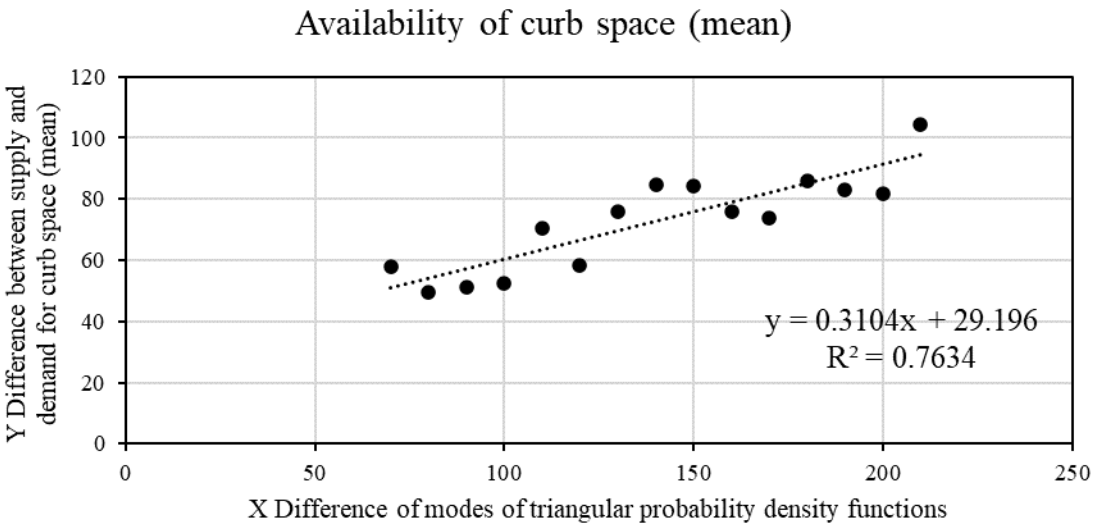


Figure 5.13: Results of 280 supply time slots and 210 demand time slots

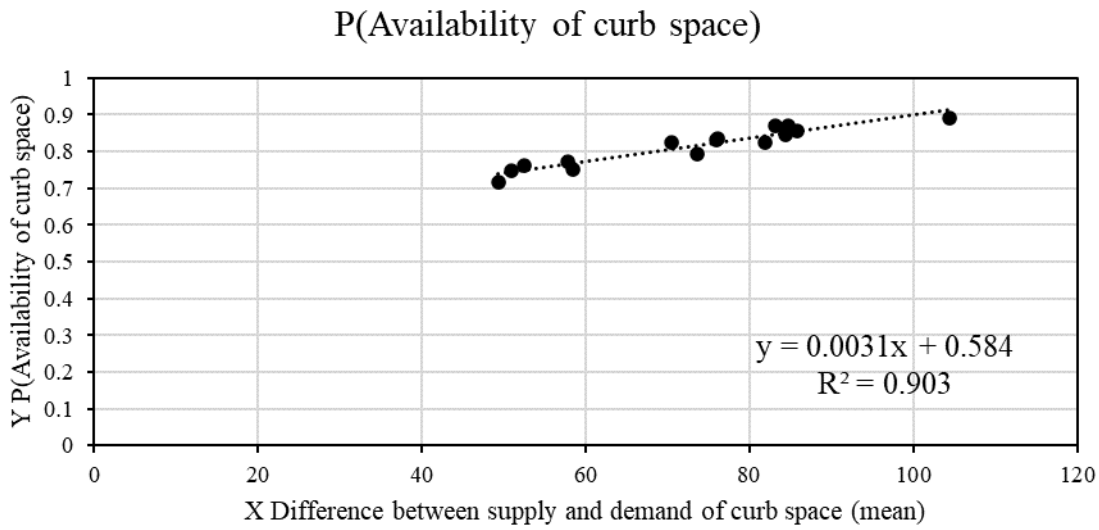


Figure 5.14: Results of 280 supply time slots and 210 demand time slots

5.3.7 Modelling Effect of 100% Increase in Demand

Next, simulations were run for 280 time slots demand and 280 time slot supply. Results are shown in Figure 5.15 to Figure 5.17. As expected, although equal number of supply and demand time slots interact, due to stochastic conditions, the level of service experience is similar to the base case condition when both demand and supply time slots were equal to 140. In these figures, LOS F results are not shown.

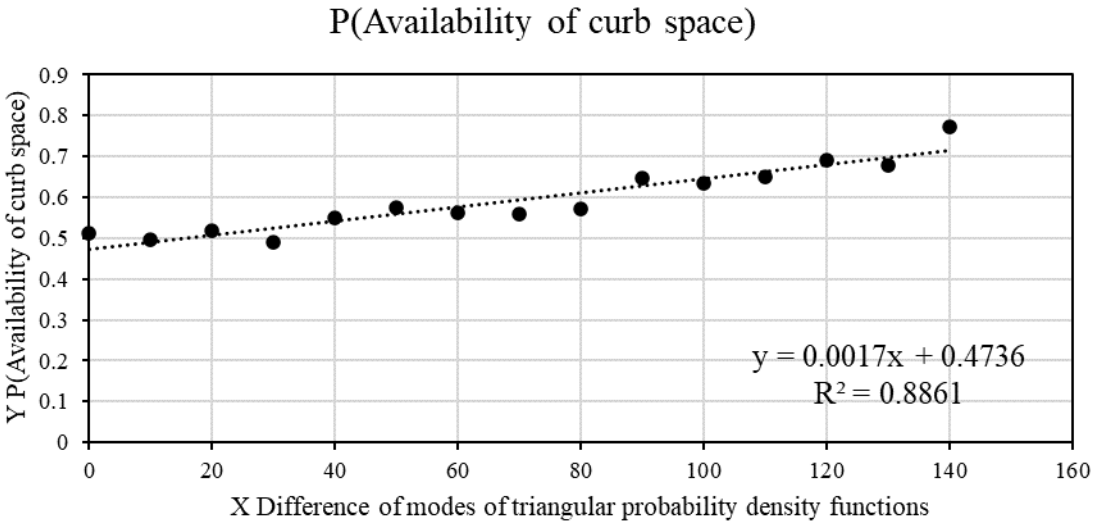


Figure 5.15: Results of 280 supply time slots and 280 demand time slots [NOTE: Probability of less than 0.5 results are not shown.]

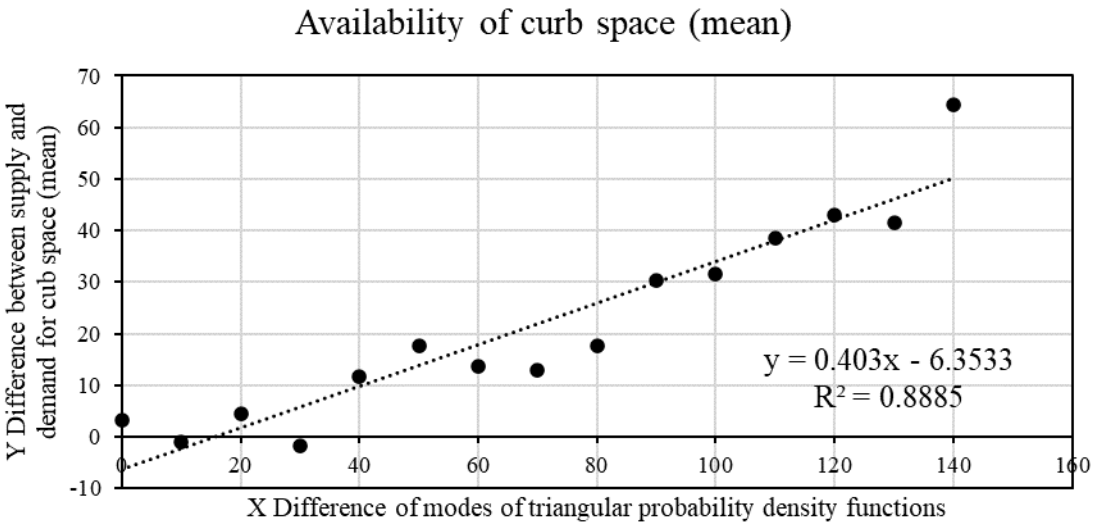


Figure 5.16: Results of 280 supply time slots and 280 demand time slots [NOTE: Probability of less than 0.5 results are not shown.]

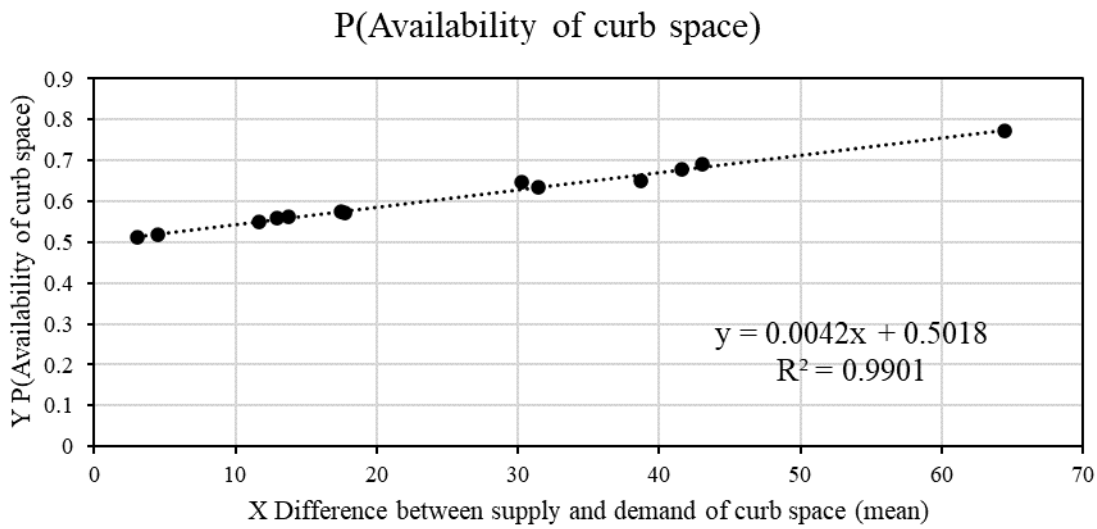


Figure 5.17: Results of 280 supply time slots and 280 demand time slots [NOTE: Probability of less than 0.5 results are not shown.]

5.4 Conclusions

The Monte Carlo based model showed how the delay at the airport can be predicted based on the demand and available supply of curb spaces. A delay index was also developed for the use of comparing different scenarios. This found a total difference in the supply and demand, or the expected mean available slots, for no delay and resulting delay after the available slots fall below this amount. Airport planners can use this index to measure performance of all hours of traffic demand, not just the year high peak hour.

In our study case the peak hour demand of 325 vehicles far exceeded the assigned time slots in the Monte Carlo based model of 140 for the base case. However, the time slots

were based off needing time for calling a vehicle to a spot and the dwell time combined. The current operation of the curbside queues all the vehicles just before the spots allowing the curb spaces to almost always be occupied during times of high demand. This brings the time per space closer to the dwell time of 96 seconds which is considerably lower than the 3 minutes used to calculate the 140 time slots. Future work could be done to allow vehicles to be called to the curbside early in anticipation of a vehicle leaving letting the approach time and dwell times overlap. Better understanding of the vehicle routing and behaviours of such automated vehicles at the curbside and people's behaviours when loading or unloading would be needed though to accomplish this.

Chapter 6: Microsimulation Based Model of Local Shuttle

This chapter describes the microsimulation work done on modelling the impacts to delay from rerouting different percent shares of traffic towards an alternative curbside where passengers transfer to a shuttle before continuing to the main curbside. Chapter 4 serves as the introduction to this chapter. Connected and Automated Vehicles (CAVs) allow for dependable design of vehicle routing. Airport authorities can tell vehicles where to go without relying on people being familiar with the space or providing enough traffic enforcement to route drivers. The nature of the connected and automated wayfinding allows vehicles to adapt to current traffic demands to reduce delay.

6.1 Methodology

In its current state, the study airport curbside services personal vehicles, taxi and taxi like services, and public transit. Personal vehicles and taxis operate in a similar fashion at this curbside due to both using the same spaces for pick-up and drop-off. Public transit was not included in the scope of the modelling. This was chosen to simplify and focus the efforts on the personal vehicle and taxi services at the curbside since public transit had its own dedicated location and limited usage. Further, since both private vehicles and taxi services used the same curbside spaces, they were treated the same as a driver picking up or dropping off travellers.

The airport curbside was simplified to its internal components without concerning the traffic on the connected public roads. This decision was made as the changes to traffic movement outside of the airport scene is outside the scope of this research. Further, the study airport's curbside has only one approach lane simplifying the input parameters for incoming vehicular traffic. All forms of drop-offs and pick-ups come to the same curbside spaces from the same lane. The airport does have areas for taxi and Transportation Network Company (TNC) staging areas, however, both come to the same curbside spaces as the private vehicle drop-offs in actual practice of using the space. This allowed for simplification of the network to focus on the curbside approach and the curbside itself. The network can be seen in Figure 6.1 below.

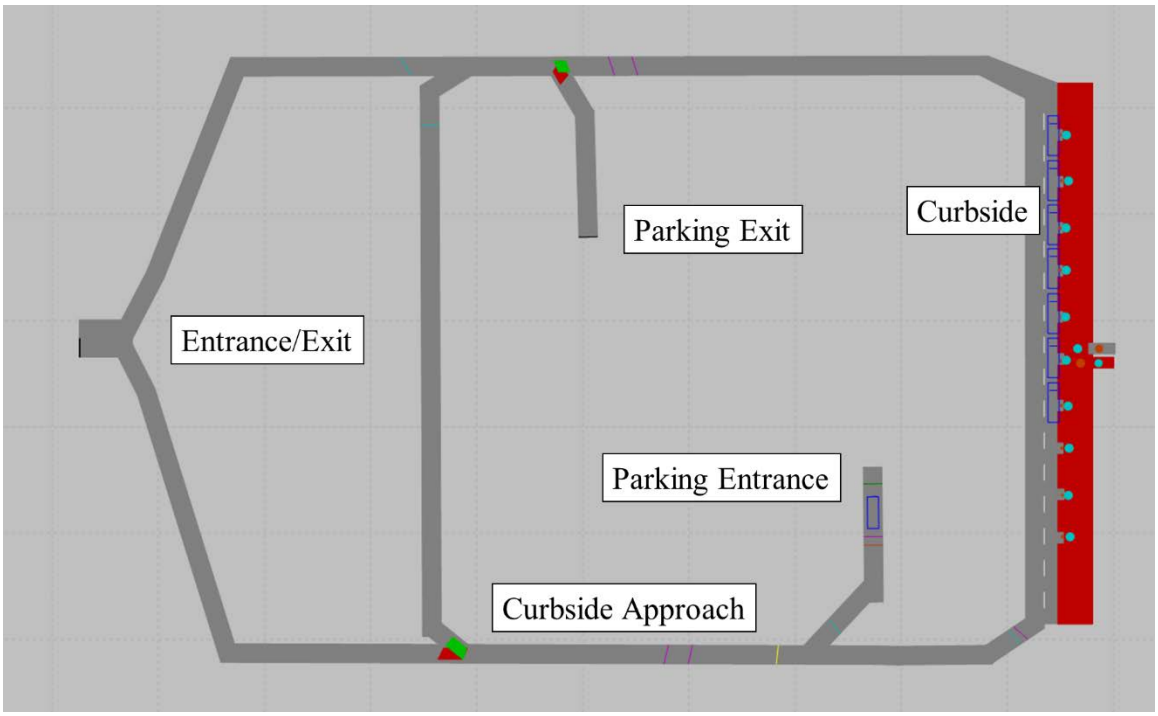


Figure 6.1: VISSIM airport network

Future modal shares and changes of demand at the airport was not considered in this study. The impact of CAVs to modal shares at airports is not certain. This would require a city-wide model where travellers make their decision on what mode to use within the model. Models of this type require knowing input factors to this decision such as out-of-pocket costs, value of time, availability, and weighting those factors based on collected data. These factors and supporting data do not exist yet for CAVs from a reliable enough and available data set, to the knowledge of the author, to explain the effects specifically to the airport.

These future changes in mode share includes the comparison of private and shared futures use cases of CAVs, which is not covered in this study. There are two major reasons why this study did not model the difference between private and shared use of CAVs. The first is the use of CAVs as private vehicles or shared vehicles is uncertain. There is no clear answer as this still depends on the decisions from government policies and on traveller behaviour. The second reason is how there is no, or limited, data to support how it would affect vehicle occupancy at the airport. Future cases with private CAVs would be expected to see similar vehicle occupancies as today. Future cases with shared CAVs could range from similar vehicle occupancies as today to high occupancy. However, without supporting data, making a change to vehicle occupancy due to a shared use of CAVs would produce results with no meaning. Vehicle occupancy can depend on traveller behaviour, profit model, route efficiency, time of travel, etc. which can all increase or decrease occupancy rates independently. Since most of these factors are not known for the study airport the results would have too many unknown factors to confidently report on any reason for differences in results.

Future aspects that carry more certainty, or support from previous modelling work found in literature, is the reduction in use of parking. As seen in the literature review, many models support the idea that both a private and shared use of automated vehicles saw a reduction in the use of premium parking spaces. The parking spaces at the airport fall into this category and can be expected to see a reduction in use. This provides the opportunity for airports to repurpose this space. This led to creating scenarios where parking or

similar areas at the airport were repurposed to increase the capacity of the existing curbside.

The repurposed parking area for this study was looked at to be used as a shuttle staging area. The shuttles were chosen to be modelled as four-person capacity vehicles that operates within the airport grounds. Their purpose is to service travellers waiting in vehicles in queue for the curbside. Instead of waiting for a curb space, vehicles are redirected to the shuttle staging area where the travellers are dropped off to board a shuttle trip to the curbside. The vehicle and shuttle routing can be seen in Figure 6.2 below. This increases the occupancy rate of vehicles at the curbside increasing the capacity of travellers the curbside is able to service.

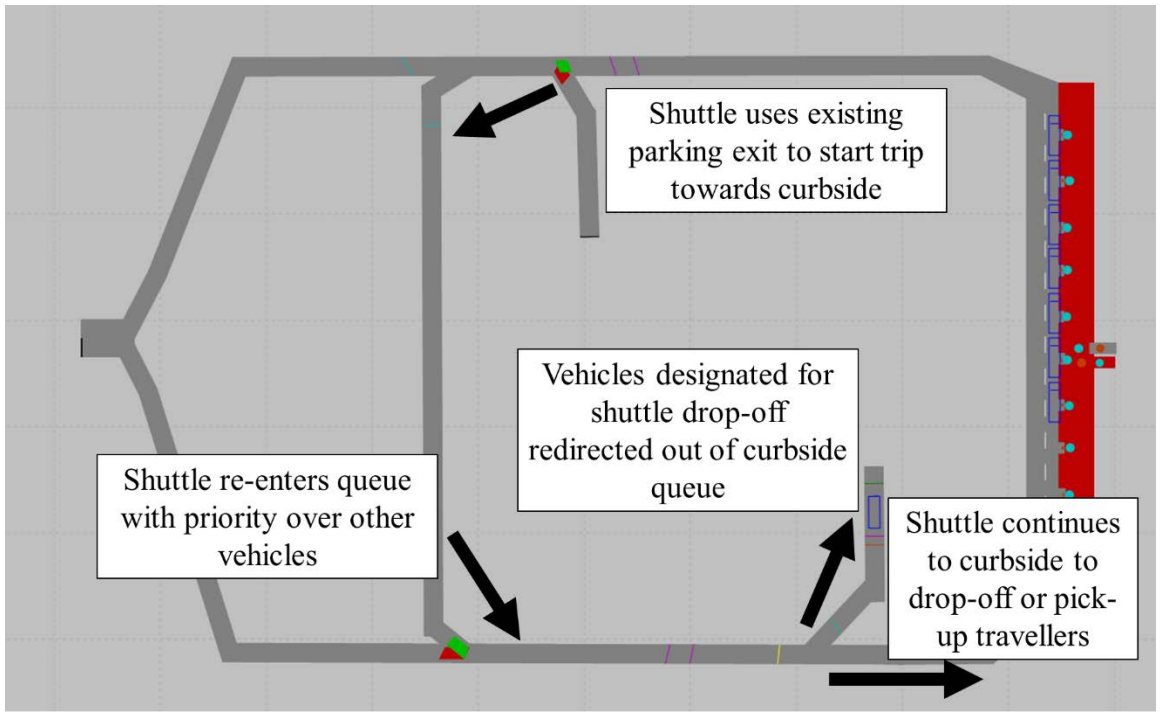


Figure 6.2: Shuttle operation layout

This repurposed area could be used also as additional curb spaces; however, this would require travellers to walk an extra distance before entering the airport buildings. Since automated technologies offer future solutions that avoid costly operating costs of a shuttle driver this makes offering a shuttle to avoid travellers needing to walk outside in winter elements a more attractive future solution. Airports with covered parking garages or weather protected connections between the parking area and the airport check-in could see more use of the repurposed area as direct drop-off or pick-up. However, the time spent walking to the airport check-in would be increased and cause more delay, which is what the use of the shuttles is trying to reduce. Further, the automated or pre-mapped

wayfinding of the automated shuttles is being utilized here to connect travellers between areas of the airport landside area without needing the travellers themselves to be familiar with the space.

Table 6.1 summarizes the model scenarios that were developed within VISSIM, the use of VISSIM itself explained after. Five scenarios were built using different levels of redirected traffic. The base case scenario is represented by the 0% utilization of the shuttles; all vehicles are routed directly to the existing curbside. The further scenarios explore the impacts of redirecting traffic towards transferring passengers to a shuttle or to the curbside for direct drop-off. The scenario redirecting 100% of traffic to the alternate curbside gives two results. The first is to compare to the shuttle use of the other scenarios while the second produces the total spaces that would be required for the airport to expand the curbside by to meet current demands without the need for alternative solutions. Each scenario was run between 45 and 54 times to produce a data set of results to obtain the averaged performance of the curbside.

Table 6.1: Airport Curbside Model Scenarios

Model Scenario	Alternate Curbside and Shuttle Use (%)	Description
1	0	Simulates the base case scenario
2	25	Minority of vehicles are redirected towards having travellers use shuttles
3	50	Half of vehicles are redirected towards having travellers use shuttles
4	75	Majority of vehicles are redirected towards having travellers use shuttles
5	100	All vehicles are redirected towards having travellers use shuttles

VISSIM 2021 was used to model the airport curbside. As discussed in Sections 2.4 and 3.2.1, VISSIM is a state-of-the-art microsimulation modelling software being used to model CAVs. Microsimulation was chosen for its ability to adjust the behaviours of each vehicle agent individually. The impact to the delay to each vehicle agent when approaching the curbside from these individual behaviours was the goal of the model. VISSIM allows for capturing of these results.

Using the collected data from Chapter 4 three main model parameters were defined for all scenarios, the total vehicle inputs, the number of curbside spaces available, and the dwell time of each vehicle while dropping or picking someone up, as seen in Table 6.2 below.

Table 6.2: Model Parameters

Model Parameters	
Vehicle Inputs	325/hour
Curbside Spaces	7
Average Dwell Time	96 seconds

The modelling software, VISSIM, handled randomizing the arrival patterns for this demand between each run of the scenarios. VISSIM handles traffic inputs using hourly volumes of each vehicle type. To create the scenario conditions, different hourly volumes for two vehicle types were used in each scenario, one for vehicles going straight to the curbside and the second for vehicles redirected to the shuttle staging area. This distribution can be seen in Table 6.3 below. Built in stochastic fluctuation of the traffic volume by VISSIM was enabled so each scenario run used a different arrival distribution within the hour. The routing of vehicles within the model was handled by VISSIM since the vehicle agents were given different vehicle types.

Table 6.3: VISSIM vehicle inputs for each scenario

Model Scenario	Alternate Curbside and Shuttle Use (%)	Hourly Volume of Vehicles Directly Using Curbside (vehicles/hour)	Hourly Volume of Vehicles Rerouted to Shuttle Staging Area (vehicles/hour)
1	0	325	0
2	25	243.75	81.25
3	50	162.5	162.5
4	75	81.25	243.75
5	100	0	325

The vehicle inputs were simplified by having the same vehicle types for pick-ups and drop-offs. Since all vehicle traffic uses the same curbside spaces this was possible. When vehicle agents are generated into the model they are assigned an occupancy. This occupancy number can be used for both pick-ups and drop-offs. In the case of drop-offs the occupancy is seen as the number of travellers already in the car waiting to be dropped off. In the case of pick-ups the occupancy is seen as the number of travellers waiting to be picked up at the curbside. This should not be confused with the different vehicle types explained above for inputs into the model. This is in reference to not needing a sub type between vehicles directly using the curbside and those rerouted toward the shuttle staging area.

Considering the general behaviours of CAVs, since CAV following distances and behaviours have not been standardized the default vehicle agent behaviours in VISSIM were used. New behaviours were needed though for this study to both model CAVs and current driving behaviours at the airport. To accomplish adding the necessary components of the behaviours for the model scenarios, custom Python script was written and implemented to the VISSIM model through the COM-Interface. This script allowed for the following features in the model:

Vehicle behaviour depending on successful use of the curbside by changing vehicle type: Vehicle agent behaviour at the airport curbside depends on the successful use of the curbside. If a vehicle agent proceeds to the curbside but does not successfully find a spot it must recirculate back to the start of the curbside or rejoin the queue, depending on the

design and current demand for the curbside. This can occur when drivers do not follow traffic guidance or if the availability of spaces is not communicated to the drivers and they must proceed to the curbside itself to find out. CAVs will have the ability to communicate to the curbside, if set up properly to do so, to only proceed if a space is available. Within the model, the code makes a check for each vehicle agent as it leaves the curbside area. If the vehicle agent has not yet used the curbside it remains as is and is guided towards the curbside again. If the vehicle agent has used the curbside the vehicle type (the vehicle type is an attribute of the vehicle agent seen by VISSIM) is changed so it can be routed to leave the airport. In the case of the shuttle agents they are redirected back to the shuttle staging area.

Adding and removing vehicle agents to shuttle staging area: When vehicle agents are routed towards the shuttle staging area they must be handled by the custom code. A parking space was added to the VISSIM model as the entrance to the shuttle staging area. When vehicle agents stop in this parking space their occupancy is recorded and stored as a variable for the Python code to use as an arriving vehicle agent. This occupancy is used when assigning travellers to shuttles. This is done for both pick-ups and drop-offs. After the code handles transferring travellers to or from a shuttle, explained below, the vehicle agent is added back into the model at the shuttle staging area exit.

Deploying a shuttle when full, or when the next waiting vehicle occupancy exceeds available seats, to the airport curbside: The python script for deploying the shuttles checked the occupancy of each arriving vehicle agent to add the passengers to the next

available shuttle agent. If the shuttle was at capacity it was deployed towards the curbside by creating a vehicle agent within the VISSIM model designated to behave as a shuttle and with full occupancy. However, it was assumed travellers arriving as a group would not split between multiple shuttles. Therefore, the script checked how many passengers were in the next vehicle agent and if that number exceeded the number of seats available the shuttle was deployed under capacity. The next vehicle agent would then transfer its passengers to the next empty shuttle.

Keeping track of the total number of shuttle trips made: The number of shuttle trips was stored during the running of the custom python script and output into a text file. This was done to provide the total number of shuttle trips that would be needed within the hour to understand the relative difference in required shuttle fleet size.

Keeping track of the maximum number of vehicles at the shuttle staging area at any given time: The maximum number of vehicles at the shuttle staging area, not including shuttles, was stored during the running of the custom python script and output into a text file. This was done to understand the needed spaces for the shuttle staging area. If an airport does not want to repurpose all of the parking area or is interesting in building new infrastructure this figure provides insight for sizing purposes.

VISSIM link results were used to capture the time spent on the curbside approach link and the relative share of time spent delayed. This share, expressed as a percent, and total time could then be used to calculate the time spent delayed on the link. Time spent

transferring to a shuttle was considered as further delay. It was assumed it would take passengers the same time to be dropped off to or picked up from a shuttle as it is to be dropped off at or picked up from the curbside. The average time of 96 seconds was used for the delay to each vehicle in this case as the transfer is done internally by the Python script. The complete methodology of modelling the delay to a traveller can be found in Figure 6.3 below.

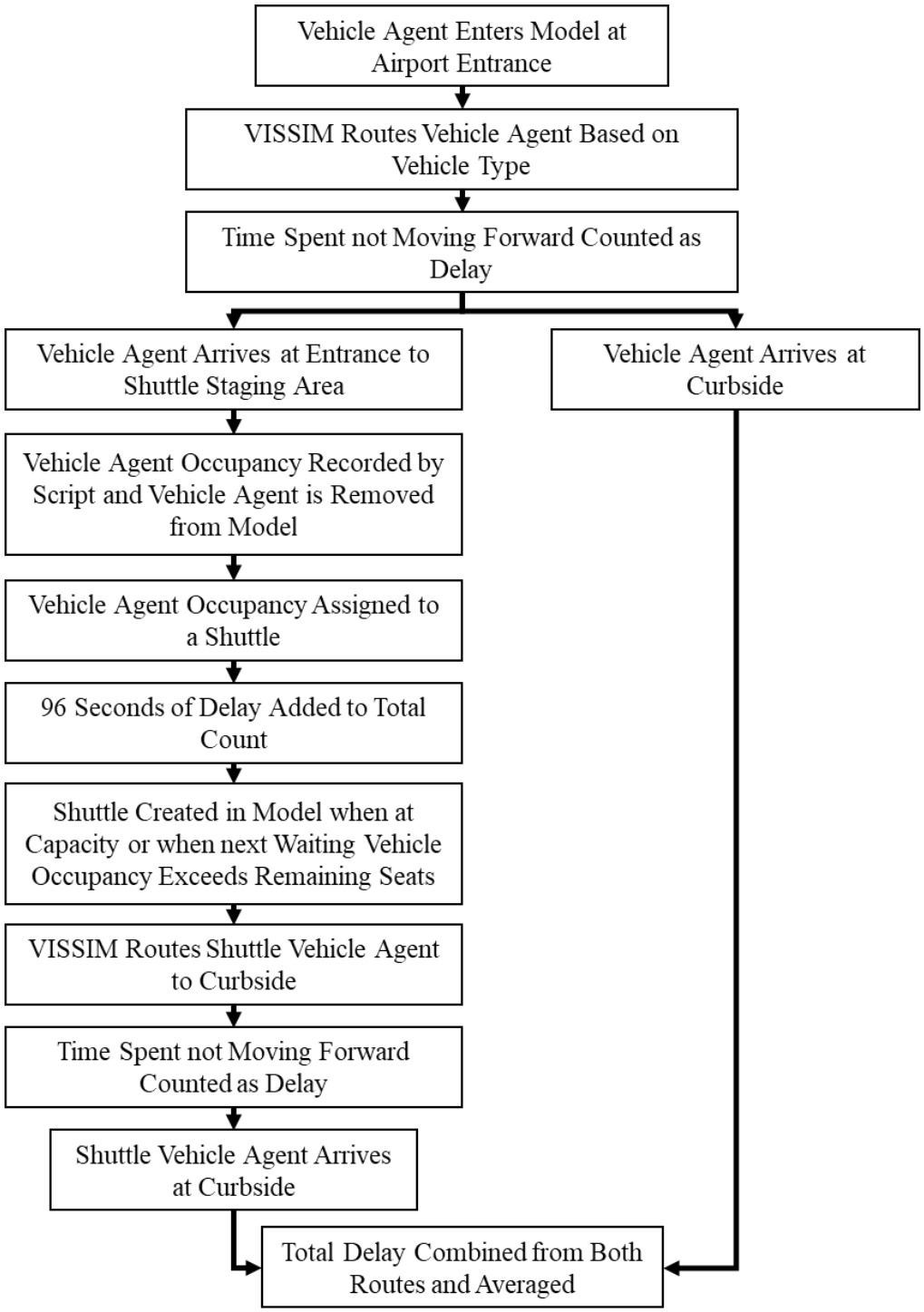


Figure 6.3: Local shuttle and vehicle delay methodology

Time spent being dropped off at the curbside was not considered as delay since this is time spent by the traveller actively progressing towards their goal. Therefore, delay can be understood as any additional time compared to the free flow condition between arriving at the airport and stopping at a curb space.

6.2 Results

The results from the microsimulations are presented in Table 6.4, Table 6.5, Figure 6.4, and Figure 6.5.

Table 6.4 summarizes the results showing the use of the alternate curbside for a shuttle staging area, this being the repurposed parking area or an expansion away from the existing curbside in our model. As expected, the required number of spaces at the shuttle staging area increased as the percent of vehicles that was rerouted to this area was increased. It saw an average needed spaces of 9.2 at 25% rerouted and 16.2 when 100% was rerouted. The standard deviation in required spaces reduced as the percent using the area increased.

The average 16.2 needed spaces for the 100% scenario can also be interpreted as the total number of spaces needed at the curbside to meet the current year high peak hour with traffic remaining in operation as-is. The shuttle staging area was handled by the custom code which did not have a capacity restraint like the existing curbside handled by VISSIM. This allowed as many spaces as necessary to be occupied at any one time.

The total number of shuttle trips also increased as the percent of vehicles going to the shuttle area increased. Of note, the number of shuttle trips required to service this scaled faster than the ratio of vehicles coming to the area. With 25% being rerouted to the alternative curbside only an average of 24.6 shuttle trips were needed to service the demand while when 100% of the vehicles were rerouted then an average of 120 shuttle trips were needed to service the demand. This difference is discussed in Section 6.3.

Table 6.4: VISSIM Model Results – Alternate Curbside Usage

Model Scenario	Alternate Curbside and Shuttle Use (%)	Parking Spaces Needed at Shuttle Staging Area			Shuttle Trips		
		Average	Standard Deviation	Max	Average	Standard Deviation	Max
1	0		NA			NA	
2	25	9.2	2.9	17	24.6	5.7	37
3	50	11.7	2.1	20	52.4	8.1	68
4	75	14.3	1.5	18	91.8	7.6	109
5	100	16.2	1.6	21	120	6.2	133

Table 6.5 presents the number of vehicles that entered the model and the delay experienced per vehicle for each scenario. The total demand is 325 vehicles entering the airport within the hour. The first observation that is made is the increase of the average vehicles entering the model within the hour simulation as more vehicles are rerouted to the alternate curbside. All vehicle agents attempt to enter the model in all scenarios. However, if there is no space available on the curbside approach link the agents wait in queue outside of the active model. The number of vehicles that did make it onto the curbside approach link are recorded in the Average Vehicles Entered within the Hour

column. Additionally, there is a trend of reduced delay experienced per vehicle until the 100% rerouted scenario. Since there is a queue of vehicles waiting to enter the active model not all of the delay could be captured by measuring the delay on that link. Therefore, the delay of the time waiting in that queue to enter the model was also calculated. The calculation formula is shown after the table. These trends can be seen more clearly in the following figures.

Table 6.5: VISSIM Model Results – Vehicles Serviced and Time Spent Delayed

Model Scenario	Alternate Curbside and Shuttle Use (%)	Average Vehicles Entered within the Hour	Time Spent Delayed per Vehicle within Model (seconds)	Theoretical Time Spent Delayed per Vehicle (seconds)
1	0	215	102	155
2	25	252	92	111
3	50	287	88	94
4	75	321	82	82
5	100	322	103	103

Figure 6.4 and Figure 6.5 give a visual presentation of the results presented in the tables. The trend of more vehicles making it into the model from available space up to the 75% and 100% scenarios can be clearly seen. At this point, all vehicles are making it into the model since the queue for the curbside is clearing and the curbside can meet the demand. The delay per vehicle can be seen decreasing until the 100% rerouted scenario. The calculated delay is also presented and was found using the following equation:

$$Calculated\ Delay = \frac{Delay\ Captured\ in\ Model}{\left(\frac{Total\ Vehicles\ Entered\ Model}{Total\ Demand}\right)}$$

This equation can be understood as increasing the delay by the ratio of vehicles that did not make it into the model. Since the delay represents the total time spent delayed waiting for a curbside space this ratio works to extend the delayed time by offering a way to count the time spent in queue before the vehicle enters the model. The less vehicles that make it into the model, the larger the difference between the delay captured in the model and the calculated delay since there will be a longer queue outside of the model. In all scenarios the demand is 325 vehicles for the hour. Looking at the first scenario we can see that this results in a ratio of 215/325. When the captured delay is adjusted by this ratio it increases from 102 seconds to 155 seconds. From this, the delay per vehicle of the scenarios rerouting less than 75% of the vehicles saw an increase in the delay per vehicle.

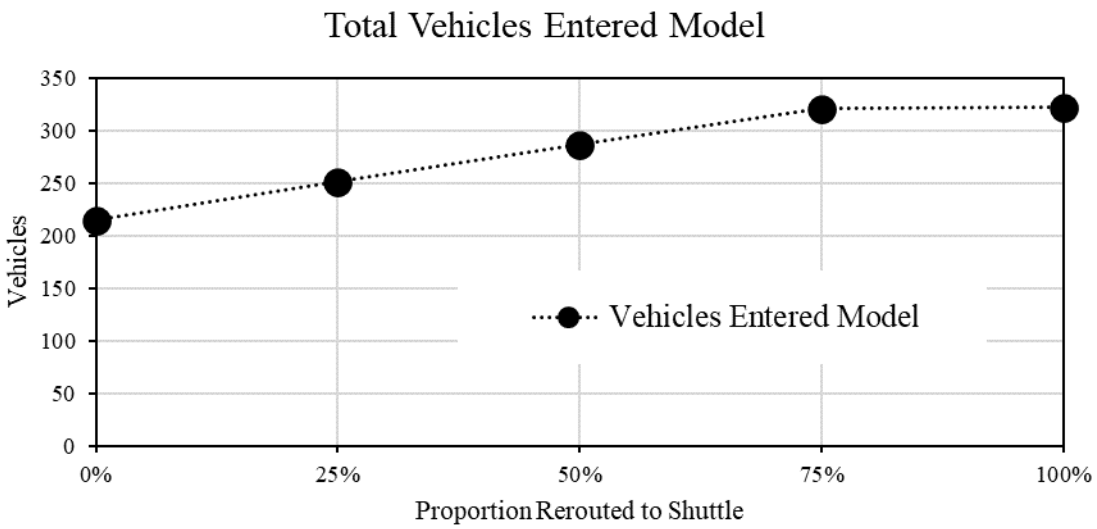


Figure 6.4: VISSIM model results - Vehicles entered model

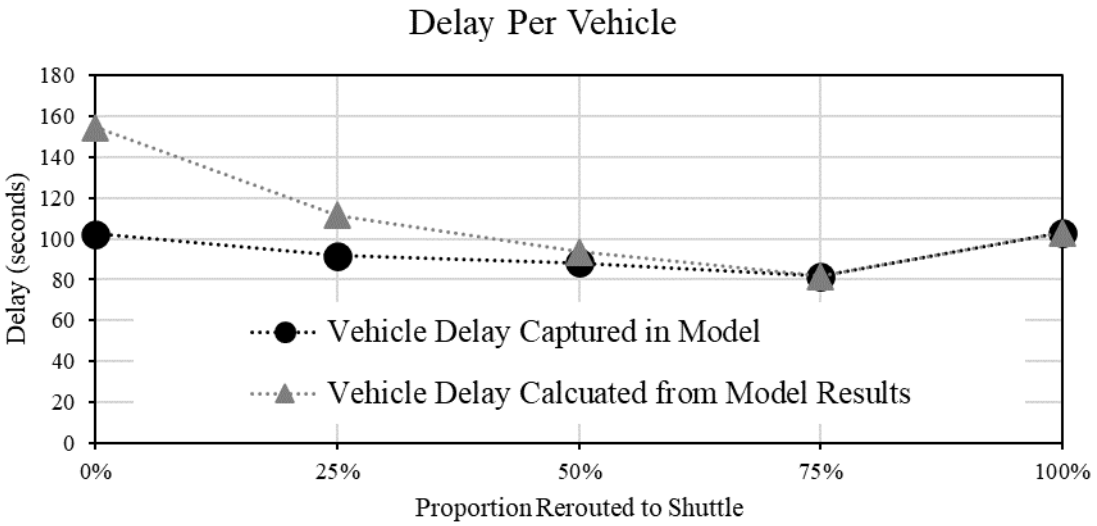


Figure 6.5: VISSIM model results - Time spent delayed per vehicle

6.3 Discussion

The airport curbside as-is cannot meet the year high peak demand under normal use cases. To meet this demand, travellers are double parking or using other areas around the curbside to pull over at and drop-off or pick-up travellers. This was evident in the results seen in the first scenario where only 215 of the 325 vehicles made it into the model. The delay experienced was found to be 155 seconds in the calculated results from the model which is higher than the average dwell time of the vehicle at the curbside of 96 seconds.

The use of automated vehicle routing was shown to be able to redirect traffic towards the shuttle staging area to allow the current curbside to meet the demand. The use of a shuttle between the staging area and the original curbside allowed all vehicles to be serviced while decreasing total delay. However, it was seen that when all vehicles were redirected to the alternative curbside for passenger shuttle transfer that the delay went back up. This is due to the transfer to the shuttle being considered delay. Once the demand could be met by redirecting 75% of the traffic towards the alternative curbside the original curbside had the capacity to take the remaining traffic as-is so the transfer to the shuttle produced unnecessary delay. Past 75% of traffic transferring to shuttles there are empty curb spaces that are not being used. These spaces would be best used serving travellers directly instead of forcing them to transfer to a shuttle.

This shows that there is future optimization potential in this design of balancing when to direct a vehicle to use a shuttle. The suggestion from this research is to design a solution

where the choice to redirect travellers towards shuttle use would be a calculated decision based on expected delay before a curb space would be available. A traveller would then be directed to take a shuttle when it is found to reduce their delay at the airport. From this research, these results are expected to be similar to the 75% shuttle use case but instead be optimized also for the traveller and not just the airport.

When the percent share of the vehicles going to the shuttle staging area increased the total number of shuttle trips made increased at a faster rate. This could be due to how the shuttles were coded to behave when checking capacity compared to the next waiting vehicle. As explained previously, the code had each group of people from each incoming vehicle stay together. This resulted in shuttles leaving when not at full capacity if they did not have enough empty spaces for the next vehicle. As a larger portion of the arriving vehicles use the shuttles it also increases the occurrence of shuttles leaving while not at full capacity which would reduce the efficiency of the service. This reduction in efficiency is an area that could be solved with future research into optimizing the assignment of travellers to shuttles.

An area of interest that was not able to be explored was modelling the difference between private and shared alternatives. For this to be done a city network wide model would have to be run. This is because while we can refer to other studies on the uptake and overall impact of private vs shared alternatives, we cannot infer the impact to origin and demand. The shared vehicle does not guarantee that it will increase the number of passengers within each vehicle arriving at the airport. The optimal route may include dropping all

but one passenger off before arriving at the airport while alternatively could have the vehicle be at capacity when it arrives. This occupancy depends on the local origin and demand of the city in which the airport is located. A wider scope would be needed to complete this analysis.

6.4 Conclusions

The microsimulation efforts showed a more finite analysis of the delay using the current vehicle counts from the study airport. This effort focused on the delay per vehicle and explored different effects to delay when vehicles were rerouted away from the main curbside for passenger transfer to a shuttle. The results showed success in reducing the delay per vehicle. It showed that airport planners can adjust where traffic is headed to depending on the demand to best service customers in reducing the average delay experienced when accessing the curbside. However, the microsimulation scenarios were not able to explore future case conditions. To account for future conditions a city-wide model would be needed.

The microsimulation also showed the total demand could be met with only the curbside if 17 or more curb spaces were provided. This is an increase of 10 spaces, or an almost two and half times larger curb space than currently available. Increasing the curbside by this amount is not a realistic alternative available to many airports. Exploring other means may be more feasible.

Chapter 7: Microsimulation Based Model of City Shuttle

This chapter covers the work of modelling a shuttle agent connecting travellers between a hotel within the city and the airport curbside. Chapter 4 serves as the introduction to this chapter. Within this chapter the agent will be referred to as the bus agent, city shuttle agent, and shuttle agent. This should not be confused with the shuttle modelling done in other sections. Bus is used as it is the built-in agent that best fits the characteristics of the real-world city shuttle. If mentioned outside of this section, the shuttle connecting the airport to the off-site city location will always be referred to as the city shuttle unless otherwise specified in reference to this section.

7.1 Methodology

The commuter airport currently utilizes a shuttle that connects travellers to a hotel within the city. Airports can use shuttles to popular off-site locations to reduce the demand of personal vehicles or taxis at the curbside. The shuttle picks up and drops of passengers at both the airport and city locations. However, demand and supply of the service should be examined to be aware of the experience by travellers using this option.

The shuttle used in this research copied the properties of the existing real-world shuttle used at the airport. The shuttle has a capacity of 20 people and can accommodate a limited number of passengers using wheelchairs at that capacity. It is scheduled to depart at the airport and city location every 15 minutes. The arrival time of the shuttle aligns

with the departure of the previous shuttle. However, due to traffic conditions of the public roads the route needs to take, this time is not always exact, and the shuttle can arrive early or late. Delays at the airport itself can also contribute if there is a long queue of vehicles waiting for access to the curbside since the shuttle shares the same access road. The route concept is shown in Figure 7.1 below.

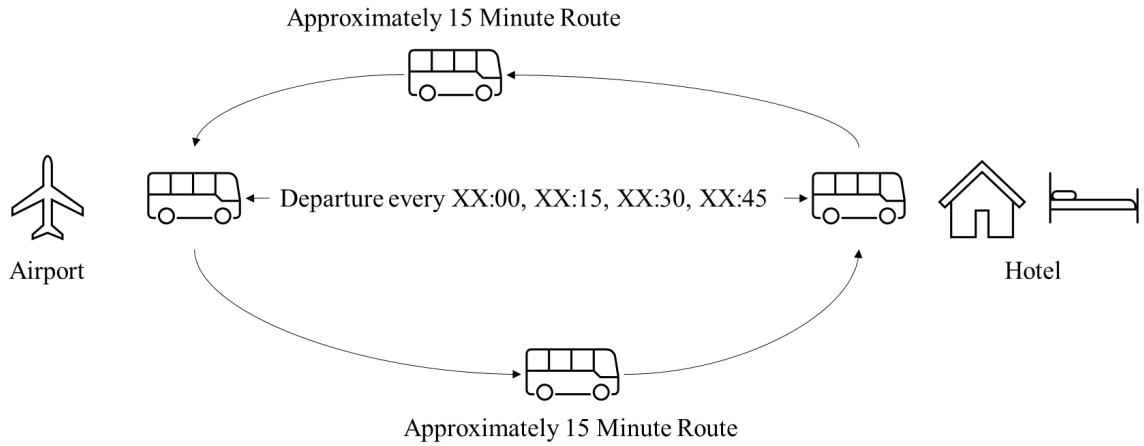


Figure 7.1: City shuttle route

The design involves having travellers wait inside the stationary shuttle at the airport until its departure time. If a shuttle is late though, the current shuttle will leave to maintain its schedule so travellers will have to wait at the curbside. However, the people at the airport can wait for the shuttle inside the nearby building to stay warm in cold weather or to avoid standing in the rain. This provides a large enough waiting area to service the travellers using the shuttle at different levels of demand.

The VISSIM model was used to examine the effects of the city shuttle at different levels of supply and demand. Within VISSIM, shuttles of this nature can be modelled as bus agents. This allows them to use special parking locations separate from other vehicles in the model. Additionally, VISSIM supports using a bus schedule for the agent. The bus schedule is input by the user by telling VISSIM which simulation second the bus is scheduled to arrive at the airport. From here, the arrival time can be set to be static or stochastic. In a static setting, the bus agent is always generated into the model at that time with no variance. This can be useful when modelling scenarios where busses are starting their route or when the times given are matching observed conditions. However, for the airport the time being modelled is through the day while the busses have already started their routes. This introduces unexpected variance to the arrival times to the airport. For this reason, the arrival times to the airport were set to follow a stochastic nature. Properties of the real-world shuttle and route that were used for the shuttle agent are shown in Figure 7.2 below.

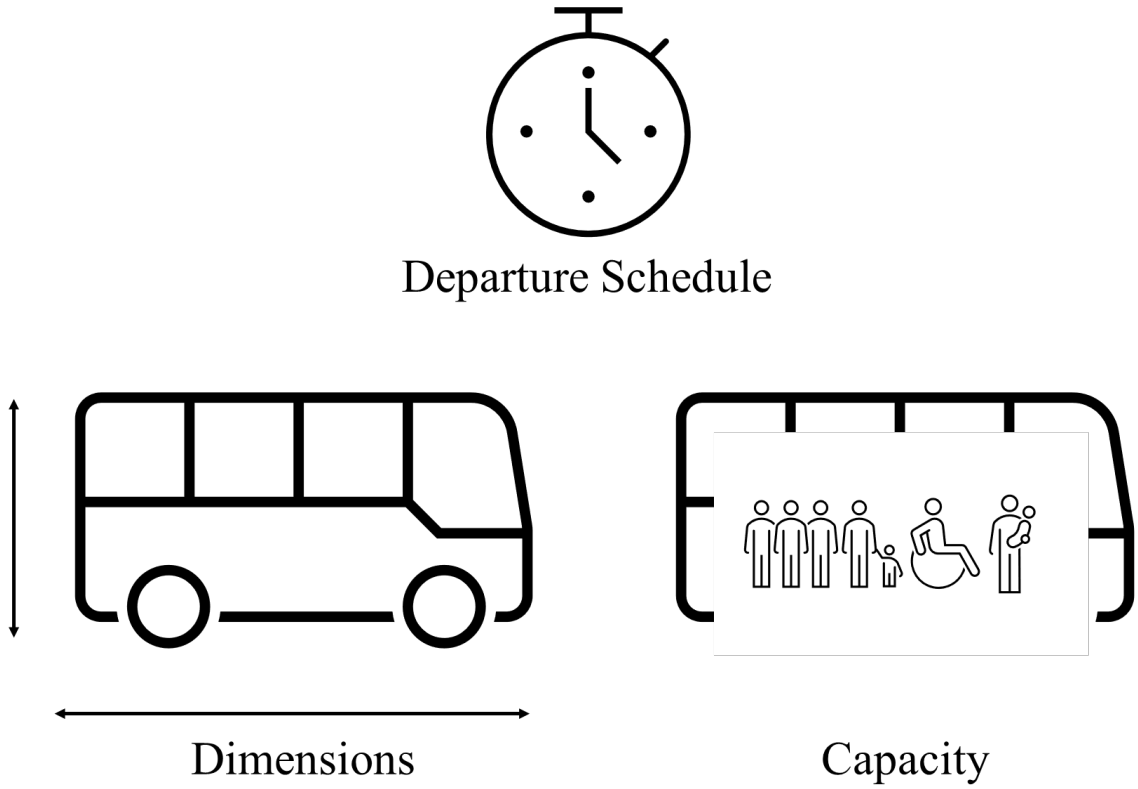


Figure 7.2: Example shuttle properties given to model agent

7.2 Impacts to the Airport Curbside

The goal of this research is to understand the impacts to the airport curbside, not the route of the city shuttle. Therefore, the whole shuttle route was not modelled. Instead, just the airport area is modelled and the shuttle enters and exits the model at the airport entrance and exit. A single bus stop was modelled at the curbside for the shuttle agents to use. Since a shuttle leaves before the next shuttle arrives only the one location is required. The shuttle route is shown in Figure 7.3 below.

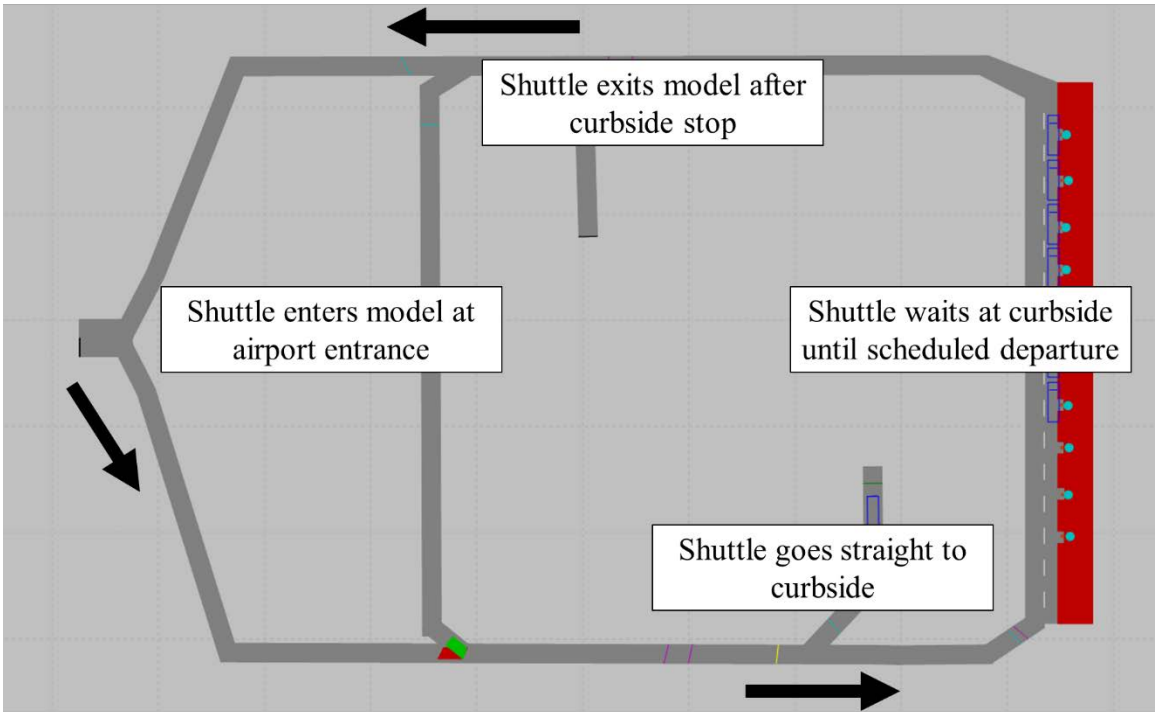


Figure 7.3: City shuttle route within the model

This use case and model structure required handling of the occupancy of the shuttles using custom code. VISSIM does support bus agents being generated into the model with existing occupants. However, these occupancy levels follow given numbers and do not vary. VISSIM is also built for handling only small numbers of pedestrian agents at any time. To avoid these constraints, pedestrians waiting for the city shuttle were handled by the custom Python code but pedestrian inputs still utilized VISSIM. This interaction is explained next and shown in Figure 7.4 below.

VISSIM pedestrian inputs use an hourly volume input provided by the user. The distribution of arrivals of pedestrian follows a random distribution handled by VISSIM.

Pedestrian agent inputs are located on special areas that are designated for pedestrian use. An area is different from a link as the pedestrians can move freely in any direction while on these areas and can be input at specific points instead of at the starting position. When a pedestrian is generated into the model it is created as an agent with basic movement properties. For this portion of the research, the properties of the agent representing pedestrians were not used. Instead, as each pedestrian was generated on the areas it was counted and then removed from the model. The pedestrian count was instead kept in the Python code. This was done for both the airport and city location.

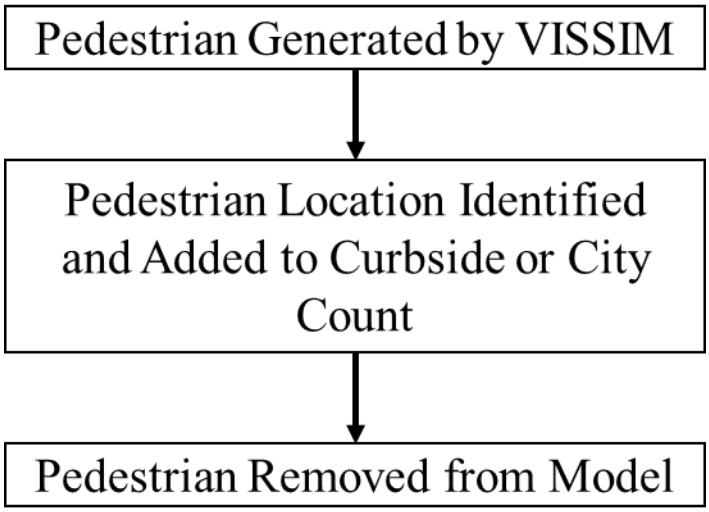


Figure 7.4: City shuttle traveller inputs and counting

When the city shuttle agent enters the model it starts with no occupants. The Python code then identifies it as a shuttle agent that has not yet had its occupancy from the city location assigned to it. The number of travellers to add to its occupancy is checked

against the current count of waiting travellers for the city location. First, the total number of waiting travellers is checked. If it is less than or equal to 20, the maximum capacity for the shuttle, then all travellers are added to the shuttle agent and the count of waiting travellers is reset to zero. If there are more than 20 travellers waiting then the occupancy for the shuttle agent is set to 20 and the number of waiting travellers is reduced by 20. Lastly, the shuttle is given a marker so the code is aware that it has been given occupants and should not be used again to take travellers waiting at the city location.

When the city shuttle agent departs from the curbside the Python code again checks for travellers to assign but instead now from the count for the curbside. All occupants of the shuttle agent that were assigned previously are assumed to have alighted upon arrival allowing space for up to 20 travellers from the airport curbside to board. The number of travellers to board and resetting or reducing the count is handled in the same way as when the shuttle agents first enter the model. Again, a marker is given to the shuttle agent so that the code does not use it multiple times. The assignment of travellers to the shuttle at both the city and curbside locations is shown in Figure 7.5 below.

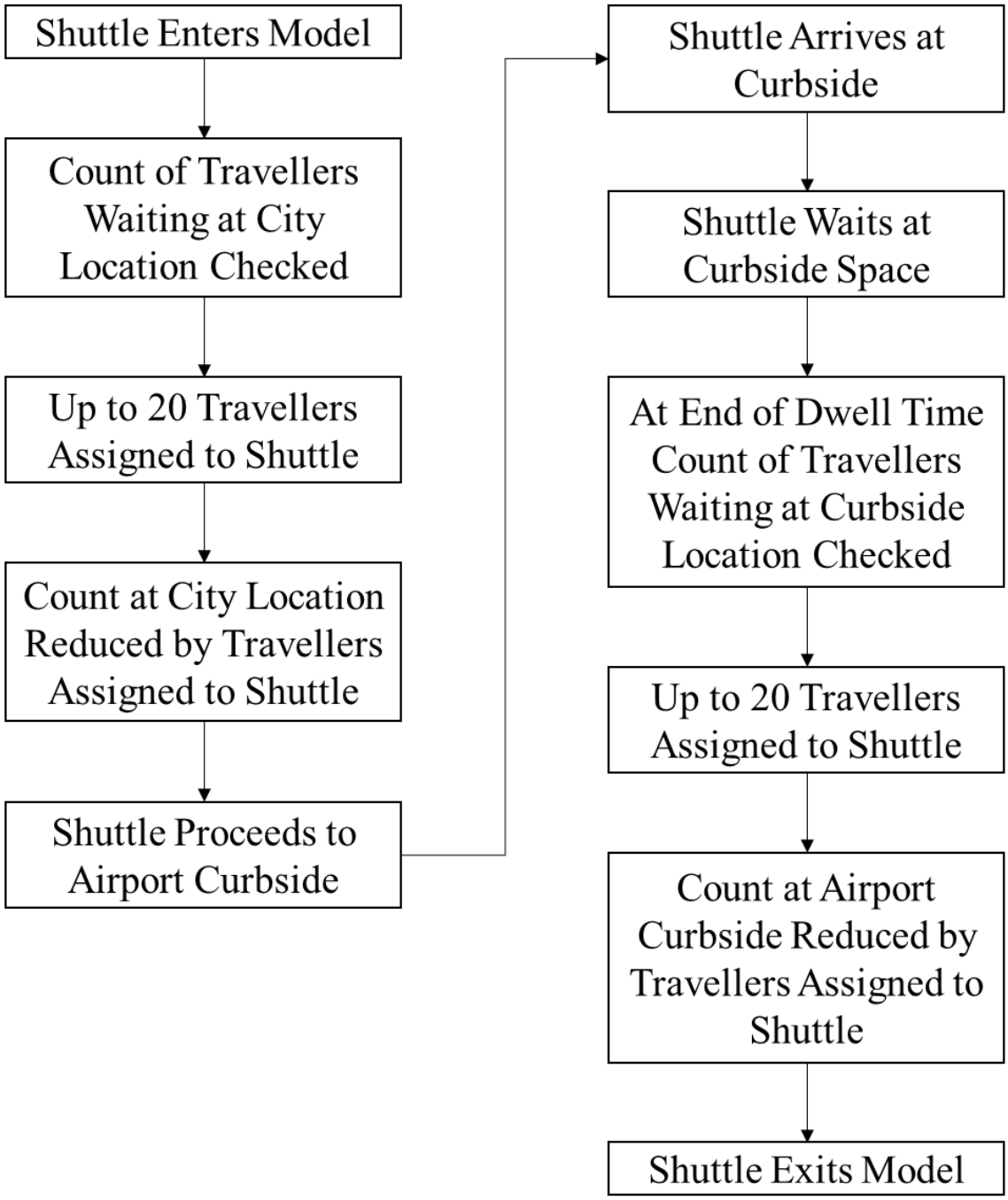


Figure 7.5: Assigning travellers to city shuttle agent

Between arriving in the model and departing from the curbside the code also has a function to handle adjusting the dwell time of the city shuttle agent. By default, the shuttle agent is given either a static dwell time or a dynamic dwell time that reacts to the number of travellers alighting and boarding. However, the nature of the curbside does not fit either of those scenarios. Instead, the dwell time must be at least the time until the next scheduled departure or enough time to allow all current travellers to alight and board, whichever is larger. To accomplish this the dwell time of the shuttle was handled in multiple steps. First, VISSIM assigned a static dwell time as a bus agent to the bus stop location so the agent stops properly. Once stopped, the custom Python code checks the dwell time, the current simulation second, and the next scheduled departure time. The dwell time is adjusted so that the shuttle agent will depart at the next scheduled departure time.

After this, the number of travellers arriving on the shuttle plus the number of travellers waiting at the airport curbside when the shuttle agent first arrived at the curbside are counted. This count is used to check against a minimum allowance of 2 seconds time for alighting and boarding per traveller. This is in the case where a city shuttle is behind schedule due to the variance in arrival time into the model and the delay in the curbside approach due to other vehicles. If the dwell time set to meet the next scheduled departure is less than this required time for alighting and boarding then the dwell time is extended past the scheduled departure time. The dwell time of the city shuttle agent is not adjusted after this point. This process is shown below in Figure 7.6.

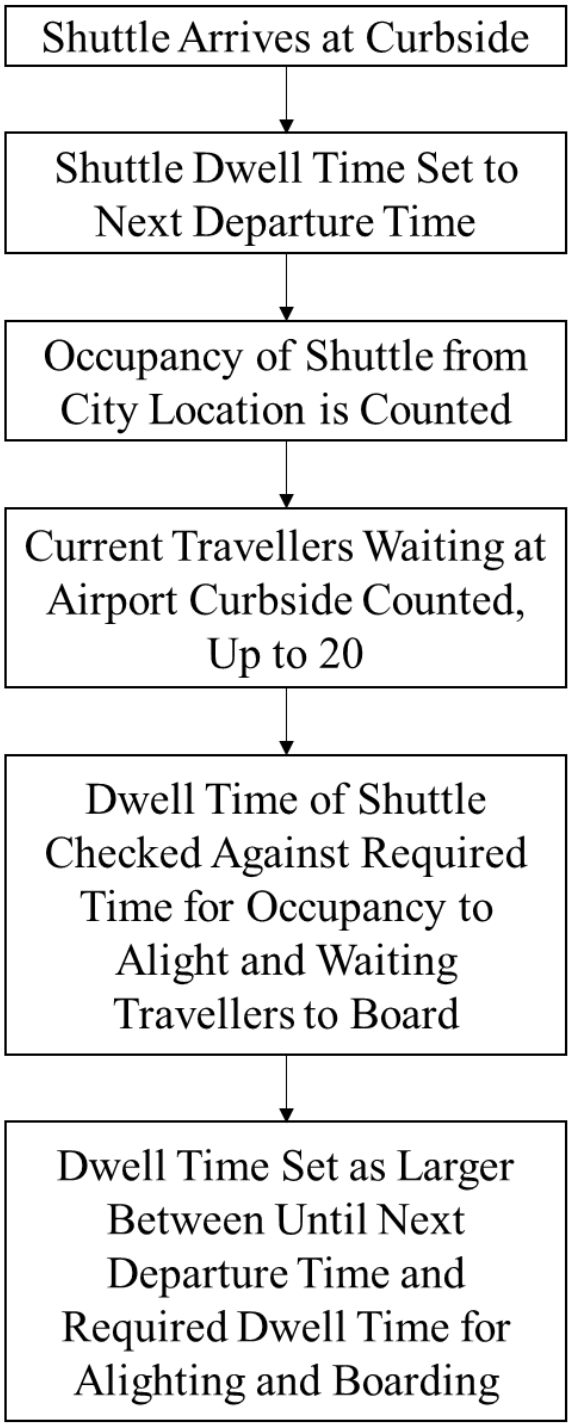


Figure 7.6: Adjusting the dwell time for the city shuttle agent

Since the parameters are handled by the custom code they were also recorded by the custom code. This output the city shuttle agent's arrival and final dwell times and the average wait time of all travellers waiting for the shuttle at each location. Scenario descriptions below followed by a summary provided in Table 7.1.

Scenario 1: Existing capacity

The first scenario modelled the shuttles at capacity. The shuttles have a 20 person capacity and are scheduled to depart every 15 minutes. This provides a supply of 80 available spots on the city shuttle within the hour. Demand for the shuttle was set at a rate of 80 travellers per hour. A total of 50 simulations were run with this supply and demand.

Scenario 2: Double Supply

The second scenario modelled the shuttles with doubled supply. The supply was doubled by reducing the time between shuttle departures. Instead of every 15 minutes a shuttle was scheduled to depart every 7.5 minutes. This would require at least 6 shuttles as the time between locations remains 15 minutes: 2 shuttles waiting at each stop and 4 shuttles travelling between locations. This provides 160 available spots on the city shuttle within the hour. Demand for the shuttle was set at a rate of 80 travellers per hour at each location. This was done by using an hourly input of 80 travellers at each location. A total of 50 simulations were run with this supply and demand.

Scenario 3: Double Supply, 50% Increased Demand

The third scenario modelled the shuttles with doubled supply and demand increased by 50%. The supply was doubled in the same way as in Scenario 2, read above for details. Demand for the shuttle was set at a rate of 120 travellers per hour at each location. This was done by using an hourly input of 120 travellers at each location. A total of 50 simulations were run with this supply and demand.

Scenario 4: Double Supply, Double Demand

The fourth scenario modelled the shuttles with doubled supply and doubled demand. The supply was doubled in the same way as in Scenario 2, read above for details. The demand was increased in the same way as in Scenario 3, instead to 160 travellers per hour at each location to match the supply levels. A total of 50 simulations were run with this supply and demand.

Table 7.1: City shuttle scenarios

Scenario	Supply (Travellers/Hour)	Demand (Travellers/Hour)	Simulation Runs
1	80	80	50
2	160	80	50
3	160	120	50
4	160	160	50

7.3 Results

The dwell time of the shuttles and average waiting time of travellers waiting at each location by the end of the hour were collected during this study. The dwell time of the

shuttle acts as an indicator of how well the city shuttle maintained its schedule considering the stochastic nature of the 15 minute trip between the locations and the traffic within the airport. Shorter dwell times compared to the expected 15 minutes (900 seconds) for a supply of 80 and 7.5 minutes (450 seconds) for a supply of 160 results in longer periods of time where there is no shuttle waiting at the curbside to service travellers. The results from each scenario can be seen in Table 7.2 below.

Table 7.2: Average dwell time of city shuttle at curbside

Scenario	Supply	Demand	Average Dwell Time (seconds)	Standard Deviation (seconds)
1	80	80	483	253
2	160	80	321	125
3	160	120	332	116
4	160	160	335	114

The wait times for the shuttle give a direct comparison of the impact to travellers between each scenario. The wait time at the city location is not impacted by the delay due to the queue in the curbside approach due to other vehicles. This wait time is the time between a traveller arriving at the city location or curbside shuttle stop and the shuttle leaving. Time spent waiting within a parked shuttle is counted as time spent waiting. Average wait times for the city location are shown in Table 7.3 and average wait times for the curbside are shown in Table 7.4.

Table 7.3: Scenario results for the shuttle wait time at the city location

Scenario	Supply	Demand	Average Wait Time at City Location (seconds)	Standard Deviation of Average Wait Time at City Location (seconds)
1	80	80	521	89.4
2	160	80	227	18.6
3	160	120	235	21.8
4	160	160	316	64.3

Table 7.4: Scenario results for the shuttle wait time at the curbside

Scenario	Supply	Demand	Average Wait Time at Curbside (seconds)	Standard Deviation of Average Wait Time at Curbside (seconds)
1	80	80	555	118
2	160	80	300	61.5
3	160	120	364	78.0
4	160	160	514	114

7.4 Discussion

Scenario 1 shows the base-case or current design of the shuttle if it were operating at maximum capacity, same hourly demand as supply. The shuttle is scheduled to arrive at 15 minute intervals and due to a 15 minute travel time between locations this requires at least 4 shuttles to maintain this schedule.

As was seen in Table 7.2, the dwell time for the shuttle is 483 seconds compared to the expected 900 seconds, or 54% of the time there was a shuttle at the curbside. This is due to multiple factors. The first being if a shuttle is early to arrive at the airport, it will never

actually wait at the curbside for more than 900 seconds as it must wait for the shuttle in front of it to leave first. When a shuttle is late to arrive at the airport its dwell time is less than 900 seconds. This means that even in free flow conditions of the queue to the curbside the shuttle will on average spend less than 900 seconds dwelling at the curbside. This is due to the model adding random deviation from the 15 minute arrival schedule for the shuttle to simulate the effects of traffic between the locations. The other factor is the delay due to the queue to the curbside from other vehicles. The city shuttle shares the same queue as private vehicles using the curbside. Therefore, the shuttle experiences the same delay to arrive at its curbside location. This was the major contributor to the dwell time of the shuttle being lower than the perfect 900 second dwell time.

Scenarios 2 through 4 showed the effects of doubling the supply which was accomplished through increased frequency of arrival of shuttles to the curbside. These scenarios scheduled the shuttles to depart from both the curbside and city locations every 7.5 minutes. However, the travel time between locations remained at 15 minutes. To maintain this schedule then at least 6 shuttles are required, 2 waiting at each location and 4 in transit. This is only a 50% increase in required shuttles to accomplish a 100% increase in supply. Further increases of frequency will have diminishing returns on relative increases of supply.

Scenarios 2 through 4 saw similar dwell times for the shuttle at the curbside, refer to Table 7.2. Scenarios 2, 3, and 4 saw dwell times of 321, 332, and 335 seconds, respectfully. Since the maximum dwell time is 450 seconds, doubling the supply saw a

shuttle at the curbside 71-74% of the time. This is a notable increase from Scenario 1 and was seen for all demand cases. Scenarios 2 through 4 suffered from the same reasons as Scenario 1 for why the dwell time is less than the perfect 450 seconds. However, as seen by the increased percent of time having a shuttle available, the increased frequency is less effected by these factors.

Dwell time at the city location was not included. This would require building the model network for this location and understanding the local traffic which was outside the scope of this thesis.

The wait times for travellers was also captured during the simulations, refer to Table 7.3 and Table 7.4. Scenario 1 saw similar times for the wait times between the city location and the curbside, 521 seconds and 555 seconds respectfully. Scenarios 2, 3, and 4 saw reduced wait times at the city location. Scenarios 2 and 3 saw a similar wait time, 227 seconds and 235 seconds, while Scenario 4 increased to 316. This increase is expected as the demand matches the supply. However, we can see that the increased frequency has reduced the waiting time. The wait times at the curbside for Scenarios 2, 3, and 4 did not see as large of decreases in wait times. Scenarios 2 and 3 saw wait times of 300 seconds and 364 seconds while Scenario 4 saw a wait time of 514 seconds.

At the curbside, the wait time found in Scenario 4 is only 41 seconds shorter than Scenario 1. This is due to the cases where the shuttle is delayed in reaching the curbside. Even though the average dwell time at the curbside is increased this does not eliminate

the cases where the shuttle is highly delayed in reaching the curbside. This can result in the shuttle leaving late compared to its originally scheduled departure time. This has a large impact on the average wait time since there can be many travellers waiting for that shuttle. The longer the shuttle is delayed, the more travellers will be impacted thus making the impact even larger. The city location was not affected by this behaviour as the model assumes it is not delayed by local traffic and can keep its schedule better.

Of note, the average wait time for the travellers in Scenario 4 is greater than the time between departures of the shuttle, 514 seconds compared to 450 seconds. This suggests that it is likely that there are a number of occurrences where more than 20 travellers are waiting for a shuttle by the time the shuttle is scheduled to depart. While no level of service index has been created for this shuttle, an average wait time being longer than that of the shuttle departure suggest a level of service of F. This exposes that this transportation design struggles to recover from large spikes in demand or delay of supply. As this issue was not seen for Scenario 1 or at the city location it suggests that this issue is caused by the relationship between the local delay and the frequency. The higher the frequency the higher the potential for issues due to local delay.

Due to the nature of the design for the city shuttle dwell time the wait time for travellers is never going to reduce to zero. Instead, in a perfectly evenly distributed scenario the wait time for travellers will average to half the scheduled departure frequency of the shuttle. However, due to delays and a random arrival distribution for both the shuttle and demand of travellers this will not be the case for the real-world. The model captures this

by having random arrival distributions for the shuttle and the demand of travellers and we can see the effects of this in the results. Even in cases where the supply is twice that of the demand with a dwell time of 450 seconds, which would give an average wait time of 225 seconds in a perfectly evenly distributed environment, the average wait time is 300 seconds. The city location did see an average wait time of 227 seconds when the supply was twice that of the delay. However, it is expected that the average wait time would increase if the local traffic was accounted for in the model, much like as seen at the curbside even if not to the same level.

7.5 Conclusions

These microsimulation scenarios showed how the city shuttle dwell times and travellers' average wait times are expected to change with different supply and demand of spaces on the shuttle. Increased frequency was shown to have a good impact on increasing the percent of time of the curbside seeing a shuttle. However, as was seen in the results for the average time spent waiting by travellers this did not translate to benefits easily. The city location, an area modelled to be unaffected by local delay, showed strong benefits to the wait times with increased frequency. However, the curbside, where local delay was included in the model, did not show the same level of benefits. As demand increased, the average wait times increased. It resulted in an average wait time larger than that of the time between departures of the shuttles when demand and supply were equal at the higher values.

These scenarios showed that the city shuttle can be a useful tool to transport people to and from the airport curbside, but the ratio and the total supply and demand should be considered. While total supply and demand are low, the ratio to supply and demand can be closer to 1 as a temporary delay to supply or spike in demand have smaller overall effects. However, as total demand increases the total supply should be kept higher than that of demand since delays to supply or spikes in demand have the potential to have larger relative effects to expected service times as the higher the frequency of shuttles the larger the impact that the local delay can have.

Chapter 8: Airport Corridor

This portion of the study aimed to examine the pedestrian movements within the airport corridor. The behaviours specifically on the moving walkways (people movers) inside the airport's underground corridor were the focus of the study. These pedestrian facilities effect the way people move within a space. They attract the majority of the traffic and provide faster movement speeds while still allowing pedestrians to continue to walk at their own pace. This effects the overall travel time between the airport curbside and up to but not including the security check of the airport. This travel time and understanding of pedestrian behaviours can be used to understand when to expect travellers to arrive at different areas within the airport based on entering each end of the corridor.

To accomplish the goals of the study, two main topics were covered. The first of these topics involved the data collection and analysis of people movement data of the inter-city North American Airport used for this thesis. Data for the study was collected on site from existing security footage inside the corridor of the airport over the holiday (winter) season of 2019. This data was then analyzed to collect two results: the spot speeds within the corridor of each demographic, separated by luggage type, analyzed using kinematic software and the average total travel time from arrival in the corridor to exit at the other end. Analysis found people's spot speeds were high in these spaces, at a pace of over two metres per second while on the people movers. The time of total travel is useful for emergency considerations and future planning and use of the airport (ie, passenger

pickup). This data collection and analysis were done in preparation for the second part of the study: modelling pedestrian flow in the corridor. This required developing custom code for the modelling software used, MassMotion 10.6 (Oasys 2022), as without it model agents would not be able to treat moving walkways differently than other parts of the model. By implementing this code, agents were able to travel with different behaviours depending on if they were moving on regular floor space or using the moving walkways. This included its own distribution of movement speeds based on the standard deviation as collected from the observed behaviours. Results of the modelling showed faster overall travel times through the corridor than the observed times. Modelled travel time gave an average time of 3:59 minutes and 4:20 minutes for those without luggage and those with roller luggage, respectively, compared to the observed average travel time of 5:22 minutes for mixed traffic. However, as can be seen in the lower travel time for those without luggage, this travel time responded to changes in agent demographics as expected from collected data showing that the model can be used to simulate relative differences. The shorter travel time of the modelled agents is also due to the model assuming constant and regular progression of the agents towards their destination. By design, the model does not account for travellers temporarily slowing down or stopping to adjust their luggage, receive phone calls, or interact with others outside of a social forces context.

8.1 Introduction and Background

The Society of Fire Protection Engineers research roadmap (SFPE 2018) and recent SFPE demographic movement and anthropometry study (Gales, Ferri, et al. 2020) have identified that new movement and anthropometric parameters reflective of today's society are essential as proper input parameters into evacuation and pedestrian modelling. Human behaviour and data collection were two of the four areas identified as needing the most attention in the SFPE roadmap. The sections relevant to this thesis were covered in Theme 1 – Human Behavior. The most critical data needed was identified as demographics, specifically for vulnerable populations, anthropometry, and cultural differences. This is then followed by a need for a basis for numbers in codes and response to notification. The theme also identified required design tools. These included behavior-based models that cover cultural, pre-evacuation time, and actions other than evacuating. The work done for this thesis targets the areas of collecting data for the basis for numbers in codes and behavior-based models for actions other than evacuating at airport environments.

The lack of data leads to designs relying on old information and unverified models. A commonly referenced work for pedestrian movement is that of John Fruin and his study (Fruin 1970) (Fruin 1971). This study categorized movement speeds by density and developed different levels of service depending on these densities, these densities and correlated levels of service can be seen below in Figure 8.1. However, this work is dated

and was done using still images and focused on movement around stairs. Service capabilities and level of service were also related directly to the space available instead of factors relating to the actual ability to promote flow through the space.

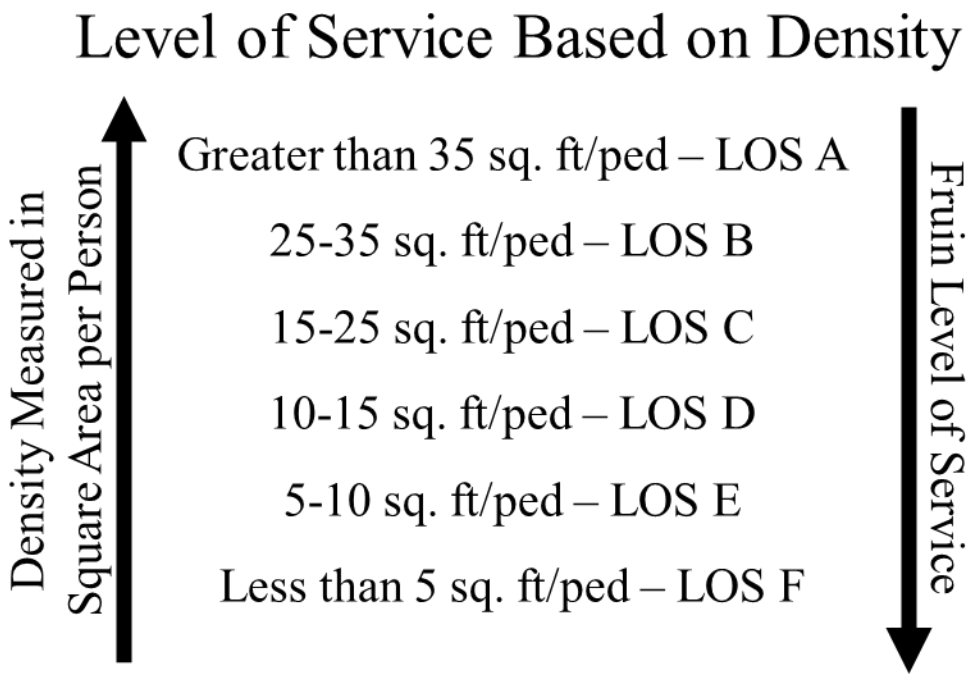


Figure 8.1: John Fruin density examples for different levels of service

This theory has been put into practice for the design of off-street pedestrian and bicycle facilities. This can be found in the Highway Capacity Manual provided by the Transportation Research Board (Transportation Research Board 2016) which defines these facilities as those far enough away from vehicle traffic. This led to design methods using effective width and measuring level-of-service by density. However, it admits that this does not account for accessibility in its measurement. The facilities that were studied

for the manual were those in laterally confined pedestrian spaces such as bridges and tunnels.

While the findings from Fruin's research has usefulness today in understanding how people move, the scope of application is acknowledged as limited (Society of Fire Protection Engineers 2019). If people are moving differently depending on age, culture, location, destination, and accessibility needs then these factors need to be collected and understood. Further, a study on the use of macroscopic versus microscopic pedestrian modelling exposes the limitations of the Fruin profile or other studies of aggregated movement (Teknomo 2006). The study points out that this macroscopic approach limits itself to suggesting that only allocating more space is the solution to improving flow. In contrast, modern technology allows for a microscopic level of modelling person movement behaviours and can be used to show that pedestrian flow can be improved through design of the space already available. This means using the Fruin levels of service as a comparison point is not fully applicable to microscopic models of individual speeds and is not included in this report, to avoid making comparisons without a proper framework of measurement.

The research presented in this section of the thesis is similar to a previous study published in 1999 (S. B. Young 1999). This older paper looked at the behaviours of people at the San Francisco International Airport and Cleveland Hopkins International Airport on and off moving walkways. They found the free-flow speeds to match that of

Fruin. This study, however, found no differences between demographic groups, which does not agree with other studies found, discussed next.

Other efforts known to the author to investigate pedestrian flow characteristics and create a speed profile include efforts from North America, London, Singapore, and Hong Kong, and Israel. North American research looked at finding information for sidewalk design and pedestrian walking speeds by investigating flow characteristics on walkways at the University of Missouri campus (Navin and Wheeler 1969). Another compared their findings of flow characteristics in central business districts between Canada and Sri Lanka finding those in Canada to move faster than in Sri Lanka (Morrall, Ratnayake and Seneviratne 1991). Additionally, the movements of pedestrians were looked at to be used in route choice behaviour (Seneviratne and Morrall 1985). The London efforts analyzed the speed-density relationships for the London underground stations focusing on pedestrian passageways, stairs, and platforms to renew design parameters (Daly, McGrath and Annesley 1991). Other London findings included looking at the pedestrian flow characteristics for shopping streets (Older 1968). Singapore findings used a set length of sidewalk to analyse pedestrian movements and collect speeds, they found people in Singapore move slower than in America but had a higher peak flow rate (Tanaboriboon, Hwa and Chor 1986). Research in Hong Kong collected pedestrian speed-flow relationships for the main facilities found in underground stations (Lam and Cheung 2000). Finally, the study in Israel looked at movements on sidewalks from video tape recordings and a digital clock and used a three-part piecewise linear fit model to

describe the speed-density relationship (Polus, Schofer and Ushpiz 1983). These data sets, though, are dated and may not consider the modern factors of this study's focus of luggage and moving walkways.

To address the dated data, more modern studies have been conducted to begin calibrating and validating pedestrian movement models. One such study looked at pedestrian movement at multiple locations that included London, Hong Kong, New York, Monaco, and Leeds using data collected from video cameras (Berrou, et al. 2005). They suggested that their findings show that there is not a straightforward flow-density relationship. The data, though, was collected at locations serving pedestrians at rail transit stations, ports, a shopping district, and outside a stadium. Another study looked at an observed phenomenon of capacity drop due to flow exceeding critical density for model optimization (Cepolina 2009). Experiments were completed at the University College London using volunteers between the ages of 20 and 30 years old, though, which means the results lack the influence of traveller behaviour due to being in a particular environment. The experiments also relied on telling the volunteers how fast to move or using individuals among the volunteers to try to influence other's behaviour. Further, a study looked at extending the capabilities of a pedestrian flow model to include a person's response to visual information (Wang, et al. 2014). This was tested against observations for pedestrians in a shopping mall in Hong Kong, though, which may be biased towards pedestrians more interested in reacting and changing their actions than in

a transportation facility. All these found studies lack looking at the behaviours of people at airports or in corridors.

Further in the collection of data are more studies of pedestrian behaviours within buildings. Of the types of buildings considered by contemporary researchers to date (Care homes, hospitals (A. Rahouti, et al. 2020) (Folk, et al. 2020), Cultural Centres (Gales and Champagne 2022), Stadia (Larsson, et al. 2020) (Young, et al. 2021) (Chin, Young, et al. 2022) (Chin, Young, et al. 2022), and office occupancy (A. Rahouti, et al. 2021) etc.) all have shown that previous guidance of movement speed and behavior is not reflective of contemporary demographics. In the above-mentioned studies, modelling validation exercises were completed.

The first of the hospital studies (A. Rahouti, et al. 2020) looked at pre-evacuation times, evacuee horizontal travel speeds, exit selection, and total evacuation times over two unannounced fire drills at a public hospital in Auckland, New Zealand. Pre-evacuation times ranged from 8 to 63 seconds for patients and 8 to 141 seconds for staff. Staff not helping patients and patients without movement impairments walked at a similar speed of 1.06 and 0.93 m/s respectively. However, patients with impairments that needed staff to help them walked at a speed of 0.52 m/s. The second hospital study (Folk, et al. 2020) examined nine fire drills at six Canadian long-term care homes and observed the evacuation behaviours of 37 staff members and 56 residents. This study found 72% of residents required full assistance at all stages for evacuation. These show in these areas travel speeds can be highly affected by mobility and the need to assist others.

Looking at stadia, it was found that weather can have a measurable effect on velocities, flows and densities of crowd (Larsson, et al. 2020). Flowrates observed at a large stadium in the UK found that they were below 60 people/m*min, which is lower than the maximum value of 82 people/m*min recommended in the 2018 Guide to Safety and Sports Grounds. Further, stadia in Canada and third-party video for other stadiums found that egress behaviours differ depending on the level of urgency (Young, et al. 2021). Gate densities were found to be higher by a factor of 1.5 for high motivation egress. This study also found that staff play a critical role in reducing or extending premovement regardless of the level of urgency.

Further stadia work was done for data collection (Chin, Young, et al. 2022) and validation of egress modelling (Chin, Young, et al. 2022) of a Canadian study. Demographic distribution, pedestrian speed, route choice, and areas of congestion were studied using cameras. The collected data found that the variance in individual walking speed impacted the overall egress time. A numerical model space was built to simulate the behaviours and showed that using the real-world data was able to improve the model's accuracy.

Finally, to better understand evacuees' behaviour during an unannounced fire drill data was collected from two buildings located at CERN, Switzerland (A. Rahouti, et al. 2021). In this study, 142 pre-evacuation time measurements, 121 evacuee walking speeds on staircases, and 336 evacuee walking speeds on floors were collected. The pre-evacuation times found were lower compared to existing data and speeds in corridors were

comparable to previous studies. However, walking speeds on descending stairways were higher than previous studies.

Those studies (A. Rahouti, et al. 2020) (Folk, et al. 2020) (Gales and Champagne 2022) (Larsson, et al. 2020) (Young, et al. 2021) (Chin, Young, et al. 2022) (A. Rahouti, et al. 2021) have indicated that there are pronounced differences in movement in different building types as well. In addition, these recent studies are not inclusive of all infrastructure types where some have not received much research attention. To date, airports, which require the use of pedestrian modelling for planning purposes (passenger pick up etc.), in emergency evacuation, high motivation, and non-emergency conditions, have not seen a modern public study that any practitioner can draw upon for movement speeds to date. Existing analyses are over twenty years old (S. B. Young 1999) and contemporary discussions are either lab based and do not necessarily capture the stimuli found in a real airport setting or are policy centered (Bateman and Majumbar 2020). It is essential that this infrastructure type be studied.

Movement characteristics of their demographics must be compared to archival movement data and contextualized for their associated uncertainties in various egress scenarios or for future pedestrian planning (passenger pick up for example). This is to ensure that contemporary design for pedestrian movement in airports is considered conservative and wholistic of the expected behaviours seen in this setting.

How we expect people to move in our built environment and the travel time between destinations can change how we design these spaces. Airport transportation terminals are an important consideration as they are constantly in use by many people who are using the space to connect between two different modes of transportation and often for the first time. This can lead to a different level of familiarity of the space compared to spaces such as bus or subway terminals which instead may be used daily in a work commute and affect people's knowledge of the time it takes to progress through the area (National Fire Protection Association 2021). Missing a flight can also have a larger delay and financial cost to an individual than a flight. Familiarity with a space or an emergency event and their original reason for being in the space can cause different behaviours in people, such as ownership or perceived safety (Knuth, et al. 2014). Large airports can also serve levels of traffic comparable to downtown sections of cities. An older study of behaviours at an airport found that the issues airports were facing were delays in service focused around not being able to service levels during holidays or from the introduction of higher capacity airplanes (Ashford, et al. 1976). However, that study and others looking at airport pedestrian behaviours (Kalakou and Moura 2015) were limited in looking at the decision of activities of pedestrians over their movement behaviours. Further, other studies found on pedestrian movements used techniques calibrated for vehicle movements in their analysis for tunnels (Virkler and Elayadath 1994).

In Airports, movement may be further complicated and require additional detailing as they feature a variety of unique features such as moving walkways and corridor systems.

Moving walkways are being looked at for further development in these spaces, and others, for achieving higher flow rates through updated acceleration technology (Scarinci, et al. 2017). This is intended to solve congestion issues, service larger volumes without the need for larger spaces, or make walking more attractive. They are also being looked at to be used in areas of increased length to serve larger transportation gaps with attractive speeds from the acceleration technology and compete with other forms of short-range transportation (Kusumaningtyas and Lodewijks 2008). These facilities and their advancements are being seen as useful solutions to transportation issues, but without a proper understanding of how people currently move on them.

Corridors, the other feature, pose a variety of fire safety concerns. By nature, they lack escape options, are commonly sloped, underground, and serve pedestrian traffic or require a walkable route to safety in the case of emergencies. This leads to smoke being able to cut people off from safety and can confuse people of the route to safety; going down a corridor slope deeper underground or climbing up stairs to safety during a fire may not be recognized by the general public as the proper course of action. The ability to adjust their design after construction is also limited; widening a corridor to provide a larger service capacity is often not financially feasible.

This calls for needing to understand how people move within them to promote better use of space. The information that can be found on pedestrian movement within corridors, though, is limited. Studies found include volunteers navigating a simulated emergency scenario of a vehicle tunnel with different levels of artificial smoke (Porzycki, Schmidt-

Polonczyk and Was 2018) or investigations of crowd crushing situations (Ma, et al. 2013). For the study of movement with different levels of smoke, the people involved had to navigate out of a bus to safety through the smoke. The same people though, were used for each smoke level and looks at the behaviours of people transitioning from passengers to escaping on foot within an environment designed for vehicles. The crowd crushing study was a review of footage from the Love Parade disaster. This disaster occurred at the T-Junction meeting point of a 20 m tunnel and the ramp to access the event. That study shows the critical situations that can occur around tunnels; however, it was not a study of the movements within the tunnel but instead looked at modelling the movements of dense crowds. Both tunnel studies, though, looked at specific cases and not during regular movement. Corridors need to be understood closely for their safety concerns but there is a lack of data of the regular movements of people through pedestrian corridors. For these reasons corridors are a topic of fire safety and the modelling of pedestrian behaviours within them are of need.

The individual movement profiles of pedestrians in airport and corridor environments for use in microscopic applications are important to the progress of fire safety research and pedestrian modelling and more specific data are required to make informed decisions of our future developments. This study aims to examine the use of pedestrian modelling software and progress its ability to adapt to dynamic changes in agent movement behaviour depending on facility use. The facility in question for the study was movement on moving walkways within a landside airport underground corridor. Moving walkways

are a main feature of the airport corridor at the study location. Pedestrian behaviours in corridors are a topic of interest to emergency evacuation such as fire as they present an environment of limited escape options and visibility within the corridor can suffer quickly in the event of smoke. These behaviors are also important to quantify as the infrastructure ages and is subjected to increased demand where day-to-day safety and efficacy are needed to be ensured.

This thesis addresses the area of everyday use of the corridor though with the focus being on the human behaviours related to overall travel time when not interrupted by a safety event. The direct application of the results will be discussed as it relates to how it can be used to better understand how people move regularly through the corridor and on the people movers. The modelling work is also focused on improving the ability to model more aspects of human behaviour in a general use-case for the corridor.

8.2 Motivation

This work herein is in collaboration with research to collect and present a more complete data source for human movement behaviours, which has completed research on movement for stadiums, railway stations, museums, and care homes but not for airports (Gales, Ferri, et al. 2020). These efforts of this study hope to further the scope of knowledge that is available on pedestrian movement and how to integrate this into a model space so the influencing factors as to why people may move differently can be understood.

The study aims to examine the development of people movement data for airports through use of innovative kinematic tracking algorithms. Movement with luggage and demographics will be examined. The subsequent use of pedestrian modelling software for verification and parametric analysis of expected circulation egress scenarios will follow. The modelling herein will be adapted through software development kits to adapt to dynamic changes in agent movement behavior depending on barrier and technology features of contemporary airports. This discussion however will not focus only on one pedestrian modelling package but generalize algorithm steps for incorporation in any. A future research roadmap will be discussed with emphasis on the motivation stimuli for evacuation and associated uncertainty of data in various egress scenarios. Airport planning will also be discussed. The following sections will also provide consideration for the difficult to study the nature of these structures, involved ethics, and attention to the data's use and function in the future of airports given that these infrastructure types are undergoing critical changes in the next few years.

To accomplish these goals of the study, two main topics were covered. The first of these topics involved the people movement data collection and analysis of an inter-city North American Airport. Data for the study was collected on site from video recordings over the winter of 2019 at the landside portion of the airport. This data was then analyzed to collect two results: the spot speeds of each demographic (separated by luggage type) and the average total travel time from arrival in the corridor to exit on the other end. Data collection and analysis was done in preparation for the second part of the study:

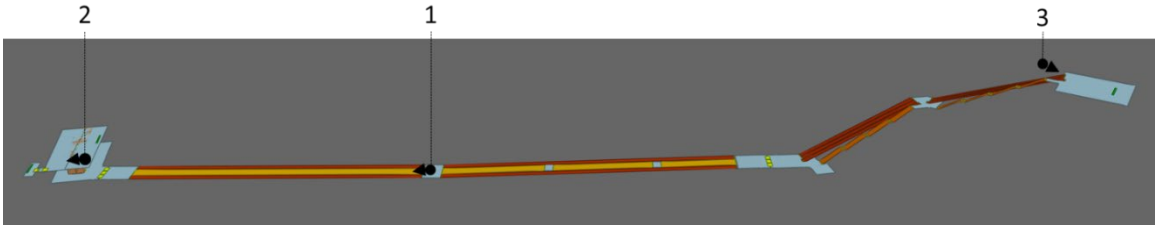
expanding the capabilities of pedestrian models for facilities found at the airport. These topics will be discussed as they relate to fire safety and pedestrian behaviours in general.

The connection of the pedestrian behaviours and its impact to the airport is the focus though. This work connects the traveller's journey between the airport entrance and the airport security. It helps give a more complete view of the traveller's experience while at the airport and the ability to design to improve that experience.

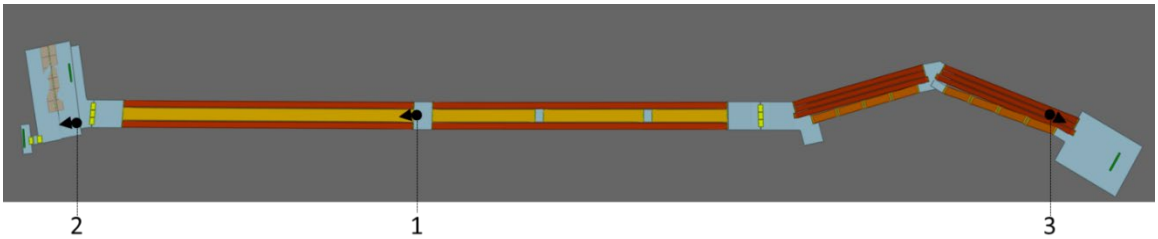
8.3 Data Collection Methodology

The location of study for this report is an inter-city North American airport, with focus on the pedestrian access corridor on the landside. The other portions of the airport were not accessible at the time of the study. This access corridor has many features of interest making it an optimal for a movement study. In consultation with the airport authority, the authors were permitted existing footage taken over the course of three days from the landside terminal to utilize. The regional authority holds control over the landside area of the airport, which includes the curbside drop-off and pick-up, shuttle bus stop, corridor access, and the corridor itself. Their control up to the airport ends at the end of the corridor. Following this a mutual agreement to not disclose the airport location or specific features was agreed upon, and ethics protocols from the authority and university department holding the research grant governed the data collection protocol of the study herein.

A Sketchup model based on design drawings provided to the researchers by the authority of the landside airport was built. Particularly this features a corridor system for the predominate length of the terminal side. This was then migrated into the pedestrian movement software as can be seen in Figure 8.2 below for later model verification. As drawings were provided and verified to be built to scale a full dimensional survey of the resulting space was not required by the authors.



(a)



(b)

Figure 8.2: (a) Profile layout of corridor (b) Floorplan layout of corridor

(Camera locations 1, 2, and 3 are shown)

Video surveillance from permanent security cameras was collected from the corridor to provide a full and accurate source of data of pedestrian movement. Videos were provided

to the research team in consultation with the authority. Optimal positioning of the video feeds were discussed to focus on angles which illustrated movement through the corridor space from start to end. A total of three cameras were used for the purposes of collecting the data used in the corridor portion of the study, while footage from more cameras were also available in specific cases where occupants were difficult to fully resolve in their movement path. Camera locations can be found in Figure 8.2 above. All cameras were mounted on the ceiling angled down to see the pedestrian movements. Footage from camera 1, used to calculated speeds as explained later in this section, had a resolution of 2592x1944 px at 12 frames per second. The two cameras at each end of the corridor, cameras 2 and 3, had a resolution of 1920x1080 px. Behavioral data should be noted to not incorporate characteristics of emergency evacuation though elements of high motivation evacuation stimuli are considered inherent in the data captured (see (Young, et al. 2021)) therefore the data will be subjected to limitation and uncertainty as will be discussed in Section 8.5.

Volumes and speeds were collected primarily from footage during the peak hour, showing the highest level of activity at the curbside, for the airport. The peak hour was chosen as the speeds and densities should represent some of the more critical cases of these environments. Peak hour was determined through consultation with the authority. The day that the footage was taken from was chosen by the airport authority based on maximum air traffic levels to ensure the data collected represented peak conditions. Since the footage from a day is saved and can be chosen after the traffic levels are confirmed

the data is known to represent true peak conditions in comparison to footage from other days. This was verified for the study.

Collection of the speeds themselves was done using a video image tracking software. This software called Kinovea, shown in Figure 8.3 below, is a freeware, open-source sports kinematics software. The image provided for Kinovea is from work done studying a heritage cultural centre in which validation of Kinovea is presented therein (J. Gales, R. Champagne, et al. 2022). Due to maintaining confidentiality of the airport, footage of Kinovea applied to the airport corridor is not provided. In regular use, Kinovea can track user-specified objects in video footage, in this case each person's head. The positions in the footage are converted into distances by using a measured grid imposed onto the footage. However, Kinovea in its default state could not directly provide average speeds for an entire population, nor could it adapt to the occasional duplicate frames observed in low-framerate CCTV Video. Instead, the data collected from Kinovea was exported to be post-processed using custom excel VBA scripts to determine average speeds over the course of tracking, while also detecting and accommodating frame duplicates from the camera footage. The developed script also sorts and categorizes the final average speeds based on the names manually given to the tracked objects within Kinovea. By using the frame rate of the footage and the recorded positions the travel speed of each targeted individual was calculated as a function of distance over time at each frame as an instantaneous speed. The final travel speed for each person was then calculated as the average of these instantaneous speeds. Travel speeds were collected for different

demographics, classified by luggage, of pedestrians in the corridor. The travel speeds were also separated depending on if they used the moving walkways or walked on the ramp and by direction, airport departures or arrivals, in the corridor. The grouping of these speeds together for a demographic average was also done during the post-processing in excel. This provided speed profiles by demographic, using the moving walkway or the ramp, and if they were walking up (departures) or down (arrivals) the incline. An assorted sample number of each demographic were collected for the spot speeds of each demographic as available based on being present. Of note the software has specific limitation in that it can only track unimpeded speeds therefore group behaviour was not a focus of this study but is being considered in future research.

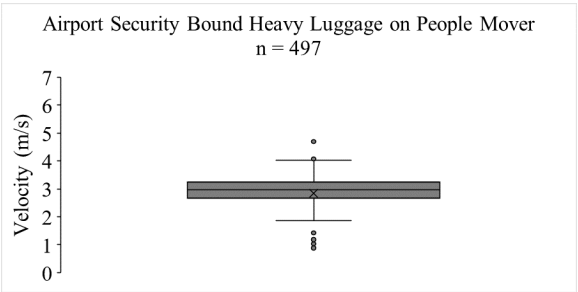
Figure 8.3: Kinovea tracking person movement with surveyed grid (J. Gales, R. Champagne, et al. 2022) (T. Young 2022)

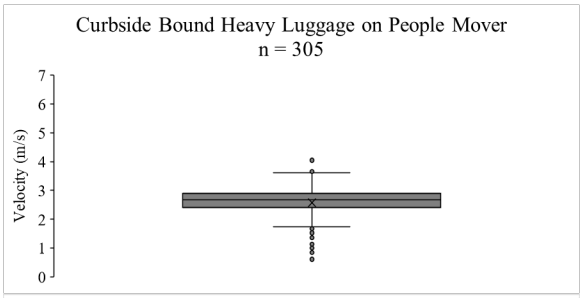
To measure the overall travel time in the corridor people were tracked over footage from cameras at each end of the corridor (cameras 2 and 3). These cameras were located at the surface entrance before the elevators on one end of the corridor and at the top of the escalators at the other end. This data was collected more simply than the spot speeds by noting the time stamp on the footage for when each person crossed a checkpoint at either end. People had to be tracked manually by visual inspection for this data collection. A sample of 128 people arriving at the airport during the peak hour were analyzed for this portion of the study. The sample size was limited to this number as persons had to be

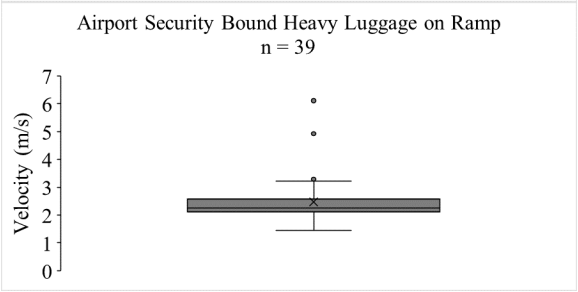
confidently matched between footage if their times were to be used and representative of unimpeded flow. Footage at each end of the corridor showed persons from different angles so not every person could be matched. Of note, this sample was collected for only one direction in the corridor, that of departing airport passengers, and is a mix of all demographics. There were not enough matching people between the two points seen for those in the other direction to create profiles.

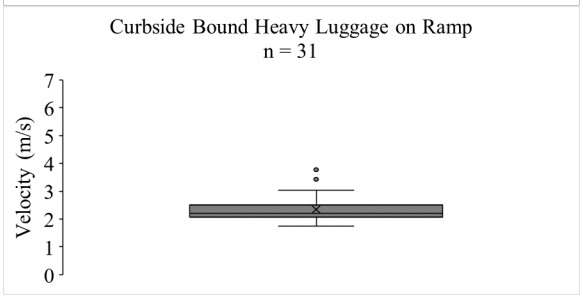
8.4 Data Collection Results

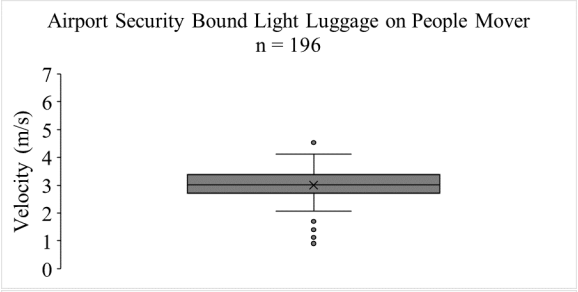
Analysis of the video footage resulted in the movement speed profiles presented in Figure 8.4 below. Sample sizes for each demographic are included in each graph, samples of less than 50 should be regarded only as pointing towards potential profiles. While there is no set threshold of samples for obtaining a statistically significant estimation of speed, this number has been chosen to warn against using profiles with less confidence from the study. The reason for collecting this data is to improve our understandings over other profiles and relying on low sample size profiles would contradict the efforts of this research. Looking at the profiles with enough samples, these movement profiles show that speeds within this area of the corridor are higher than expected compared to traditional values. It can also be seen that luggage type and facility use has a noticeable effect on the movement speed observed. Movement speed for the speeds of those on the moving walkways includes the tread speed of the moving walkway, approximately 0.7 m/s.

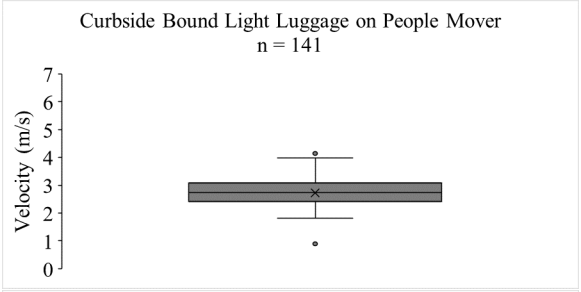

Airport Security Bound Heavy Luggage on People Mover
n = 497
Velocity (m/s)
0
1
2
3
4
5
6
7

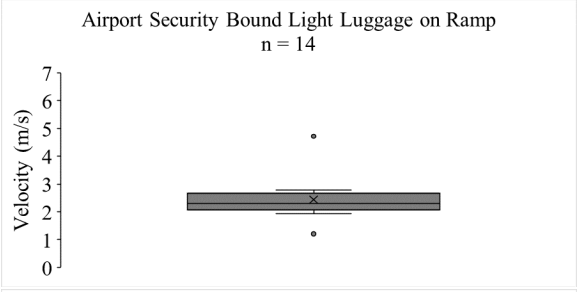

Curbside Bound Heavy Luggage on People Mover
n = 305
Velocity (m/s)
0
1
2
3
4
5
6
7

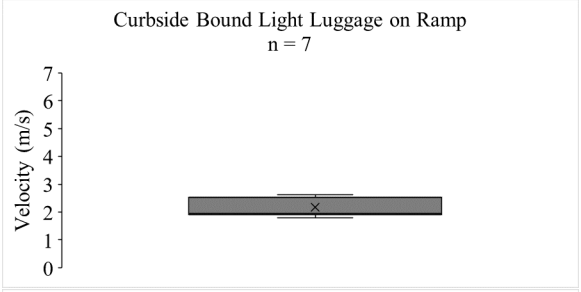

Airport Security Bound Heavy Luggage on Ramp
n = 39
Velocity (m/s)
0
1
2
3
4
5
6
7

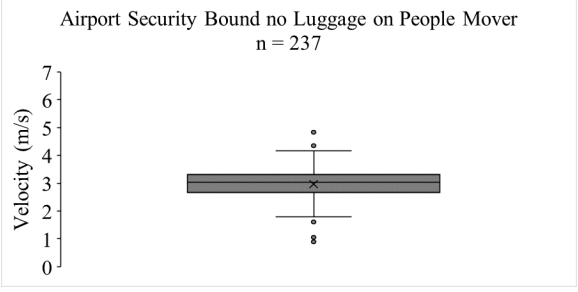

Curbside Bound Heavy Luggage on Ramp
n = 31
Velocity (m/s)
0
1
2
3
4
5
6
7

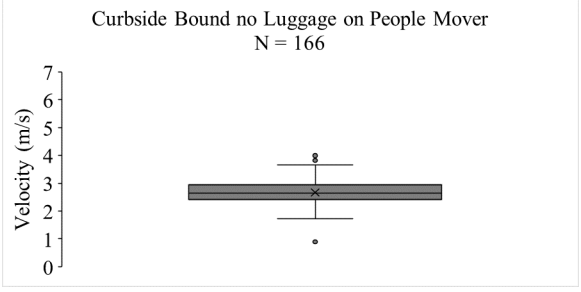

Airport Security Bound Light Luggage on People Mover
n = 196
Velocity (m/s)
0
1
2
3
4
5
6
7


Curbside Bound Light Luggage on People Mover
n = 141
Velocity (m/s)
0
1
2
3
4
5
6
7


Airport Security Bound Light Luggage on Ramp
n = 14
Velocity (m/s)
0
1
2
3
4
5
6
7


Curbside Bound Light Luggage on Ramp
n = 7
Velocity (m/s)
0
1
2
3
4
5
6
7


Airport Security Bound no Luggage on People Mover
n = 237
Velocity (m/s)
0
1
2
3
4
5
6
7


Curbside Bound no Luggage on People Mover
N = 166
Velocity (m/s)
0
1
2
3
4
5
6
7

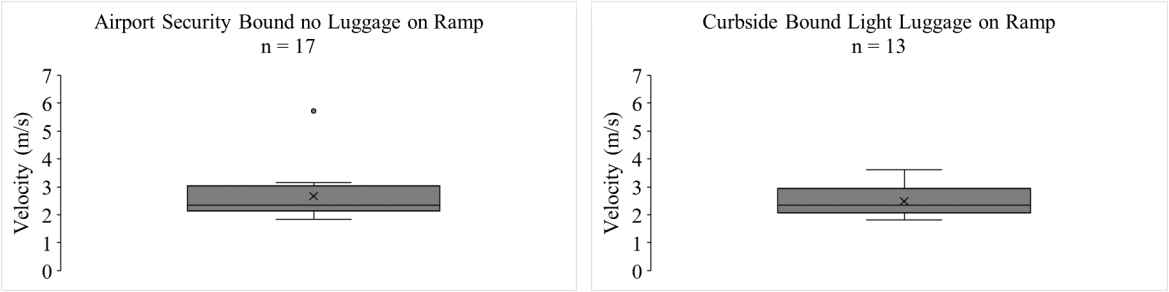
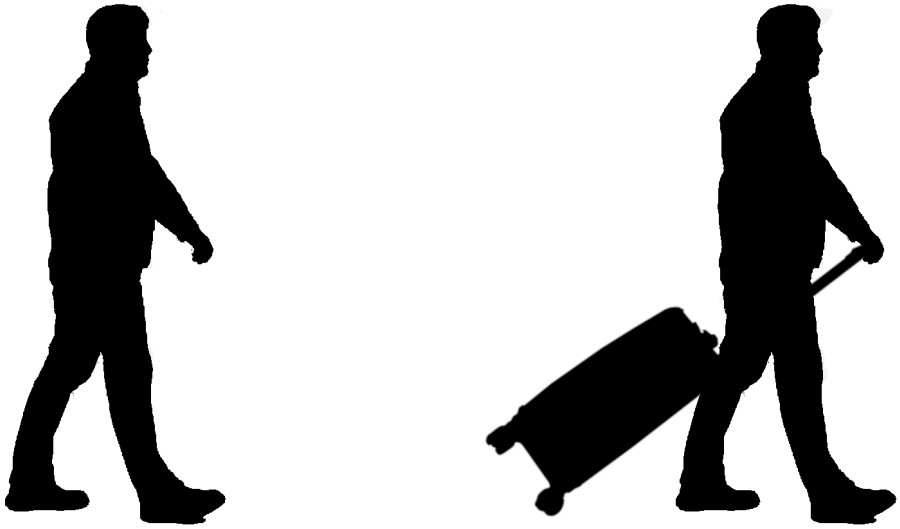


Figure 8.4: Speed profiles for each demographic

Speeds from the above figures used for direct comparison in the study are presented in Table 8.1 and Table 8.2 below, these numbers include the tread speed. These speeds and standard deviations were used in the custom code to create the new movement profiles for use in the different scenarios. The average travel time for all demographics through the corridor is presented in Table 8.3 below and for comparison to the results found from the model scenarios. Sample size comparison for the Roller Luggage to No Luggage profiles is due to a larger number of people travelling through the corridor with roller luggage; the differences in sample size for other speed vary for the same reason. Figure 8.5 below shows a profile silhouette of each demographic for clearer understanding.



(a) No Luggage (b) Roller Luggage

Figure 8.5: Graphic of demographics

The average spot speeds were tested against the null hypothesis that they are the same speed using a t-test analysis. Analysis found a T-Value of -0.0899 with 572 Degrees of Freedom resulting in failing to reject the null hypothesis. This concludes that there is no statistical difference in the walking speeds of people with or without roller luggage when amalgamating all times.

$$T - Value = \frac{mean1 - mean2}{\sqrt{(\frac{var1}{n1} + \frac{var2}{n2})}}$$

Null Hypothesis: They are different speeds.

T-Value: -0.0899, Degrees of Freedom: 572

Conclusion: No statistical difference between speeds

Table 8.1: Peak Hour vs Off Peak Speeds

Demographic		Average Spot Speed (m/s)	Standard Deviation	Sample Size
Peak hour	Roller luggage	2.96	0.64	257
	No Luggage	2.97	0.60	117
Off Peak	Roller luggage	2.73	0.67	240
	No Luggage	2.98	0.58	120

The average spot speeds of passengers with roller luggage were tested against the null hypothesis that they are the same speed between the peak hour and off peak using a t-test analysis. Analysis found a T-Value of -3.93 with 90.7 Degrees of Freedom resulting in rejecting the null hypothesis concluding that there is a statistical difference between the speeds of passengers with roller luggage on and off-peak hour.

$$T - Value = \frac{mean1 - mean2}{\sqrt{(\frac{var1}{n1} + \frac{var2}{n2})}}$$

Null Hypothesis: Different speeds between times of day

T-Value: -3.93, Degrees of Freedom: 90.7

Conclusion: Statistical significance that they are different speeds.

Passengers with no luggage were found to have the same speed on and off the peak hour with no need to conduct a statistical analysis.

Table 8.2: Observed aggregate spot speeds on moving walkway

Demographic	Average Spot Speed (m/s)	Standard Deviation	Sample Size
Roller luggage	2.85	0.66	497
No Luggage	2.97	0.59	237

Table 8.3: Observed Travel Time

Actual Travel Time	Standard Deviation	Sample Size
5:22	0:40	128

These speeds, with consideration of the speed of the treads, are faster than those seen by Fruin and others. The speed given by Fruin was 265 ft/minute (1.35 m/s) for 1000 non-baggage-carrying pedestrians (Fruin 1971). This is noticeably slower than what is seen for the airport corridor. The study that looked at the speeds crossing intersections, though, found an average speed of 1.63 m/s across all intersection sites and 1.42 m/s at mid-block sites (Bennett, Felton and Akcelik 2001). While these speeds are still lower than what is seen at the study corridor, it shows that observed speeds can vary between similar activities. Both locations were looking at people crossing a street; however, they showed a difference in speed of 0.21 m/s.

8.5 Data Collection Discussion

The movement data was not collected in an emergency situation so there are limitations and contextualization to how the data may be used outside of standard use of the corridor. Pedestrian behaviors in corridors are a topic of interest to emergency evacuation such as fire as they present an environment of limited escape options and visibility within the corridor can suffer quickly in the event of smoke. The application of this data and its uncertainty in specific scenarios will be discussed in the context of similar corridor structures in airports in general.

This data collection can be improved upon by further efforts that would result in a better model and movement profiles. This would include collecting spot speeds at multiple points throughout the corridor and a measurement and locations of delay in movement through the corridor. This would provide a better speed profile to be used for the travel times to better match that of the observed case. Specific cases where behaviours may change due to the density of people should also be looked at for future need to calibrate the agent behaviours in the model. Profiles from other airports and corridor facilities are also needed so the results can be compared. This will inform us if the movements found are unique to each airport or corridor facility or if these behaviours are seen in multiple locations.

These efforts lead towards developing a clear and usable data for developing movement models for the full airport scene. Understanding how people move within the corridor

will allow the research to compliment the further studies for the airport. This includes the pedestrian and vehicle use of the landside curb space at the entrance to the corridor. Further research is planned to analyze the movements and utilization of the curb space. This includes analyzing arrival patterns, mode share, waiting times, and the impacts of future developments which can then be combined with the research that was presented herein to produce an understanding of the movements at the airport from arrival mode up to security at the airport.

Additional data about the movement characteristics of the people using the corridor were collected and have been presented in Table 8.4 below. These characteristics were not used for the construction of the model, instead, this data is presented to provide clarification of the use characteristics. The classification of proportion of males presented in the table should be interpreted as outward appearing physical features that were able to be identified from the camera angle. This included facial hair and build. Clothing had an influence as winter wear covered some identifying features, thus correlation of fashion choice to others identified as masculine presenting was used. This is a binary classification for physical characteristics and should not be used to define the use of airports by sex or gender. This analysis should be repeated by multiple investigators to confirm the masculine identification.

Table 8.4: Additional Movement Characteristics

Additional Data	Percent	Sample Size
People Using the Moving Walkway	93%	1665
Passing on the Left	81%	67
Proportion of Males[1]	65%	193

People headed towards the airport were also observed to be travelling slightly faster during busier times while those travelling away from the airport did not show evidence of travelling faster during busier times. This was tested against a 95% confidence interval. Testing for this difference in the model was outside of the scope of the project so the results of these tests have not been included.

8.6 Modelling Methodology

Considering the layout of the corridor itself in the terminal, the entrance at the curbside is through elevators with the nearby stair (use not captured in study) access being marked for emergencies. On the airport security side there are escalators, stairs, and elevators; the escalators are the main access into and out of the corridor utilized on this side and service a depth of 26.8 m, split between two landings making for two flights of 13.4 m depth each. The whole corridor is also on two separate inclines, 0.573 and 2.29 degrees (1% and 4%), which add to the complexity of the study as behavior would have to be considered on slight grade as opposed to complete level surface. These grades run a

[1] Masculine Presenting

length of 76.43 m and 76.375 m, respectively, with a 3.7 m landing between them. The total width of the corridor is 7.6 m wide. Throughout the corridor proper running the lengths of the grades there are moving walkways, which are 2.1 m wide including railings, and are a primary focus of the research done for this study as they are utilized significantly more than the adjacent floor space, referred to as the ramps later, and found in likewise infrastructure globally. Pedestrians move differently on these moving walkways from other areas of the corridor and this difference in behaviour needs to be understood so it can be properly accounted for and modelled.

It has been assumed that pedestrian movement within the corridor is unique compared to the regular walking environment considered for pedestrians, such as a sidewalk. A person may behave and move differently at a transportation terminal from on the sidewalk, at the park, or in their own home. Studies looking at the movement behaviours of people have found that they change when moving around corners (Dias, et al. 2019) and even show different speed profiles if crossing streets at signalized intersections compared to mid-block crosswalks (Bennett, Felton and Akcelik 2001). Each area may have its own movement patterns and, more importantly for this study, movement speeds; for this reason, existing movement profiles cannot be fully relied upon. While the comparison of movement speeds between different environments is outside the scope of this study, it is a large factor to the motivation behind why the data was collected at the airport itself and why the speed profiles of people within the corridor were generated.

Once the data had been collected this work was brought into the working model of the corridor space. This model was built to run simulations for general movement in the corridor and has not been built specifically for emergency egress purposes. The modelling software used for this study was MassMotion 10.6 (Oasys 2022). MassMotion uses a social forces model to simulate agent movement behaviour. Each agent is always pulled towards their goal by this force to accelerate to their maximum desired speed regardless of circumstances around them. To simulate reactions to changes that would keep a person from travelling at their desired speed in the real world MassMotion introduces opposing forces from obstacles or other modelled pedestrians. Pedestrians within the model are given a 0.25 m radius and as the edges of their radiuses near the force they push against each other increase. Obstacles and walls also exhibit a force on the agents in a similar manner. This results in a net force vector on an agent causing acceleration in that direction. As a result of this framework, the social forces model, as used by MassMotion, assumes that all pedestrians, while unimpeded, will travel at their maximum desired speed for the whole trip. Without any obstacles or other pedestrians their speed will remain constant and the path taken will remain direct and close to the most optimal. This is not always reflective of the real world. However, MassMotion is a state-of-the-art modelling software being used for other research making its use in this research a valid choice for comparison with the current standard for pedestrian modelling.

Considering this, MassMotion has many capabilities of modelling pedestrian spaces and was able to be modified to accept the new movement behaviours as observed in the footage. In the context of this study other pedestrian movement software could be used as the focus herein is more verification as opposed to validation with the approach generally applicable to any package. Within the model, the escalators, doors, and elevators in the corridor are all features supported by MassMotion and were left as default for this study. The moving walkways were originally coded as escalators; however, for this modelling case the behaviours of the people on the moving walkways needed to be added to the software's capabilities since this had not been an option available previously from the software. This meant giving the software the ability to determine when an agent was on a moving walkway compared to other parts of the model and, if so, giving them a new movement profile to use. This dynamic assignment of movement profiles for agents in the model was used to allow agents to act differently depending on if they were walking on floor space as supposed to the moving walkways.

The code written to support the MassMotion model is built to run at all times during the simulation. Each simulation time step the code checks the location of every agent within the model. If an agent is found to not be on a people mover it gives control of the agent to the base code of MassMotion and the agent's movement follows the behaviours as if the code was not present. However, if an agent is found to be on a people mover then the code assumes control of the agent's movement. The agent is then checked to see if it has been assigned a movement speed to use while on the people movers. This is done by

checking the agent's unique tag against all the stored tags of previously encountered agents. The first time an agent steps on a people mover it will always not find a speed to use. The code will then create a speed from a random distribution built from the observed walking speeds on the people movers. This speed, along with the agent's tag is then stored for all next simulation time steps that the agent is found on a people mover. By doing this, all agents are assigned a random desired walking speed while on the people mover that is different from each other.

Once the desired speed of the agent on the people mover has been determined the code then gives it a movement vector to match. This vector is created in the direction of flow of the people mover and adds on the linear speed of the people mover treads itself. By adding on the speed of the people mover treads at this stage, it allows the agent to have a base desired speed of 0 m/s, representing travellers who do not walk while on the people movers. The vector direction also acts as the pulling force towards the agent's goal to be used in the social forces model by MassMotion, explained next.

At this stage the agent needs to react to other agents or obstacles in the model. Control of this behaviour is handed back to MassMotion. This allows the code to take advantage of the social forces model structure for the resulting movement vector of the agent. By doing this, agents are able to walk around each other, slow down for those in front of them, or speed up due to others behind while on the people movers.

Since this control is run for every time step once the agent steps off of the people mover it returns to behaving as it did before the code took control. Its desired speed is reset to what it was before and the code stops affecting its movement. This is done as was explained at the start of the code logic, by checking the location of the agent each time step before deciding if the custom code should be used.

An example of the added logic to the MassMotion software can be found in Figure 8.6 below, as shown previously in Section 3.2.2. This logic allowed the agents to behave with reactionary behaviours calibrated by MassMotion while off the moving walkways and still allow for the new movement speed distributions while using the moving walkways.

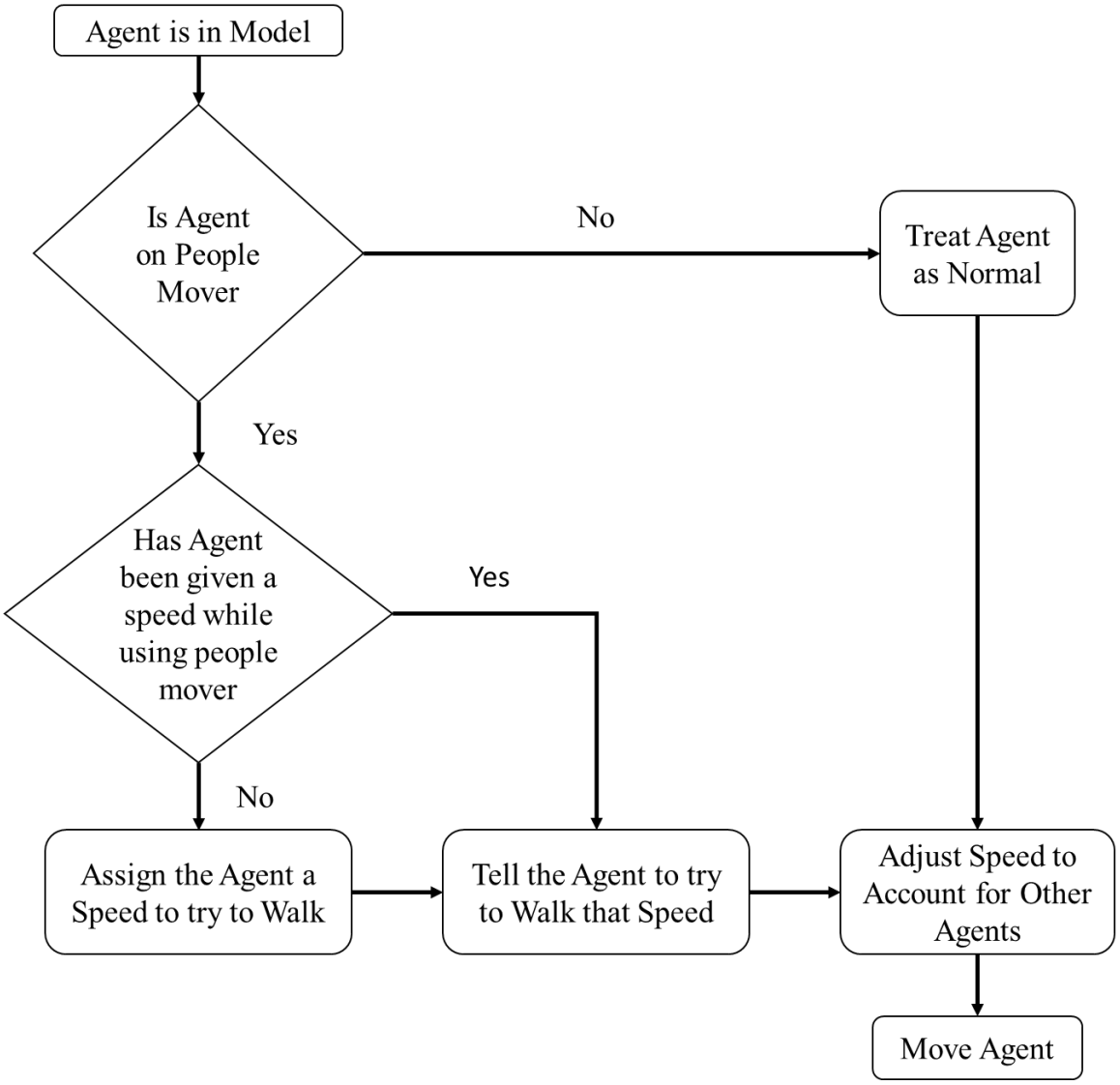


Figure 8.6: Flowchart of person movement speed

While the reactionary behaviours of the agents off the moving walkways was mentioned to already be calibrated, this does not mean that the movement of the agents through the model could be considered calibrated. For this reason, full simulation runs of movement through the whole corridor needed to be run to check the speeds. This was done by

creating a movement scenario of airport departure trips from the top of the elevators to the top of the escalators on the other side of the corridor. The volume of people in scenarios were able to be matched generally to the volume of people arriving at the airport and the speed profile was set to match those found in the spot speed data collection. To test different aspects of model's capabilities the following scenarios were run:

Table 8.5: List of model scenarios

Scenario	Inputs	Duration	Goal
1	Departure Direction 150 people distributed randomly	15 Minutes	To verify model's ability to handle large volumes
2	Departure Direction 200 people distributed throughout and as groups arriving every five minutes Roller luggage only	1 hour	To verify modelled condition of pedestrians with roller luggage at peak hour conditions for the departure direction
3	Departure Direction 200 people distributed throughout and as groups arriving every five minutes No luggage only	1 hour	To verify modelled condition of pedestrians with no luggage peak hour conditions for the departure direction

These three scenarios look to verify the model's ability to handle high flow rates over a short period of time or to compare travel times of demographics when using more realistic levels of demand. Scenario 1, the high-volume scenario, was used to test the model's ability to avoid agents becoming stuck, creating blockages to flow, or showing behaviours that do not fit what was observed in the actual corridor. Scenarios 2 and 3

were built to compare the travel times through the corridor for the two demographics that should have a noticeable difference in travel times.

8.7 Modelling Results

The data collection and analysis were done in preparation for the second part of the study, verification of modelling pedestrian flow in the corridor to interpolate travel time through the airport which has use for future planning – particularly passenger pick up. This required developing custom code for the modelling software, as without it the modelled agents would not be able to treat moving walkways differently than other parts of the model. Which can be an issue for default modelling packages. By implementing this custom code, agents in the model were able to travel with different behaviors depending on if they were moving regularly or using the moving walkways. This included its own distribution of movement speeds based on the standard deviation as collected from the observed behaviors. Results of the modelling showed consistent overall travel times through the corridor with the observed times. Modelled travel time gave an average time of 3:59 minutes and 4:20 minutes for those without luggage and those with roller luggage, respectively. However, as can be seen in the lower travel time for those without luggage, this travel time responded to changes in agent demographics as expected showing that the model can be used to simulate relative differences.

With the information from the speed profile analysis, the scenarios defined in Section 8.6 were run through MassMotion as adjusted by the custom code. The results of the average

travel time found in these scenarios have been presented in Table 8.6. Average travel time and standard deviations were calculated using each agent's total time in the model that completed the full trip before the scenario ended.

Table 8.6: MassMotion results: Total travel time through full corridor length

Total Travel Time			
Scenario	Average Travel Time	Standard Deviation	Comment
1	4:18	0:43	
2	4:36	2:51	
2*	4:20	0:46	*Scenario 2 results with outliers/agents not following realistic movements removed
3	3:59	0:26	

Results of the travel times for the moving walkways themselves were also examined as these were the areas specifically targeted for the study. In this case the travel time was compared to that of the results for a standard run of MassMotion using the default functionality, results can be found in Table 8.7 below. As expected, the default showed all agents spending the same time on the moving walkways and moving at the same speed as they are programmed to stand still and let the moving walkway progress them towards their goal. Those with and without luggage had similar travel times and the results show that the model is producing a deviation in the travel time as seen in the observed condition.

Table 8.7: MassMotion results: Travel Time on People Movers

Travel Time Across People Mover			
Scenario	Average Travel Time	Standard Deviation	Comment
Default	2:00	0	All agents had the same time as movement is static by default
2*	0:40	0:06	*Times over 2:00 were removed as these agents were stuck in the model
3*	0:35	0:11	

Since the length of the corridor is serviced by the people movers this resulted in an incorrect agent grouping that originates at the elevators during the default run. Figure 8.7 below provides an image of the model during a run using the default settings. As can be seen, the agents are moving as distinct groups after descending from the elevator bay because there is no variation in movement while on the people movers. Scenarios 2 and 3 did not suffer from this issue.

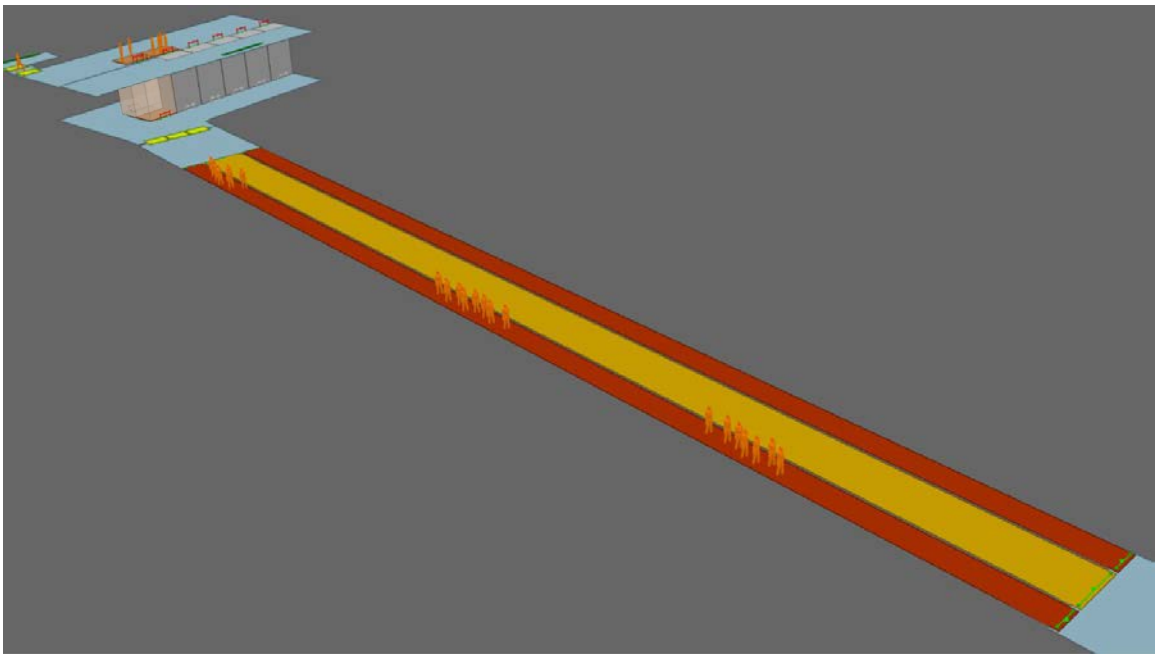


Figure 8.7: Example image of agent grouping

8.8 Modelling Discussion

The total travel times across the corridor length are all faster in the models than that found when measuring the actual travel time through the corridor, as was presented in Table 8.3 in Section 8.4. This difference in total travel time could be from how the data was collected. The data collected for the movement of people were of two categories, spot speeds and total travel time. By using the spot speeds for the desired speeds throughout the corridor in the model this assumes that the speeds are independent of where they are in the corridor. However, as can be seen, it was found during the modelling efforts that the total travel times were shorter than those found by examining the recorded footage. This suggests an assumption that the location of spot speeds is

biased towards an area where speeds are higher than the average travel speed throughout the corridor or that there may be delays of movement that are not being accounted for by the model. However, these differences aside, the model is showing that it responds to different inputs correctly. The scenario modelling people with luggage compared to the scenario of those without luggage showed a noticeable difference in total travel time of 21 seconds (comparing scenario 2* to scenario 3). The model also showed a higher standard deviation in times for those with luggage compared to those without. These differences agree with the slower travel time and higher standard deviation in speeds found for travellers with luggage.

Further, the model was able to be expanded to include agent specific movement speeds while on the people movers instead of assigning all agents the same static speed. The default model behaviour was found to be incorrect when compared to the observed behaviours of travellers on the people movers.

Results broken down by age and sex demographics have not been included. The lack of their presence in the reported data should not be interpreted that these factors are not important for understanding the movement behaviours in this area. The limitations of this study restricted multiple researchers from accessing the video due to confidentiality agreements with the authority. A single viewer introduces subjectivity and a bias to collecting demographics information from video footage. Future research should have the film looked at by multiple researchers to follow the procedures to reduce subjectivity as

defined by (Haidet, et al. 2009). In doing so, a more detailed demographics breakdown can be released with greater confidence.

8.9 Conclusions

The results of this research can be used to understand the implications of human behaviours in the corridor for fire safety and general movements. The data collection shows that movement speeds in this corridor, and potentially other similar areas, are higher than traditional movement speeds. Movement speeds of 2.85 m/s and 2.97 m/s were found for pedestrians with roller luggage and no luggage, respectively, on a moving walkway with a tread speed of approximately 0.7 m/s, inclusive. This, however, does mean the travel times in the corridor could be more sensitive to situations of higher densities.

The research also showed that it is possible to model behaviours dynamically based on transportation features. Agent travel behaviours were able to be adjusted to try to move at different speeds depending on walking on regular floor or the moving walkways and done in a way that each agent had a unique travel behaviour for the regular floor space and moving walkway. While the total travel times in the model scenarios were found to be around one minute faster than the observed 5:22 minute average travel times, expected differences between scenarios were observed to reflect the expected outcome by showing a 21 second difference in travel time between the two demographics. Getting the average travel times of the model to match that of the observed times is an effort of validating the

whole of MassMotion which is outside the scope of this study. This study aimed instead to verify that the capabilities of the model could be improved to reflect a change in travel time due to change in demographic and use of the moving walkways as the goal was to show general modelling framework capabilities over that of just MassMotion. This means the method of dynamic behaviour assignment in models can be used to give answers as to how the travel time should be expected to change if features of the corridor, or other areas of interest, are changed or if the demographic of users shifts.

In the context of the whole airport, while 21 seconds is not a large difference when comparing to the total travel time of the corridor, these same 21 seconds can have a large effect on the curbside where cars only spend an average of 96 seconds (uncongested) dropping or picking people up. If this small change in expected travel time through the corridor can be measured or modelled the time to call a vehicle to the curbside from a waiting area can be properly managed to reduce wasted time or the expected incoming demand onto security could be estimated. This could help logistics on both ends of the corridor by having vehicles properly timed and security prepared for the correct demand based on information coming from each other on the rate of people and demographic. This work brings the pedestrian model space one step closer towards increasing its capabilities to accurately model regular trip travel times of individuals and groups.

Further work, however, is needed to expand the capabilities for the model to capture realistic general movement. The airport scene is still missing critical data on human behaviours before a fully validated model can be built that matches the real-world

conditions with confidence. These areas include traveller fatigue and group behaviours. The spot speeds collected for this study were at the half-way point of the corridor before the steeper incline. Travellers could have slowed down due to the steeper incline. Group behaviours were also not examined. Each speed and travel time were collected and compared as averages for individuals. Observed results showed a grouping tendency for people by the end of the corridor. Data should be collected throughout the whole corridor length to understand why and how people group up. Additionally, it is suspect that travellers are slowed down by other activities, such as checking their phone or other personal items, while in the corridor that may contribute to the difference in the total travel time. A study examining the behaviours of individuals throughout their entire time in a space is needed to conclude which behaviours should be included in the model to achieve a better match in total travel times.

Correlation between desired travel speeds on and off the people movers was not able to be done due to the lack of proper video camera angles to capture the same people in multiple areas of the corridor correctly in the time available for the study. This data is critical for future improvement of the model to build a proper end-to-end model of agent behaviours through these spaces.

Chapter 9: Conclusions, Contributions, and Recommendations

This thesis research was intended to contribute knowledge using the methodology of developing a model to evaluate the service capacity and demand impacts of connected and automated vehicles to the airport with the supporting objectives of human behaviours and the cost-benefits for the airport. From this objective the need for new data collected at the airport was found. This data was then collected and presented to support the modelling efforts reported in Chapters 4 through 8. Although a formal study of the cost-benefits relationship of the research findings was not carried out, the research highlighted resource implications for achieving benefits.

9.1 Summary and Conclusions

The main and supporting objectives of the thesis are as copied below. Airports need to adapt to the new technology of connected and autonomous vehicles. Airports will need guidance on how they can develop in the coming years. To do so, data from the current state of airports needs to be analysed in the perspective of the autonomous era. This is done through developing models of the airport space and analysing the results, which is what has been done in this thesis.

> **Main Objective**: Develop a Model to Evaluate the Service Capacity and Demand Impacts of Connected and Autonomous Vehicles to the Airport Curbside.

Supporting Objectives: Human Behaviours, Cost-Benefit Analysis (for the airport)

Within this thesis three models were built of the airport curbside directly and a pedestrian model of the airport corridor was also built to accomplish these objectives. To support these models, data collection was also completed and presented within this thesis. This data collection focused on two areas of the airport, the vehicles at the curbside and the pedestrians within the corridor.

9.1.1 Summary

The collection of vehicle data allowed the scale of the model work to be matched to that of the real-world and was presented in Chapter 4. Vehicle counts and curbside properties were collected for the peak hour of the curbside. This data was then used as inputs for the three models built for the curbside. The data collection allowed for the work of the thesis to compare its results to real-world conditions. Without it, the conclusions from the results would be fully theoretical. With real-world data, this allows the models to point to practical conclusions as the results can be measured against the observed conditions at the airport.

A Monte Carlo based model, presented in Chapter 5, was built to estimate the probability of an available curb space based on different supply and demand of spaces throughout the peak hour. This model was used to predict the probability of a curb space for future cases of higher supply and demand by use of available time slots to investigate their effects to

the expected delay to accessing a curb space. This expected delay in turn was used as a basis for measuring the level of service to travellers using the curbside. The model provides practical guidance for planners looking to expand the available curbside spaces at an airport to know how many time slots are needed to maintain a high level of service.

The second model using the curbside data was a microsimulation model that explored the use of a local shuttle to reroute vehicles away from the curbside, presented in Chapter 6, and explored the impact to delay based on the share of vehicles rerouted away from the curbside. This model explored the use of adding a new alternative to servicing travellers at the airport. The impact to the total delay experience by each group of travellers arriving, measured by each vehicle, was compared between different percent shares of vehicles being rerouted to have travellers make use of the local shuttle. These results showed how useful alternative solutions to curbside delay can be in a future with connected and autonomous vehicles which can be used by airport planners when repurposing or adding new space to the airport.

The third model of the curbside, presented in Chapter 7, looked at the use of a shuttle connecting the curbside to a hotel and was used to see the effects of increased supply and demand. This model gave answers to how the city shuttle's schedule was maintained and the impact to the average time spent waiting by travellers. It found a positive impact to the time spent waiting with increased frequency of departures but found these benefits suffered at higher levels of demand. These results help planners understand how a shuttle of this nature should be designed for future cases of different levels of expected demand.

The second data collection effort looked at the pedestrian corridor connecting travellers between the curbside and airport security and was presented alongside its related modelling work in Chapter 8. This provided spot speeds of travellers while inside the corridor and overall travel times between each end of the corridor. The spot speeds were used as inputs to the microsimulation model of the pedestrians within the corridor. The model showed how pedestrian speeds can be dynamic to their environment. This will allow better planning and understanding of the travel times between different locations at the airport scene. Planners can use this information when planning pedestrian spaces between major checkpoints at the airport. It will allow them to time services for better efficiencies that can be taken advantage of with automated technologies. Knowing the expected travel time through the corridor will allow planners and the active operation of the curbside to time services to be ready when travellers arrive at the curbside to best reduce delay and time spent waiting.

9.1.2 Major Conclusions

1. The Monte Carlo based model gave a tool for future planning of the airport curbside. It can be used for understanding the relationship between supply and demand of curbside spaces and the Level of Service experienced by travellers. The model showed that there is minimum number of expected mean available spots that is associated with a probability of 1 for the availability of a curb space. This number of expected mean available spots should be used against lower expected mean available spots to determine the expected delay caused when the

probability of expected curb spaces is less than 1. This provides a methodology for others to use when researching airport curbsides and provides an association with the delay index for different levels of service.

2. The microsimulation model of the airport curbside using a local shuttle explored the impacts of a future scenario where connected automated vehicles are rerouted away from the main curbside. This scenario made use of repurposing other areas of the airport that may see less use in the automated era, such as parking lots. It showed that rerouting up to 75% of the vehicles, arriving for either drop-off or pick-up, to utilize the local shuttles produced positive results in reducing the total delay experienced, measured per vehicle at the airport. Further, it showed this 75% share was a maximum before the benefits were lost as rerouting all vehicles to the shuttle did not reduce the delay per vehicle due to the added time of transferring to the shuttle.

3. Results from the microsimulation for the local shuttle were also able to be used to show how many extra spaces would need to be added to the existing curbside to service the existing demand with no delay. It found a total needed capacity of 17 spaces. This is an increase of 10 more spaces than already available.

4. The microsimulation of the city shuttle looked at the effects of different supply and demand of the transportation mode. This model showed a reduction in the average waiting time at both the airport curbside and the city location with an

increase in frequency of the shuttle schedule. However, this benefit went away at the airport curbside when the demand increased to equal that of the new supply. It showed that the local delay influences the scaling of the alternative and suggests that supply should be kept larger than demand to avoid level of service F type conditions. This work provides insight into future scaling of shuttles on static schedules connecting travellers to city locations.

5. The microsimulation of the pedestrian corridor looked at the ability to model dynamic speed profiles for pedestrian agents depending on their location within the model. This model showed that pedestrian agents could be modelled to use different desired speed profiles that were unique to each agent. The model showed expected results of agents without luggage that travel faster on the people movers having a faster overall travel time through the corridor then those with luggage. Designers of pedestrian spaces can use this approach to better model these and other pedestrian spaces to account for local human behaviours in their models.

9.1.3 Additional Conclusions

1. The dwell times of vehicles using the curbside was found to be at an average of 96 seconds. This was looked at through regression analysis to understand the impacts of luggage and passengers. It was found that the average base dwell time was 68 seconds and that each passenger added 9 seconds, making a one passenger vehicle have a dwell time of 77 seconds, and an additional 25 seconds if any of

the travellers in the vehicle brought roller luggage. This regression had no impact on explaining the variance of dwell times though. This means this regression did not provide any insight to gaining precision in predicting dwell times but does lend to a better understanding of the averages.

2. Data on the desired walking speeds of pedestrians in the pedestrian corridor were also collected. These speeds were found to be quick, at over 2 m/s, compared to other sources found in literature. These quick movement speeds were found on both the people movers and the normal walking spaces. A different desired movement speed means different human behaviours within the corridor. This data collection has helped provide further understanding of how people move within pedestrian corridors and on people movers. This is useful for reference by other researchers looking to model airport spaces and pedestrian corridors.

3. The overall travel time of pedestrians in the pedestrian corridor furthered what information can be understood from the travel speeds. This can be used in calibration efforts in the future when more data in the corridor is collected. Future research by the author or other researchers can take advantage of these results for comparison and use in other models.

9.2 Contributions of this Research

1. This research contributed to the available data from airports, specifically a North American commuter airport. While the airport itself cannot be named, the data reveals the scale of the airport which can be compared to other similarly scaled airports. Further, the human behaviour data collected for this research is expected to be applicable to other airports of all sizes. Vehicle dwell times and pedestrian movement speeds at the airport are expected to be human factors that are similar between different airports. Future research can compare results to this thesis to understand local factors to these behaviours.

2. With the Monte Carlo based model simulations, this research showed how available time slots at the airport curbside can be used to predict the probability of an available curb space for an arriving vehicle. The modelling work has provided a new methodology for airport landside planners to use when looking at future cases for the airport curbside. The methodology is a low-cost method that provides useful results without requiring computationally expensive methods of a microsimulation. This allows many different results to be compared.

3. The microsimulations of the curbside contribute to the understanding of individual delays to travellers. The local shuttle models have shown how connected and automated vehicles can be used to redirect traffic away from the curbside. It explored an option that takes advantage of CAVs ability to way find

and showed how airports can benefit from the new technology. The results also showed that these benefits have limits, so planners are aware of what factors effect how to use the new technology. The city shuttle connection models showed how this mode scales into future supply and demand cases. Airport planners can use these results to understand the effects to the city shuttle connection. The research showed increasing shuttle frequency to increase supply has direct benefits at reducing the average wait time. However, these benefits go away when demand increases to meet the supply. Airport planners can use the results from both these models to measure the benefits of using local or city connection shuttles when planning around reducing time spent waiting to travellers and in turn increasing the capacity of the curbside.

4. The microsimulation of the pedestrian corridor contributed to the development of pedestrian models and ability to predict time of required services. The work contributed to showing how microsimulation models can be expanded to include dynamic assignment and use of desired movement speeds. This work can be applicable to any pedestrian model, not just for airports. Further for the airport itself, the work helped bring the model closer to being able to predict the travel time through the corridor using actual movement behaviours. This will be useful to planners and future stakeholders of the airport curbside who wish to time arrivals of vehicles to reduce the delay to travellers.

9.3 Limitations

This research was limited by the scope of available data and the current state of CAV development.

While this research collected data for its models, data remained a major limitation. For the airport curbside, vehicle counts and dwell times were limited to the days that data was provided and time that was available. The data does not supply a comparison to non-holiday operating conditions as only the peak days were explored. Data collection was also focused on the peak hours. While these conditions do supply knowledge for designing for capacity, it limits the usefulness for finding efficiencies in design for days that are expected to see lower numbers in traffic. The dwell times are expected to see less variance between different days; however, temperature could be a factor for this data. This data was collected during winter months which could affect behaviours. Further, the winter temperatures could have influenced the arrival modes. These are unknowns of the data which could lead it inconsistencies with other data collections done at other airports.

Data collection was also limited to the airport curbside and corridor. This limited the research from investigating travellers' trips beyond these points. Travel within the city is expected to affect how people get to the airport, especially in a future with CAVs. However, this research did not have access to data on traffic movements of the surrounding city. Additionally, data collection on travellers' journeys within the airport

ended at the end of the corridor which is before the airport security. This limited the modelling to these areas.

Level 5 CAVs are not in use on today's roads. This limits the work of this thesis from using practical results of CAVs to that of exploring multiple theoretical use cases.

9.4 Recommendations

The following outlines recommendations from this research that will expand on what was done and improve upon the existing results.

1. Collection of data from multiple airports and from different seasons. By expanding the number of airports data is collected at a better understanding of general behaviours can be compiled. The current data collection is focused only on the behaviours of the local traffic. These parameters are expected to have some variance compared to other airports, much like how mode shares vary between cities. Collecting data from different seasons will also help show if the weather seen at North American airports affects the traffic.

2. Expansion of the study area to include the entire airport. The current scope was limited to the curbside and the pedestrian corridor between the curbside and airport security. Expanding this scope to include travellers' journeys from arrival at the curbside to the plane, and reverse, is recommended. This would expand the

ability to give a full understanding of movements at the airport for future planning.

3. A macrosimulation model of the connected city to expand the available scenarios for the curbside. The current work was limited by not being able to predict the future mode shares of vehicles at the curbside. A macrosimulation model of the connected city would provide future growth and change to the desired arrival and departure modes to the airport curbside. This in turn could be used as an input to find the resulting impacts. The difference between private and shared futures could be explored using this approach. Impacts to the city shuttle use and travel time could also be included in this model. This would produce results that could connect the results from the different microsimulations together.

4. Data collection of CAV behaviours to understand driving behaviour and safety considerations that should be involved in future modelling work.

5. Investigate the applicability of automated data collection from video sources. This would increase the amount of data collection that could be done.

6. Increase the granularity of data collection to consider more factors that could affect dwell times at the curbside and movement speeds within the pedestrian corridor. Care should be taken to reduce subjectivity.

7. Include multiple persons in the data collection process to reduce subjectivity.

8. Investigate for behaviours within the pedestrian corridor which could contribute to slower overall travel times, such as stopping temporarily or walking slower at different points along the corridor.

9. Produce complete profiles for travellers. Current data takes each data collection separately. Individual's arrival or pick up times, dwell time at the curbside, movement speed on and off people movers, and total travel time through the corridor should be connected.

10. Include modelling the difference between privately owned and shared automated vehicles.

11. Model forecasted changes to demand at the airport.

12. Modelling the effects of timing vehicles based on pedestrian locations within the airport corridor. This should be done to explore if further reduction in delays can be achieved by trying to release vehicles from staging areas to the curbside based on the location of the intended passenger in the corridor. Effects would be more noticeable in conditions with a higher share of arrivals.

The above recommendations suggest a complete picture for the airport. The recommended direction for this research is to grow into a model or series of models that follows the traveller from between their origin or destination within the city and the airport.

It is further recommended that this work be done in collaboration with other human behaviour studies. Human behaviours at the airport can inform the development of microsimulation model structures. As was seen, existing models can be expanded, and should be, to include these behaviours so non-airport areas with similar characteristic can take advantage of them. In turn, new developments from research in non-airport areas should be investigated for their use in expanding the models used in this area.

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Appendix A: Knowledge Gained from Participation as an Intern in NSERC Program for Building Trust in CAV

The author participated in the NSERC CREATE Program for Building Trust in CAV (TrustCAV, logo shown in Figure A.1 below) so as to gain knowledge on a number of subjects of interest. Professor F. Richard Yu (Carleton University) is the Principal Investigator. A number of Investigators, including Professor Ata M. Khan (Carleton University), are collaborating with Professor Yu in implementing the TrustCAV program that offers internship opportunities to graduate students. The author served as an Intern during summers of 2021 and 2022. This Appendix describes highlights of what knowledge was gained from industry experts that provided a deeper understanding of CAVs. This knowledge was appreciated when researching applications in real world services such as landside service at airports.

The host organization and participating experts contributed necessary technical knowledge related to CAVs that is not readily available from literature sources. As noted in the highlights of internship activities, knowledge was gained on how to analyze the vulnerabilities and risks of CAVs and understanding design and operations for safe and secure applications of CAVs.

Figure A.1: TrustCAV Program Logo

A.1 Summer 2021 Internship Activities

A.1.1 Introduction

This internship consisted of attending the virtual and in-person workshops provided by the Area X.O CAV Talent Catalyst Pilot Program. All attendees were provided access to the virtual workshops in the early months. To ensure equity, attendance to the in-person workshops was chosen through a mix of stated prerequisite knowledge and random selection. The selection used the prerequisite information disclosed in the signup survey to ensure attendees could benefit from the workshop and then randomly assigned them to workshops they qualified for. The virtual workshops were offered as short sessions covering general information about what the company offers and how they work in the developing autonomous space. The in-person workshops covered information in more detail as they ran over a full day or multiple days and allowed for interactive opportunities. Each workshop was run by the representing industry partner. See Table A.1 for industry partners at Area X.O.

A.1.2 Workshops

CAV Talent Catalyst Orientation, Virtual

This acted as an introduction to the workshops and the industry partners at Area X.O. It gave an overview of how the different industry partners are using the space to cooperate in their development. The orientation also outlined how the future in-person workshops were to operate with the proper health guidelines in place.

Table A.1: Participating Industries

Industry Partners at Area X.O

Anchor Partners	Invest Ottawa City of Ottawa AVIN Ontario Government of Canada
Founding Partners	Microsoft Nokia NCC Accenture Blackberry|QNX Ericsson Juniper Networks
Sponsor	Farm Credit Canada
Research Partners	Algonquin College Carleton University La Cité University of Ottawa
Technology Partners	Aurrigo CENGN ENCQOR 5G Hexagon | AutonomouStuff Kongsberg Pessl Trimble Canal Geomatics | Terris GPS Cohda Wireless Farmers Edge InDro Robotics MH Corbin Telesat Swift
Ecosystem Partners	CAVCOE Kanata North Business Association

CAV 101 Industry Partner: Accenture, Virtual

The CAV 101 workshop covered a general overview of the company's projected direction of autonomous vehicles and what they are working on to prepare for the future.

This workshop covered how the vehicle may change its design to go from the driver-oriented layout to instead focusing on livable space. This would allow people to spend their time more comfortably within the vehicle doing activities they would have otherwise not in a traditional vehicle. This redesign includes adding working space, connection to the internet, and availability of recreational time in the vehicle. Further, the concept of shared mobility was focused on. Connected autonomous vehicles have the potential to automatically set up carpooling on a trip-by-trip basis to both help reduce the costs for the passengers while also helping reduce the total vehicle kilometers travelled.

To accomplish this behaviour though, the technology relies on computer vision. This is made up of many vehicle sensors all reading different types of information and relaying it back to the vehicle computer as raster data. It results in many layers of raster data that the vehicle computer then processes to make its decisions on what it is seeing and then makes routing decisions based on that.

With this information, the workshop built on what they as a company and what individuals can work towards in the current development of the technology. They determined that the systems need to stop relying on local WLAN and instead use cloud-based services. Since the vehicles from companies will be spread over entire geographical areas and multiple cities the ability to control them all from one central location, for managing updates to the system and scaling, the service is easier to grow and adapt to its needs. They also determined that for vehicle services there will be a need

for predictive quality of service. The service will need to be able to plan ahead to offer passengers the travel quality that they are expecting when using an autonomous vehicle.

Beyond this the workshop also included the topic of direct development. Currently, developers have begun working at a higher level of coding, building something that builds the logic itself instead of having to code every line manually. They are giving control of the technical aspects to computers and need "humans to become more human" analysing aspects that computers are not capable of. This is done through AI, a branch of computer science. The AI development they consider important is that which mimics human intelligence and learns on its own, deep learning algorithms. However, this requires a lot of quality data which is something humans need to collect, analyse, and feed to the AI for it to be able to learn.

Last Mile Shuttle Solutions Workshop, Industry Partner: Aurrigo, Virtual

The Aurrigo workshop presented an overview of how the transportation industry has been working towards the automation of vehicles from the first autonomous vehicle, in their classification, in 1958 to today. This led to an overview of their deployment of the Aurrigo shuttle as an autonomous solution to providing transportation within an urban area. The workshop covered how the shuttle can be set up on a set route to service an area without the need for a driver. This allows the shuttle to provide affordable transportation while remaining safe through the vehicle's built-in sensors that monitor its surroundings while it operates. Because it operates on a known route it can rely on GPS

to monitor its routing decisions and confirm locations where it will be following traffic signage. The shuttle is fully capable though of making its own decisions to continue to operate in a safe manner.

EZ CAV Technology Workshop, Industry Partner: EasyMile, Virtual

This workshop focused on the software side of autonomous shuttles. The presenters covered how they are developing software packages that can be customized to customer's needs. This allows other companies to develop the hardware and set up the vehicles and then purchase software solutions to get their autonomous vehicles ready for road tests. EasyMile has its own autonomous shuttle to offer with its software package that it also uses to test development. This software solution also allows vehicle behaviour to be updated as development continues keeping autonomous vehicles safer and with more functionality as the development continues without having to rebuild hardware components or reconfigure the vehicle layout.

Emergency Response - How 5G Changes Everything, Industry Partner: ENCQOR 5G, Virtual

The development of connected autonomous vehicles comes with the need for an expanded data transfer network, which is currently focused on expanding the 5G network for its ability to transfer data at faster speeds. While this is highly useful for connected and autonomous vehicles, the infrastructure and functionality of the network can also be taken advantage of by emergency responders. The ability for the network to keep

vehicles and persons always connected and provide updated information autonomously can be greatly utilized by emergency responders. This network would quickly get information to people and keep them informed of the situation. Its ability to be integrated to technology also allows the equipment that first responders are using to take-in and pass on information itself. This allows visors on helmets to provide in the moment heads up displays of critical information or vehicle maps to update with current road blockages and best routes as the situation develops allowing drivers to navigate without having to rely on dispatchers.

Connected and autonomous vehicles themselves can also be taken advantage of during emergency situations. The vehicles can be used to rescue people from endangered areas by acting as evacuation services. This frees up first responders to focus on other tasks, such as providing medical attention, while the vehicle does the driving. The vehicles can also be used to transport equipment between areas in a larger scale emergency.

Secure Code - OWASP Top 10, Industry Partners: Software Secured, OWASP Ottawa Chapter, ADGA, In-Person

With the move towards making vehicles connected and autonomous comes the risk of opening these vehicles to cyber security vulnerabilities through web-based applications. This workshop went through the top ten current ways code is exploited to steal private information or cause malicious actions to be completed on the hacker's behalf.

1. Injection. The highest security risk for web applications. This is a vulnerability where the code takes in untrusted data and sends it to an interpreter to be used as a command or query. This allows the attacker to gain access to private information of other users of the service. This could expose user's credit card information, address, full name, current location, and other information.

2. Broken Authentication. When authentication and session management are not implemented correctly it allows attackers to compromise items such as passwords or session tokens which lets them access the service as another user temporarily or permanently. This could be used to change desired vehicle routes or charge persons for trips they did not take.

3. Sensitive Data Exposure. When sensitive data is not properly protected attackers can find ways to gain access to it while it is at rest or in transit. This occurs when information is not properly encrypted giving attackers access to people's credit card information or personal information allowing for identity theft. This could be exploited in autonomous vehicles when requesting a vehicle to know who requested the vehicle and their payment information if they have prepaid for the vehicle and sent that information in an unsecure way.

4. XML External Entities (XXE). Poorly configured XML processors allow users to evaluate external entity references within XML documents. This can occur in unexpected places, such as deeply nested dependencies a software group did not develop

themselves. This can allow the attacker to upload an XML file that queries for data that they would otherwise not have access to or to try to query an endless file in a denial-of-service attack harming the service for other users.

5. Broken Access Control. Improper regulation of what a user are allowed to do. Improper coding can allow a user who has logged on with a valid account to access data from other accounts without having to know their log in data. This is done by the program potentially only checking authentication at log in and then allowing the user to manually change the URL to access other user's information without rechecking their authentication. This could be a vulnerability for autonomous vehicle apps where an attacker could create an account and log in and then use this to access other user's personal information or automatic payment information.

6. Security Misconfiguration. The most commonly seen issue. This occurs due to insecure default configurations, incomplete configurations, open cloud storage, misconfigured HTTP headers, and error messages containing sensitive information. Attackers are targeting unpatched flaws, unused pages, and unprotected files to gain unauthorised information. This includes default accounts, possibly used for testing development such as username:admin password:admin, still being active in the public version. It may also include sending detailed error messages back to the attacker, allowing them to purposefully proc errors to get information about how to access sensitive information. This is a danger to vehicles if they allow outdated versions of apps to connect to the network.

7. Cross-Site Scripting XSS. This occurs when untrusted data is passed on to a new web page or the current page is updated with user supplied information. This allows attackers to send links to a victim and have it give access to the user session or redirect them to malicious sites.

8. Insecure Deserialization. This often allows remote code execution. If not remote code execution, it can also allow for injection and privilege elevation attacks. The attacker is able to change information to give themselves more access than intended.

9. Using Components with Known Vulnerabilities. Libraries, frameworks, and other software modules can run with the same privileges as the application which can be exploited by the attacker if these have known vulnerabilities. Using outdated versions of these components allows attackers more time to find vulnerabilities or even look up known ways to attack giving them easy access.

10. Insufficient Logging & Monitoring. A system should monitor the activity to its servers in a proper manner to investigate suspect behaviour. Without this it allows attackers to continue to attempt entry into the system without being stopped until a time long after the attack was successful. This can include seeing multiple failed attempts at an admin level log in or data base followed by the server providing sensitive information.

Computer Vision & Convolutional Neural Networks & Automotive Sensors for ADAS and AV, Industry Partners: Sensor Cortek, VIIVA Lab, and Pleora, In-Person

The computer vision and convolutional neural networks workshop consisted of two separate topics offered together over the four days. The first topic covered the computer vision aspect of autonomous vehicles. Computer vision for vehicles has been developed to mimic that of human perception. Humans see in three colours with their cones giving finer points of detail and in black and white with their rods for clearer defined movement in our peripherals and low light conditions. Human vision is also based off movement and requires constant involuntary movements of the eye to show us the most up to date image. This tells the eye the difference between what it was seeing to what it is now seeing and allows it to build an image from that. Computer vision can use the same process to develop an image for use by the computer. The computer though needs to process what it sees differently than the human brain. We do not fully understand how the human brain processes what we see for us to make use of our sight, so computer vision needs to be developed through testing different methods.

This has led to many different ways to process images to produce usable information for computers. The pixel histogram can be analysed, the image can be manipulated through mathematical morphology, erosion can be applied to replace adjacent pixels with minimum intensities found around it to open shapes up or dilation can be applied for the opposite to close shapes up or fill in holes in the image. These techniques can also be layered for more results. Saturation of surrounding pixels can also be compared to slowly increase the matching range to find potential shapes if the original image contrast was low. These can all be done using open-source code found through openCV which

acts as a starting point for research in computer vision. Since it is open source and actively developed it is currently state of the art letting researchers continue to develop new solutions without having to start from the beginning.

Another important function of computer vision compared to human vision is the ability to track points between two images. Our brains can quickly identify points in our vision and connect them together, computers need to be given an algorithm and decision threshold to do this. Fortunately, solutions to these problems already exist allowing quick identification of corners and distinct points. These points can be tracked on the movement of the image and if the object appears to be getting closer or farther away. It does this by blurring the image to simulate getting further away so it can match the two images at relative clarity. Then comes the balance of only matching points that are close enough to be matched compared to letting the points slightly change as lighting conditions and shape may adjust due to position compared to the camera. Multiple cameras can be used at the same time to do this so their relation to each other can be utilized to understand where points match between the images from the two cameras.

Finally, all of this requires testing many adjustments to the input parameters to develop a final decision on what the computer is seeing through its sensors. A solution to this problem that has been developed is to let the computer adjust the parameters itself until it achieves the needed accuracy. This is done through convolutional neural networks. Convolutional neural networks will calibrate on input data changing what it does to try to identify what it is seeing. This requires a large amount of quality data. Some object

detection has been developed through this technique to publish pre-trained weights to help researchers as they do not need their own set of quality data since properly tagging the data is time consuming.

The second topic of the workshop focused on the sensors that are used on autonomous vehicles and their use. The first sensor covered was the camera capable of image capture and chronophotography. This provides an image similar to what human drivers use to navigate vehicles today. However, the camera is limited by field-of-view, exposure to light, lens distortion, converting luminance to electric signal, and broadcasting of the information if necessary. Cameras also need to be calibrated as each camera is different. This can be done through taking images with the camera of some 3D points from different viewpoints. This expands the camera's functionality to be used alongside a second camera to be able to determine the distance of a captured feature to the camera adding depth information to the image. The camera sensor is good at identifying objects but suffers in low light conditions or when the image has a lot of obstructions or noise.

Automotive radar was the second sensor covered. Radar uses the time of flight and the frequency of the wave to determine the distance of the object to the sensor. The maximum range of the radar is limited by the time of the chirp, a longer range requires a longer chirp. To determine the direction of the object the vehicle requires more than one receiving antenna though, as radar sends out a signal in all directions and receives signals from all directions. Materials have different radar cross sections, which makes them easier or harder to detect through radar. Radars are usually calibrated to detect in a

planar fashion. Radar are good at finding distance and velocity of objects and work well during weather conditions and low light conditions but suffer with stationary objects and have low resolution.

The final sensor covered at the workshop was LiDAR. LiDAR uses a laser light to get a point cloud of the surrounding area. This sensor uses the same working principles as radar but can return data points in a larger field of view. LiDAR are good for finding depth but can return sparse point clouds, suffer in weather, and are expensive computationally.

Autonomous vehicles can take advantage of having multiple types of sensors equipped to minimize the drawbacks of each sensors challenges. This does not result in robustness in design though as there is limited overlap in benefits. The autonomous vehicle would have to be told which sensor to rely on during different conditions instead of multiple sensors giving matching information. Computing all the information from all sensors at all times could be too expensive so priorities have to be set to keep the processing time of the information from the sensors low to have high frame rates.

Automotive and Autonomy Engineering Leadership, Industry Partners: Hexagon and AutonomouStuff, In-Person

This workshop provided an overview of what out-of-the-box hardware solutions are available for companies and researchers. Hexagon and AutonomouStuff provide a service for adapting modern vehicles to have the equipment to become autonomous. This

includes attaching cameras, radar, LiDAR, GPS, and internal processing components to the vehicle. This service allows companies and researchers today to easily have a tested and calibrated starting point to work from to then build on with their own developed software. It also lets companies and researchers display their progress to investors without needing an in-house hardware solution. The workshop also included a test drive of a vehicle that can be provided. This vehicle was capable of receiving direction commands externally from the traditional steering wheel and pedals through both manual input and code-based commands. Participants were able to test out giving the vehicle commands themselves and ride in the vehicle while it drove around the Area X.O track on its own.

A.2 Summer 2022 Internship at Area X.O

A.2.1 Introduction

This internship consisted of a summer work position at Area X.O working directly with testing automated technologies. The work was done with direct interaction with Area X.O's autonomous Lexus and testing software that is actively in development for ensuring the safe operation of autonomous vehicles. The focus of the summer tests were on the capabilities of the vehicle to everything (V2X) communications to the vehicle from a 4-way intersection located on-site at Area X.O.

A.2.2 Area X.O Tests

Vehicle to everything (V2X) allows the vehicle to communicate with all other equipment and sensors. The advantages of this for safety at intersection is being explored by Area X.O and this internship involved problem solving and setup of test to enable properly testing the equipment. The process to setup the test and the conditions that the vehicle operates in will now be explained in a sequential order.

To begin, a life-sized dummy must be positioned to pose as a vulnerable road user. Vulnerable road users include children and adult pedestrians and cyclists. The vulnerable road user must also be able to move. This is to test the equipment's ability to detect a vulnerable road user entering an area of danger. To accomplish this setup a dummy on a running track connected to a launch computer was used. An example setup is provided in Figure A.2 below. The dummy is attached to the dummy movement track using a board and magnets. This allows the dummy to come off safely in the event of a collision. The driving unit houses the motor and the computer. The computer receives GNSS signals from the vehicle to control the start of the dummy movement. This ensures the dummy begins movement timed with a collision with the vehicle. By doing this, the V2X system can be consistently and repeatedly tested on its ability to communicate to the vehicle of this danger. The deflection plate acts as a counterweight to allow the dummy to move in both directions.

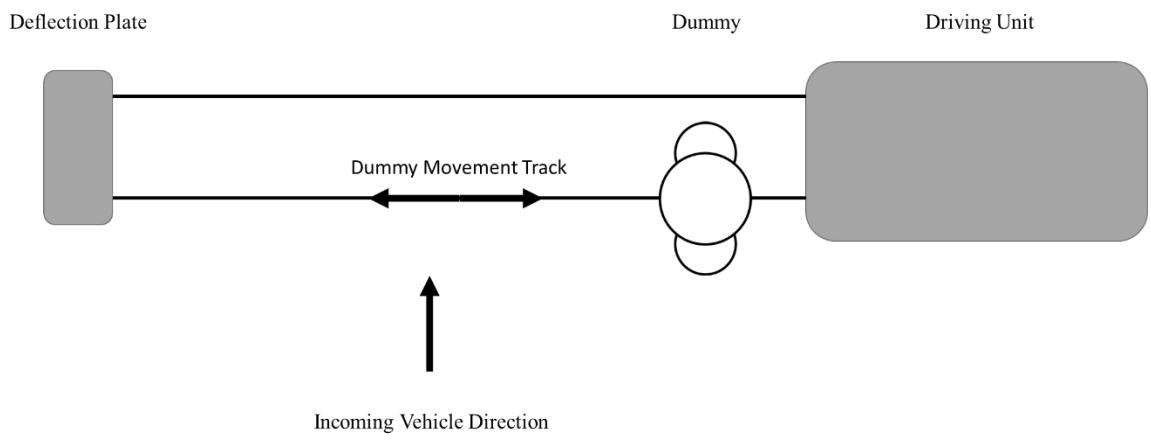

Figure A.2: Area X.O dummy setup

The dummy must also be positioned to be captured by the camera's field of view. The camera is positioned at the opposite side of the intersection from the pedestrian crossing. This is shown in Figure A.3 below.

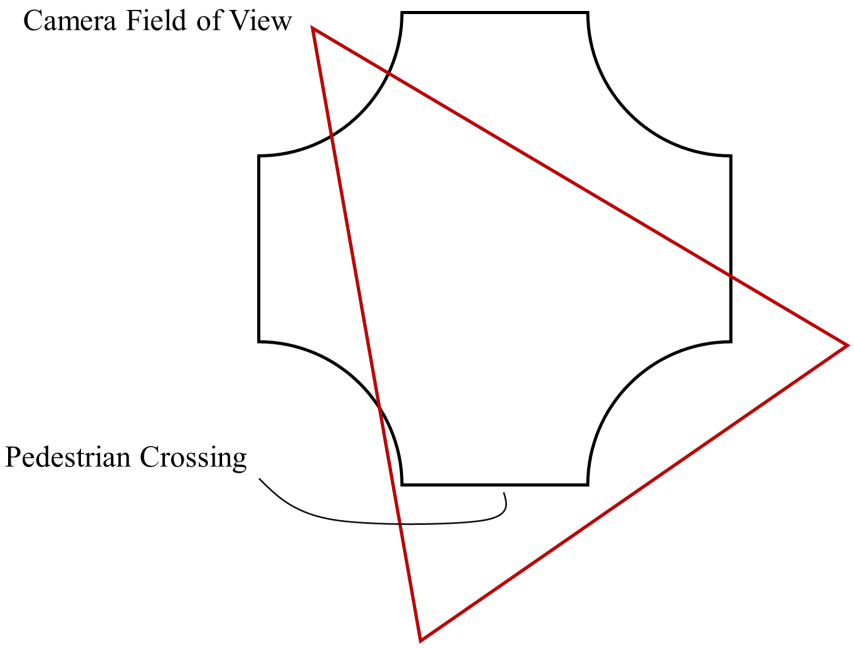

Figure A.3: Area X.O camera field of view for V2X

Once the dummy is positioned correctly the vehicle test may begin. A crash point is chosen and taught to the driving unit. It will use this to time the start of the dummy movement. The timing of the start for the dummy movement is adaptable for the vehicle speed allowing multiple vehicle speeds to be tested.

The vehicle is then brought to the start position of the test. Once the test is activated the driving unit begins to monitor the GNSS position messages from the vehicle. The vehicle itself is also put into autonomous mode and begins to monitor messages from the intersection. The intersection is always broadcasting messages as its system is designed to be always running, not just for the tests. As the vehicle approaches the intersection the dummy is then launched.

At this point the relevant data for the test begins. The equipment at the intersection must identify the dummy as an obstacle for the vehicle to stop for. The vehicle itself must identify the message from the intersection as being something it needs to stop for. This requires multiple conditions being met by both systems. The intersection sensors must be sensitive enough to pick up the pedestrian and its computer must properly interpret its location and broadcast this message in a format that vehicles can receive. At this point, the vehicle needs to receive the location of the pedestrian and check if this is an issue considering its intended driving path. The vehicle can also be programmed to not proceed if the dummy has entered dedicated zones at the intersection. These zones must be fully within the field of view of the sensors at the intersection.

At this point, the vehicle parameters control if the vehicle will automatically stop for the dummy. It is fully relying on the V2X message from the intersection to decide if it should stop and will otherwise continue on its automated driving path. The results on if the vehicle properly stopped provide answers on what these parameters should be and what their sensitivity is. At all points a safety driver is within the car to stop the vehicle once it is known that it has failed to decide to stop. This ensures all other personnel at the test site are safe and to avoid collision with the test dummy to reduce potentially damaging it after repeated failed tests.

The results from these tests will be able to inform the advantages, if any, V2X has at intersection compared to sensors mounted on the vehicle itself. Weather and occlusion scenarios are expected to show different setups favour either the vehicle’s own sensors or

the V2X message. In this case, the tests hope to inform what conditions these happen in, so that these conditions could be also communicated to the vehicle in the future allowing it to make informed decisions about the messages it is receiving.

A.2.3 Public Intersection Install

During the summer an installation of V2X equipment at a public intersection was attended. This served as an opportunity to observe the requirements needed to implement the equipment that was being tested at Area X.O. The goal of the install was to equip the public intersection with the same sensors that were at the private test intersection at Area X.O.

Here, the requirements for installing the technologies and the different considerations that need to be made that were observed will be detailed. The list of required skilled personnel and required equipment is found below in Table A.2 and Table A.3.

Table A.2: Required Skilled Personnel

Required Skilled Personnel	Roles and Required Skills
Electricians	Wiring equipment Supplying power to equipment Wiring power adapters to supply the correct voltage Pulling wire under roads during active use Pulling wire up and inside poles
Heavy Equipment Operators	Bucket Trucks Signage Trucks
Police	Traffic Enforcement Law Enforcement

These skilled personnel are in addition to those who have designed the new equipment install. The designers should also be present. Electricians make up the bulk of the work effort for installing new equipment for CAV infrastructure. The sensors are all electrical instruments which need to be installed safely by those who understand the electrical code. The electricians act as the heavy equipment operators too if properly trained to do so. The sensors should be installed at high locations on the poles for good visibility and communication range. Therefore, the electricians will need to have working at heights training and be able to operate a bucket truck.

Police will also be needed on site for the whole duration of the work. Since sensors are being installed near active traffic, lane closures may be needed and general traffic safety will need to be enforced. Additionally, connecting new wires to the power grid at an intersection requires powering off the traffic lights. Police will then need to direct traffic at the intersection during this time. Having a skilled traffic cop will keep traffic levels at the intersection low which will help keep the working environment safe.

Table A.3: Required Equipment

Required Equipment	Use
Bucket Truck	Providing safe access to elevated locations where sensors must be installed. Must be operated by a skilled and trained individual.
Passenger Vehicles	Unexpected needs for additional equipment or forgotten equipment will need to be brought to site. Additional personnel may also need or want to be present. Vehicles need to be available to go get the equipment or people without needed to rely on heavy equipment.

Traffic Arrow Board	If a road must be closed on an active intersection then signage must be provided to the drivers.
Traffic Cones	Proper distance around equipment must be provided for safety and communicated to drivers. Traffic cones should be used around equipment and open manholes.
Wire of various gauges	Wire must be run to multiple locations over long distances. Wire is run under roads, inside metal poles, within electrical boxes, and inside sensor equipment. Each area requires the correct wire gauge.
Wire Shielding	Wires are being run near conductive materials or sharp cut edges. These wires need additional shielding to be installed. Equipment provided by manufacturers may not have the proper length of connectors to provide a safe connection though conductive materials or sharp edges.
Rope	Wire needs to be run under roads and through pipes. To do this, an existing rope in the pipe is required or a new one must be run using a specialized tool. A new rope and the new wire needs to be attached to the existing rope. This allows the new wire to be pulled through the pipe and a replacement rope put in place for future use.
Sensors	The sensors for install should be on site early so the electricians can inspect them before starting work. Without seeing the sensors before working required wires or setup may not be done or work may be done incorrectly.
Clamps	Not all sensors are built with the needed connector. Custom clamps will be needed and should be on site early.
Allan Keys	Equipment may require Allan Keys to access. Both metric and imperial sizes should be available.
Screw Drivers (Handheld and Powered)	Equipment may require screw drivers to access. Handheld screw drivers are needed for delicate equipment such as accessing SIM cards which may be screwed in behind weather shielding. Powered screw drivers will be needed for securing equipment tightly.

Drills	New holes into poles or equipment boxes may be needed. Drills with proper drill bits for various materials (metal, wood, plastics) should be available.
Hard Hats	Heavy equipment and tools are being used while elevated. For safety, all personnel should wear hard hats.
High Visibility Jackets	Active traffic presents a safety concern and all personnel should wear high visibility jackets.
Police Vehicles	Traffic and law enforcement should be on site requiring the presence of a police vehicle
Cellphones	Communication to others off site will be needed. Due to the location being outside and potentially outside of internet connection a cellphone or other device that does have connection to a network is needed. Concerned citizens may also call the municipality about the work that is being done. Workers on site should be able to be contacted so citizens' concerns may be addressed.
Sunscreen	The work involves long hours in direct sunlight. For the health safety of all personnel sunscreen should be available.

Appendix B: VISSIM Python Code

This code is provided as is in a best effort to present the code used to produce the model results. The code is written to be used alongside specific VISSIM scenarios and is not applicable to other VISSIM scenarios unless they are built to fit this code. Values of the code are meant to be changed depending on the conditions of each VISSIM scenario. Not all portions of the code are relevant for every VISSIM scenario as they were built to be called as needed from within the model.

```
"""
==========================================================================
Python Script
==========================================================================
"""


    # ----------------------------------------------------------------------
-------------------------
    # Required Vissim Program properties
    # ----------------------------------------------------------------------
-------------------------
    # Links for the parking of vehicles to generate or be attractions for
pedestrians all need to be in sequence
    # This sequence should be numbered 1001 - 1999 (10000+ is default for
connectors within Vissim 2021)
    # The numbering sequence start and end is not hardcoded though and
needs to be input as a UDA

    # Areas where the associated passengers should be generated or
attracted to should be numbered the same as the link if possible or follow
a similar convention to the parking space number

    # Parking dwell times are assumed to be the same for all parking
spaces so the attributes of the one on laybyLinkNoStart is used for all
```

```
    # User Defined Attributes (UDA)

    #   PlatoonParkingCheck - Links - a number to check how many vehicles
have been sent to park
    #   VehiclePlatoonParkingCheck  - Vehicles  - a boolean to check if
the vehicle has been assigned to a parking space

    #   AlightPax       - Vehicles In Network - Vehicle attribute to store
the number of alighting passengers.  Make sure CanBeEmpty is set to true
and default is empty
    #   PickupGenerated - Vehicles In Network - Vehicle attribute to store
if a pickup passenger has been generated

    #   RelLinkNoStart  - Scripts - the start of the link sequence that
contains parking lots for generating/attracting passengers
    #   RelLinkNoEnd    - Scripts - the end of the link sequence that
contains parking lots for generating/attracting passengers

    #   AreaNoStart     - Scripts - the start of the area sequence that
passengers will be generated or attracted to
    #   AreaNoEnd       - Scripts - the end of the area sequence that
passengers will be generated or attracted to

    #   AirportDoor     - Scripts - the area number increment for the
airport door, recommended 1000

    #   ExitVehicleCheckLink - Scripts - the link number where vehicle
state will be checked before it either exits or loops through again

    #   AutonomousVehicleParkingCheckLink - Scripts - the link number
where the autonomous vehicle checks if there is an available parking space
before proceeding

    #   ParkingGarageEntrance - Scripts - The link number representing the
entrance of the parking garage
    #   ParkingGarageExit   - Scripts - The link number representing the
exit of the parking garage
    #   ParkingGarageMaxCount   - Links - A link property to store the
maximum amount of vehicles in the parking garage at a time
```

```
import ctypes
from xml.etree.ElementPath import prepare_descendant            # For
message box. A library included with Python installation.

ALIGHT_INTERVAL = 2       # [s], time between two exiting passengers
BOARDING_INTERNAL = 2     # [S], time between two boarding passengers
PICKUP_INTERVAL = 30      # [s], time for the vehicle to wait to pickup a
passenger
PAX_PEDTYPE = 100         # pedestrian type of pax
PAX_SPEED = 1.4           # [m/s] speed of alighting pax

#=========================================================================
=====================
def Initialization():
    """ General initialization, e.g. assigning values to the global
variables """

    # -----------------------------------------------------------------
-------------------------
    # Declarations of global variables
    # -----------------------------------------------------------------
-------------------------
    global laybyLinkNoStart          # Vissim link no. of the layby link
where the parking lot sequence starts
    global laybyLinkNoEnd            # Vissim link no. of the layby link
sequence end
    global laybyLink                 # Vissim object of the layby link
where the parking lot is placed
    global areaNoStart               # Vissim area number where pax should
be generated sequence start
    global areaNoEnd                 # Vissim are number where pax should
be generated sequence end
    global parkingDwellTmDistr       # Number of the dwell time
distribution associated with the parking lot where pax exit
    global parkingDwellTmLowerBound  # Lower bound of the dwell time
distribution associated with the parking lot
    global currentScriptFileNoPath   # Name of the current script without
the path information
```

```
    global airportDoor               # Vissim area number where people who
are being picked up are generated
    global exitVehicleCheckLink      # Vissim link no. of the link where
vehciles will be checked for if they should exit the airport
    global autonomousVehicleParkingCheckLink    # Vissim link no. of the
link where autonomous vehicles will check if there is an available parking
space
    global curbsidePlatoonLink1     # Vissim link no. of the link where
vehicles will platoon park
    global parkingGarageEntrance
    global parkingGarageExit

    global PEDESTRIANWAITINGATCURBSIDE   #creating a variable to store the
waiting pedestrians at the curbside in
    PEDESTRIANWAITINGATCURBSIDE = 0

    global PEDESTRIANWAITINGATCITY      #creating a variable to store the
waiting pedestrians at the city location in
    PEDESTRIANWAITINGATCITY = 0

    global PEDESTRIANWAITINGATCURBSIDEWAITTIME  #creating a variable to
store the waiting pedestrians at the curbsides total wait time
    PEDESTRIANWAITINGATCURBSIDEWAITTIME = 0

    global PEDESTRIANWAITINGATCITYWAITTIME      #creating a variable to
store the waiting pedestrians at the city location total wait time
    PEDESTRIANWAITINGATCITYWAITTIME = 0

    global PEDESTRIANWAITINGATCURBSIDECOUNT #creating a variable to store
the total count of pedestrians at the curbside
    PEDESTRIANWAITINGATCURBSIDECOUNT = 0

    global PEDESTRIANWAITINGATCITYCOUNT     #creating a variable to store
the total count of pedestrians at the city location
    PEDESTRIANWAITINGATCITYCOUNT = 0

    # Making laybyLink a list
    laybyLink=[]
```

```
    # Get the filename of the script
    pos = str(CurrentScriptFile).rfind('\\')
    currentScriptFileNoPath = str(CurrentScriptFile)[pos+1:]

    # Get the script-associated UDAs

    # Get the starting number of links with parking lots on them with
alighting/boarding passengers
    laybyLinkNoStart = GetAndCheckScriptUDA("RelLinkNoStart")
    if laybyLinkNoStart == 0:
        return
    # Get the ending number of links with parking lots on them with
alighting/boarding passengers
    laybyLinkNoEnd = GetAndCheckScriptUDA("RelLinkNoEnd")
    # Ending number needs to be larger than starting number
    if laybyLinkNoEnd < laybyLinkNoStart:
        return


    # Getting both ends of the area numbers is not necessary if they are
numbered correctly
    # This will be used as a safety check to make sure the numbering
convention was followed

    # Get the starting number of areas with parking lots to
generate/attract passengers
    areaNoStart = GetAndCheckScriptUDA("AreaNoStart")
    if areaNoStart == 0:
        return

    # Get the ending number of areas with parking lots to generate/attract
passengers
    areaNoEnd = GetAndCheckScriptUDA("AreaNoEnd")
    # Ending number needs to be larger than starting number
    if areaNoEnd < areaNoStart:
        return
```

```
    # Get the area number for the airport door
    airportDoor = GetAndCheckScriptUDA("AirportDoor")
    if airportDoor == 0:
        return

    # Get the link number for the exit check link
    exitVehicleCheckLink =
Vissim.Net.Links.ItemByKey(GetAndCheckScriptUDA("ExitVehicleCheckLink"))
    if exitVehicleCheckLink == 0:
        return

    autonomousVehicleParkingCheckLink =
Vissim.Net.Links.ItemByKey(GetAndCheckScriptUDA("AutonomousVehicleParkingC
heckLink"))
    if autonomousVehicleParkingCheckLink == 0:
        return

    #curbsidePlatoonLink1 =
Vissim.Net.Links.ItemByKey(GetAndCheckScriptUDA("CurbsidePlatoonLink1"))
    #if curbsidePlatoonLink1 == 0:
    #    return

    parkingGarageEntrance =
Vissim.Net.Links.ItemByKey(GetAndCheckScriptUDA("parkinggarageentrance"))
    if parkingGarageEntrance == 0:
       return
    parkingGarageExit =
Vissim.Net.Links.ItemByKey(GetAndCheckScriptUDA("parkinggarageexit"))
    if parkingGarageExit == 0:
       return

    # Associating the link numbers to actual links in the model
    i = 0
    while laybyLinkNoStart+i < laybyLinkNoEnd+1:

laybyLink.append(Vissim.Net.Links.ItemByKey(laybyLinkNoStart+i))
            i=i+1

    ## Get the dwell time distribution of the parking lot
    #for parkinglotroute in laybyLink[0].vehroutpark:
```

```
    #    # should be called only once because only one parking route
should include this link
    #    parkingdwelltmdistr =
parkinglotroute.vehroutdec.attvalue("parkdur(1)")


    #if int(parkingdwelltmdistr) <= 0:
    #    msgstring = "dwell time distribution associated with the parking
lot was not found. default distribution no. 1 chosen."
    #    ctypes.windll.user32.messageboxa(0, msgstring, "warning", 0)


#*************************************************************************
*************************************************************************
***
        #                    attention
    attention                                          attention

#*************************************************************************
*************************************************************************
***

        # this number should be changed to a default that does not contain
0 as a lower bound else the program will throw an error
        #the above looked for the parking time distribution in the vehicle
routes (parking lot) attributes
    parkingDwellTmDistr = 104

    # get lower bound of dwell time
    parkingDwellTmLowerBound =
Vissim.Net.TimeDistributions.ItemByKey(parkingDwellTmDistr).AttValue("Lowe
rBound")


#=========================================================================
=====================
def Main():
    """ Main program to be executed during the simulation """
    BoundsCheck()
    GeneratePassengers()
    CheckIfVehicleShouldLeave()
```

```
    CheckIfAutonomousVehicleShouldPark()
    #PlatoonParking()

#=========================================================================
=====================
def GeneratePassengers():
    """
    Generates passengers (pax) on area <areaNo> for the car on the
<laybyLink>.
    Required globals: laybyLink, ALIGHT_INTERVAL, PAX_PEDTYPE, areaNo,
PAX_SPEED
    Required link UDA: AlightPax (to show the number of alighting pax as
label)

    The number of pax is car occupancy - 1 (the driver does not exit).
    Occupancy of the vehicle is adjusted the moment it stops at the
parking location.
    Dwell time of the vehicle is properly adjusted to ensure there is
enough time to drop off the passengers as if they took time to get out
    """

    # Generates pedestrians for every link associated with a parking lot
and area
    i=0
    while laybyLinkNoStart+i<laybyLinkNoEnd+1:
        # Puts links stored in the global list into a local variable as
referencing the link properties cannot be done by referencing the link
directly
        currentLink = laybyLink[i]
        for veh in currentLink.Vehs:
            #get the destination parking space and return a corresponding
number

            parkingSpace = 0

            if veh.AttValue("DesSpeed") == 0:      # When DesSpeed changes
to 0, DwellTime is > 0
                #This throws an error if the parking route is not assigned
before checking for it
```

```
                parkingSpace =
DestinationParkingSpace(veh.AttValue("VehRoutPark"))
                if veh.AttValue("AlightPax") == 0:
                    if veh.AttValue("VehType")=="2000" :
                        veh.SetAttValue("AlightPax",veh.AttValue("Occup"))
                    else:
                        veh.SetAttValue("AlightPax", veh.AttValue("Occup")
-1)  # show the number of exiting passengers

                # This finds vehicles that have people to drop off, else
they are picking someone up
                # Makes use of above assignment of AlightPax to ensure the
vehicle orriginally was to drop off passengers
                if (veh.AttValue("Occup")>0 and
(veh.AttValue("VehType")=="2000" ) or (veh.AttValue("Occup") > 1 and not
(veh.AttValue("VehType")=="2000" or veh.AttValue("VehType")=="3000")) and
veh.AttValue("AlightPax")) > 0:
                    # generate a pedestrian and lower the occupancy of the
vehicle
                    if veh.AttValue("DwellTm") > 0:
                        # generating a pedestrian
                        #if veh.AttValue("VehType")=="3000":


#Vissim.Net.Pedestrians.AddPedestrianOnAreaAtCoordinate(PAX_PEDTYPE, 1010,
0, 0, 0, -1, PAX_SPEED)
                        #else:
                            # produces error of "cannot use operator +
between NoneType and int if the parking space does not exist"

#Vissim.Net.Pedestrians.AddPedestrianOnAreaAtCoordinate(PAX_PEDTYPE,
parkingSpace+1000, 0, 0, 0, -1, PAX_SPEED)
                        # lower the occupancy of the vehicle
                        veh.SetAttValue("Occup", veh.AttValue("Occup") -
1)
                        # ensure there is enough time to drop all
passengers off
                        if veh.AttValue("DwellTm") < ALIGHT_INTERVAL:
                            veh.SetAttValue("DwellTm",
veh.AttValue("DwellTm") + ALIGHT_INTERVAL)
```

```
                # They are picking someone up
                else:
                    # Makes use of above assignment of AlightPax to the
number of occupants-1 as this stores the orriginal occupants instead of
generating
                    # a passenger when the vehicle finishes dropping
everyone off
                    # currently doesn't attract passenger to the car, just
at the door and makes them walk with hardcoded route in network to the car
location
                    if veh.AttValue("AlightPax") == 0 and
veh.AttValue("PickupGenerated")==0:

Vissim.Net.Pedestrians.AddPedestrianOnAreaAtCoordinate(PAX_PEDTYPE,
airportDoor, 0, 0, 0, -1, PAX_SPEED)
                        veh.SetAttValue("PickupGenerated", 1)
                        if veh.AttValue("DwellTm") < PICKUP_INTERVAL:
                            veh.SetAttValue("DwellTm",
veh.AttValue("DwellTm") + PICKUP_INTERVAL)
            else:
                veh.SetAttValue("AlightPax", 0)
                veh.SetAttValue("PickupGenerated", 0)
        i=i+1
#=========================================================================
=====================

#=========================================================================
=====================
def CheckIfVehicleShouldLeave():
    """
    Checks the state of the vehicle after exiting the curbside area to
check if it should be updating to leave the airport area or retry to drop
off or pick up a vehicle
    """


#*************************************************************************
*************************************************************************
***
```

```
    #                    ATTENTION
ATTENTION                                          ATTENTION

#*************************************************************************
*************************************************************************
***
    #The below vehicle attributes are user added and need to be adjusted
to fit the values picked for the scenario

    for veh in exitVehicleCheckLink.Vehs:
        # if the vehicle was assigned a parking space change it back to
simply being a parked vehicle type
        if veh.AttValue("VehType")=="5001" or
veh.AttValue("VehType")=="5002" or veh.AttValue("VehType")=="5003" or
veh.AttValue("VehType")=="5004" or veh.AttValue("VehType")=="5005" or
veh.AttValue("VehType")=="5006"or veh.AttValue("VehType")=="5007"or
veh.AttValue("VehType")=="5008"or veh.AttValue("VehType")=="5009"or
veh.AttValue("VehType")=="5010"or veh.AttValue("VehType")=="5011"or
veh.AttValue("VehType")=="5012"or veh.AttValue("VehType")=="5013"or
veh.AttValue("VehType")=="5014"or veh.AttValue("VehType")=="5015"or
veh.AttValue("VehType")=="5016"or veh.AttValue("VehType")=="5017"or
veh.AttValue("VehType")=="5018"or veh.AttValue("VehType")=="5019"or
veh.AttValue("VehType")=="5020":
            veh.SetAttValue("VehType",1000)

        # checks if there is only one person in the vehicle and that the
vehicle is currently of the type to drop someone off (last edit check hard
coded as 1000 as a customly added Vehicle Type)
        if  veh.AttValue("Occup")==1 and veh.AttValue("VehType")=="1000":
            # Vehicle type 9999 hardcoded as vehicle with a routing
decision to leave
           veh.SetAttValue("VehType",9999)

        if veh.AttValue("Occup")==0 and veh.AttValue("VehType")=="2000":
            #autonomous vehicle has successfully dropped people off at the
curbside so it should return to the parking garage
            veh.SetAttValue("VehType",2001)
def DestinationParkingSpace(ParkingSpace):
    """
```

```
    Series of if statements to find the parking space.  The parking space
numbering is connected to the Parking Routing Decision not the parking
space number
    This function is hardcoded and must be adjusted for the scenario in
question

    """
    if ParkingSpace == "1-1" or ParkingSpace == "1-1" or ParkingSpace ==
"11-1":
        return 1
    elif ParkingSpace == "1-2" or ParkingSpace == "2-1" or ParkingSpace ==
"12-1":
        return 2
    elif ParkingSpace == "1-3" or ParkingSpace == "3-1" or ParkingSpace ==
"13-1":
        return 3
    elif ParkingSpace == "1-4" or ParkingSpace == "4-1" or ParkingSpace ==
"14-1":
        return 4
    elif ParkingSpace == "1-5" or ParkingSpace == "5-1" or ParkingSpace ==
"15-1":
        return 5
    elif ParkingSpace == "1-6" or ParkingSpace == "6-1" or ParkingSpace ==
"16-1":
        return 6
    elif ParkingSpace == "1-7" or ParkingSpace == "7-1" or ParkingSpace ==
"17-1":
        return 7
    elif ParkingSpace == "1-8" or ParkingSpace == "8-1" or ParkingSpace ==
"18-1":
        return 8
    elif ParkingSpace == "1-9" or ParkingSpace == "9-1" or ParkingSpace ==
"19-1":
        return 9
    elif ParkingSpace == "1-10" or ParkingSpace == "10-1" or ParkingSpace
== "20-1":
        return 10
    elif ParkingSpace == "1-11":
        return 11
    elif ParkingSpace == "1-12":
```

```
        return 12
    elif ParkingSpace == "1-13":
        return 13
    elif ParkingSpace == "1-14":
        return 14
    elif ParkingSpace == "1-15":
        return 15

def CheckIfAutonomousVehicleShouldPark():
    """
    A script to control autonomous vehicle behaviour
    Relies on knowing which links the autonomous vehicle is on in the
model
    """

    i=0
    vehiclesInCurbsideParkingArea=0
    while laybyLinkNoStart+i<laybyLinkNoEnd+1:
        # Puts links stored in the global list into a local variable as
referencing the link properties cannot be done by referencing the link
directly
        currentLink = laybyLink[i]


#*************************************************************************
*************************************************************************
***
        #                    ATTENTION
    ATTENTION                                          ATTENTION

#*************************************************************************
*************************************************************************
***
        #The below vehicle attributes are user added and need to be
adjusted to fit the values picked for the scenario
        for autoveh in autonomousVehicleParkingCheckLink.Vehs:
            #autoveh.SetAttValue("Test",1)
            vehiclesInCurbsideParkingArea=0
            for veh in currentLink.Vehs:
                if not veh.AttValue("VehType") == "3000":
```

```
                    vehiclesInCurbsideParkingArea +=1

            if vehiclesInCurbsideParkingArea >= 7: #number of parking
spaces in model
                #autoveh.SetAttValue("VehType",1001)
                autoveh.SetAttValue("Speed",0)
                autoveh.SetAttValue("DesSpeed",0.00)
            else:
                #autoveh.SetAttValue("VehType",1000)
                autoveh.SetAttValue("DesSpeed",20)


        i=i+1
def PlatoonParking():
    """
    A script to simulate autonomous vehicles parking in a platoon fashion.
 All vehicles move together to take up all available parking spaces so
there is no need for a driving lane
    """


#*************************************************************************
*************************************************************************
***
    #                    ATTENTION
ATTENTION                                          ATTENTION

#*************************************************************************
*************************************************************************
***
    #code below must be customized to how many lanes are being used to
park

    # a rolling total of vehicles assigned to parking to keep track of
where to assign the next vehicle to park
    global vehiclesAssignedToParking
    vehiclesAssignedToParking =
autonomousVehicleParkingCheckLink.AttValue("PlatoonParkingCheck")

    # assigns each vehicle
```

```
    for autoveh in autonomousVehicleParkingCheckLink.Vehs:

        if autoveh.AttValue("VehiclePlatoonParkingCheck")==0:

            if vehiclesAssignedToParking==0 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5001)
            elif vehiclesAssignedToParking==1 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5002)
            elif vehiclesAssignedToParking==2 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5003)
            elif vehiclesAssignedToParking==3 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5004)
            elif vehiclesAssignedToParking==4 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1
```

```
autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5005)
            elif vehiclesAssignedToParking==5 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5006)
            elif vehiclesAssignedToParking==6 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5007)
            elif vehiclesAssignedToParking==7 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5008)
            elif vehiclesAssignedToParking==8 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5009)
            elif vehiclesAssignedToParking==9 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1
```

```
autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5010)
            elif vehiclesAssignedToParking==10 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5011)
            elif vehiclesAssignedToParking==11 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5012)
            elif vehiclesAssignedToParking==12 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5013)
            elif vehiclesAssignedToParking==13 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5014)
            elif vehiclesAssignedToParking==14 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1
```

```
autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5015)
            elif vehiclesAssignedToParking==15 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5016)
            elif vehiclesAssignedToParking==16 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5017)
            elif vehiclesAssignedToParking==17 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5018)
            elif vehiclesAssignedToParking==18 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5019)
            elif vehiclesAssignedToParking==19 and
autoveh.AttValue("VehType")== "1000":
                vehiclesAssignedToParking+=1
```

```
autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
                autoveh.SetAttValue("VehiclePlatoonParkingCheck",1)
                autoveh.SetAttValue("VehType",5020)
            # all parking spaces have been assigned, restart the
assignment
            elif vehiclesAssignedToParking == 20:
                vehiclesAssignedToParking = 0

autonomousVehicleParkingCheckLink.SetAttValue("PlatoonParkingCheck",vehicl
esAssignedToParking)
def ParkingGarageShuttle():
    """
    Using the parking garage as extra staging space for more people per
vehicle at the curbside
    Theory is vehicles spend the same time unloading at the parking garage
as they would have otherwise unloading at the curbside.
    Record maximum needed parking spaces needed at the parking garage to
make this work
    """
    global parkingGarageVehiclesOccupationAndDwellTime
    global parkingGarageVehiclesCount
    global parkingGarageVehiclesCountMax
    global parkingGarageVehiclesThatHaveLeft
    global autonomousShuttleOccupancy
    global autonomousShuttleCount

    if Vissim.Net.Simulation.SimulationSecond < 10:
        autonomousShuttleOccupancy=0
        autonomousShuttleCount=0
        parkingGarageVehiclesCountMax = 0
        parkingGarageVehiclesThatHaveLeft=0
        parkingGarageVehiclesCount=0
        parkingGarageVehiclesOccupationAndDwellTime=[[0, 0, 0]] #thus
[0,0,0] is empty and should be never referenced


#*********************************************************************
```

```
*************************************************************************
***
    #                    attention
attention                                          attention

#*************************************************************************
*************************************************************************
***
    if Vissim.Net.Simulation.SimulationSecond == 3599:
#ATTENTION(simulation time is manually set) manually record the max number
of vehicles in the parking garage just before the simulation ends at max
time
        f=open("Test.txt","a+")
        f.write("Max Parking Garage Occupancy by Arriving Vehicles: %d\r"
%parkingGarageVehiclesCountMax)
        f.write("Total Autonomous Shuttle Trips: %d\r"
%autonomousShuttleCount)
        f.close()


#*************************************************************************
*************************************************************************
***
    #                    attention
attention                                          attention

#*************************************************************************
*************************************************************************
***
    for veh in parkingGarageEntrance.Vehs:

            if veh.AttValue("DesSpeed") == 0 and not
veh.AttValue("VehType")=="2001":      #ATTENTION(number for vehicle type
is manually added) When DesSpeed changes to 0, DwellTime is > 0
                #This throws an error if the parking route is not assigned
before checking for it

parkingGarageVehiclesOccupationAndDwellTime.append([veh.AttValue("Occup")-
1,veh.AttValue("DwellTm"),Vissim.Net.Simulation.SimulationSecond])
                veh.SetAttValue("DwellTm",0)
```

```
                parkingGarageVehiclesCount += 1
            else: # it is a returning autonomous vehicle, don't add it to
the garage count
                veh.SetAttValue("DwellTm",0)


    # if current simulation time is equal or greater than vehicle arrival
time plus dwell time then increase the occupancy of the shuttle vehicle by
the occupancy of the current
    if parkingGarageVehiclesCount >= 1:
        i=1
        while i<len(parkingGarageVehiclesOccupationAndDwellTime):
            if Vissim.Net.Simulation.SimulationSecond >=
parkingGarageVehiclesOccupationAndDwellTime[i][2] +
parkingGarageVehiclesOccupationAndDwellTime[i][1]:
                #only assign the people to the shuttle if they can stay
together

#Vissim.Net.Links.ItemByKey(301).SetAttValue("Test",Vissim.Net.Links.ItemB
yKey(301).AttValue("Test")+1)
                if autonomousShuttleOccupancy +
parkingGarageVehiclesOccupationAndDwellTime[i][0]<=4:
                    autonomousShuttleOccupancy
+=parkingGarageVehiclesOccupationAndDwellTime[i][0]
                    parkingGarageVehiclesCount += -1
                    parkingGarageVehiclesThatHaveLeft += 1
                    # code to create "empty" vehicle on link 401

Vissim.Net.Vehicles.AddVehicleAtLinkPosition("9999",401,1,0,40,1)
                    # remove the entry from the list

parkingGarageVehiclesOccupationAndDwellTime.remove(parkingGarageVehiclesOc
cupationAndDwellTime[i])



                # they could not stay together so send the shuttle to the
curbside
                # sends shuttle to curbside at first occurance of not
having space instead of optimizing by searching the next vehicle, this
functionality could be added
```

```
                else:
                    # code to create autonomous shuttle on link 401

Vissim.Net.Vehicles.AddVehicleAtLinkPosition("2000",401,1,0,40,1)
                    autonomousShuttleCount += 1
                    for autoShuttle in parkingGarageExit.Vehs:
                        if autoShuttle.AttValue("Occup")==1:

autoShuttle.SetAttValue("Occup",autonomousShuttleOccupancy)
                    autonomousShuttleOccupancy = 0
            i+=1
    if parkingGarageVehiclesCount > parkingGarageVehiclesCountMax:
        parkingGarageVehiclesCountMax = parkingGarageVehiclesCount

parkingGarageEntrance.SetAttValue("ParkingGarageMaxCount",parkingGarageVeh
iclesCountMax)


def CityShuttle():
    CheckDepartureTimeOfCityShuttle()
    CityShuttlePassengers()


def CheckDepartureTimeOfCityShuttle():
    """
    This function controls ensuring that the departure time of the shuttle
is upheld at the curbside. VISSIM currently handles bus times as
scheduling arrival times, with some ability to add variance,
    and then giving a dwell time distribution to the bus at the stop. This
dwell time can follow either a given dristribution or be calculated based
on the occupants. At the airport this dwell time depends instead
    on leaving based on a set time so it is variable depending on when the
bus arrived at the stop. To accomplish this, this code checks the arrival
time of the shuttle compared to when it should have arrived
    and adjusts the dwell time accordingly. It adds time to allow all
boarded passengers to leave if needed. It adds time to allow boarding
passengers to board if needed.
    """
    # getting the layby(curbside) link
    i=0
    while laybyLinkNoStart+i<laybyLinkNoEnd+1:
```

```
        currentLink = laybyLink[i]
        # checking all the vehicles on the curbside link
        for veh in currentLink.Vehs:

#*************************************************************************
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***
            #                    attention
        attention                                          attention

#*************************************************************************
*************************************************************************
***
            # if the vehicle is a city shuttle. Manually created vehicle
type
            if veh.AttValue("VehType")=="3000" and not
veh.AttValue("CityShuttleArrivalCheck"):
                # getting the current second of the simulation
                simulationSecond = Vissim.Net.Simulation.SimulationSecond
                #checking the dwell time compared to each 15 minute
departure time. Doesn't account for if the shuttle is behind by a full
time slot
                if veh.AttValue("DwellTm") + simulationSecond > 450 and
simulationSecond < 450:
                    veh.SetAttValue("DwellTm",450-simulationSecond)
                    if
veh.AttValue("DwellTm")<(veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIANW
AITINGATCURBSIDE*BOARDING_INTERNAL):

veh.SetAttValue("DwellTm",veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIAN
WAITINGATCURBSIDE*BOARDING_INTERNAL)
                elif veh.AttValue("DwellTm") + simulationSecond > 900 and
simulationSecond < 900:
                    veh.SetAttValue("DwellTm",900-simulationSecond)
                    if
veh.AttValue("DwellTm")<(veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIANW
AITINGATCURBSIDE*BOARDING_INTERNAL):

veh.SetAttValue("DwellTm",veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIAN
WAITINGATCURBSIDE*BOARDING_INTERNAL)
```

```
                elif veh.AttValue("DwellTm") + simulationSecond > 1350 and
simulationSecond < 1350:
                    veh.SetAttValue("DwellTm",1350-simulationSecond)
                    if
veh.AttValue("DwellTm")<(veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIANW
AITINGATCURBSIDE*BOARDING_INTERNAL):

veh.SetAttValue("DwellTm",veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIAN
WAITINGATCURBSIDE*BOARDING_INTERNAL)
                elif veh.AttValue("DwellTm") + simulationSecond > 1800 and
simulationSecond < 1800:
                    veh.SetAttValue("DwellTm",1800-simulationSecond)
                    if
veh.AttValue("DwellTm")<(veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIANW
AITINGATCURBSIDE*BOARDING_INTERNAL):

veh.SetAttValue("DwellTm",veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIAN
WAITINGATCURBSIDE*BOARDING_INTERNAL)
                elif veh.AttValue("DwellTm") + simulationSecond > 2250 and
simulationSecond < 2250:
                    veh.SetAttValue("DwellTm",2250-simulationSecond)
                    if
veh.AttValue("DwellTm")<(veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIANW
AITINGATCURBSIDE*BOARDING_INTERNAL):

veh.SetAttValue("DwellTm",veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIAN
WAITINGATCURBSIDE*BOARDING_INTERNAL)
                elif veh.AttValue("DwellTm") + simulationSecond > 2700 and
simulationSecond < 2700:
                    veh.SetAttValue("DwellTm",2700-simulationSecond)
                    if
veh.AttValue("DwellTm")<(veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIANW
AITINGATCURBSIDE*BOARDING_INTERNAL):

veh.SetAttValue("DwellTm",veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIAN
WAITINGATCURBSIDE*BOARDING_INTERNAL)
                elif veh.AttValue("DwellTm") + simulationSecond > 3150 and
simulationSecond < 3150:
                    veh.SetAttValue("DwellTm",3150-simulationSecond)
```

```
                    if
veh.AttValue("DwellTm")<(veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIANW
AITINGATCURBSIDE*BOARDING_INTERNAL):

veh.SetAttValue("DwellTm",veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIAN
WAITINGATCURBSIDE*BOARDING_INTERNAL)
                elif veh.AttValue("DwellTm") + simulationSecond > 3600 and
simulationSecond < 3600:
                    veh.SetAttValue("DwellTm",3600-simulationSecond)
                    if
veh.AttValue("DwellTm")<(veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIANW
AITINGATCURBSIDE*BOARDING_INTERNAL):

veh.SetAttValue("DwellTm",veh.AttValue("Occup")*ALIGHT_INTERVAL+PEDESTRIAN
WAITINGATCURBSIDE*BOARDING_INTERNAL)

                CityShuttleArrivalCheck(veh.AttValue("DwellTm"))

        i=i+1

def CityShuttleArrivalCheck(cityShuttleDwellTime):
    """
    Handles checking if the city shuttle has arrived at the parking spot.
Records this time and the related dwell time of the city shuttle
    """
    i=0
    while laybyLinkNoStart+i<laybyLinkNoEnd+1:
        currentLink = laybyLink[i]
        for veh in currentLink.Vehs:
            if not veh.AttValue("CityShuttleArrivalCheck") and
veh.AttValue("VehType")=="3000" and veh.AttValue("DesSpeed")==0:
                veh.SetAttValue("CityShuttleArrivalCheck",1)
                f=open("CityShuttleDwellTime2xSupply2xDemand.txt","a+")
                f.write("Shuttle Arival Time: %d\r"
%Vissim.Net.Simulation.SimulationSecond)
                f.write("Shuttle Dwell Time: %d\r"
%(cityShuttleDwellTime))
                f.close()
        i=i+1
```

```
def CityShuttlePassengers():
    """
    Keeps track of all the pedestrians that have been gerenated to wait
for a city shuttle
    """

    global PEDESTRIANWAITINGATCURBSIDE
    global PEDESTRIANWAITINGATCITY
    global PEDESTRIANWAITINGATCURBSIDEWAITTIME
    global PEDESTRIANWAITINGATCITYWAITTIME
    global PEDESTRIANWAITINGATCURBSIDECOUNT
    global PEDESTRIANWAITINGATCITYCOUNT


    if Vissim.Net.Simulation.SimulationSecond == 3599:
#ATTENTION(simulation time is manually set) manually record the max number
of vehicles in the parking garage just before the simulation ends at max
time
        f=open("CityShuttleWaitingPassengers2xSupply2xDemand.txt","a+")
        f.write("Total Count of Passengers Arrived at City Location: %d\r"
%PEDESTRIANWAITINGATCITYCOUNT)
        f.write("Total Time Spent Waiting by All Passengers at City
Location: %d\r" %PEDESTRIANWAITINGATCITYWAITTIME)
        f.write("Remaining City Location Passengers Waiting: %d\r"
%PEDESTRIANWAITINGATCITY)
        f.write("Total Count of Passengers Arrived at Curbside: %d\r"
%PEDESTRIANWAITINGATCURBSIDECOUNT)
        f.write("Total Time Spent Waiting by All Passengers at Curbside
%d\r" %PEDESTRIANWAITINGATCURBSIDEWAITTIME)
        f.write("Remaining Curbside Location Passengers Waiting: %d\r"
%PEDESTRIANWAITINGATCURBSIDE)
        f.write("")
        f.close()


    #counting the wait time by the travellers at the curbside and city
location (counts at every full second)
    if Vissim.Net.Simulation.SimulationSecond % 1 == 0:
        PEDESTRIANWAITINGATCURBSIDEWAITTIME =
PEDESTRIANWAITINGATCURBSIDEWAITTIME + PEDESTRIANWAITINGATCURBSIDE
```

```
        PEDESTRIANWAITINGATCITYWAITTIME = PEDESTRIANWAITINGATCITYWAITTIME
+ PEDESTRIANWAITINGATCITY




    #counting the pedestrians at the curbside
    for ped in Vissim.Net.Areas.ItemByKey("2").Peds:
        if not ped.AttValue("PedestrianCounted"):
            PEDESTRIANWAITINGATCURBSIDE = PEDESTRIANWAITINGATCURBSIDE + 1
            PEDESTRIANWAITINGATCURBSIDECOUNT =
PEDESTRIANWAITINGATCURBSIDECOUNT +1
            ped.SetAttValue("PedestrianCounted",1)

    #counting the pedestrians at the city location
    for ped in Vissim.Net.Areas.ItemByKey("3").Peds:
        if not ped.AttValue("PedestrianCounted"):
            PEDESTRIANWAITINGATCITY = PEDESTRIANWAITINGATCITY+1
            PEDESTRIANWAITINGATCITYCOUNT = PEDESTRIANWAITINGATCITYCOUNT +
1
            ped.SetAttValue("PedestrianCounted",1)

    # removing travellers from the city shuttle when it arrives at the
curbside
    i=0
    while laybyLinkNoStart+i<laybyLinkNoEnd+1:
        currentLink = laybyLink[i]
        # checking all the vehicles on the curbside link
        for veh in currentLink.Vehs:
            #
            if veh.AttValue("VehType")=="3000" and
veh.AttValue("DesSpeed")==0 and veh.AttValue("DwellTm")<5 and not
veh.AttValue("CityShuttleHasDroppedOff"):
                if PEDESTRIANWAITINGATCURBSIDE<=20:
                    veh.SetAttValue("Occup",PEDESTRIANWAITINGATCURBSIDE)
                    PEDESTRIANWAITINGATCURBSIDE = 0
                elif PEDESTRIANWAITINGATCURBSIDE > 20:
                    veh.SetAttValue("Occup",20)
```

```
                    PEDESTRIANWAITINGATCURBSIDE =
PEDESTRIANWAITINGATCURBSIDE - 20

                veh.SetAttValue("CityShuttleHasDroppedOff",1)
        i=i+1


    for veh in Vissim.Net.Links.ItemByKey("11").Vehs:
        if veh.AttValue("VehType")=="3000" and not
veh.AttValue("CityShuttlePassengersFromCity"):
            if PEDESTRIANWAITINGATCITY <= 20:
                veh.SetAttValue("Occup", PEDESTRIANWAITINGATCITY)
                PEDESTRIANWAITINGATCITY = 0
            elif PEDESTRIANWAITINGATCITY > 20:
                veh.SetAttValue("Occup", 20)
                PEDESTRIANWAITINGATCITY = PEDESTRIANWAITINGATCITY - 20

            veh.SetAttValue("CityShuttlePassengersFromCity",1)

#==========================================================================
=====================

#==========================================================================
=====================
# Helpers
```

```
#==========================================================================
=====================

def GetAndCheckScriptUDA(udaName):
    """
    Reads the value of script UDA 'UdaName' and returns it if > 0.
    Otherwise stops the simulation and returns 0.
    Required globals: currentScriptFileNoPath.
    """

    if CurrentScript.AttValue(udaName) <= 0:
        msgString = "Please enter a valid number for the script attribute
'" + udaName + "'\n" + "for '" + currentScriptFileNoPath+ "'"
        ctypes.windll.user32.MessageBoxA(0, msgString, "Warning", 0)
        Vissim.Simulation.Stop()
        return 0

    return CurrentScript.AttValue(udaName)

#==========================================================================
=====================
def BoundsCheck():
    """
    Ensures that the script period is small enough for the script to run
correctly.
    Required globals: parkingDwellTmLowerBound, ALIGHT_INTERVAL,
currentScriptFileNoPath

    As the script period may be changed during a simulation run, the
bounds check is not only run
    before sim start but every time the script is executed.
    The script GeneratePassengers needs to be exectured at least as often
as passengers are allowed
    to alight (ALIGHT_INTERVAL) and as often as the min. dwell time before
the first passenger exits.
    """

    simRes = Vissim.Simulation.AttValue("SimRes")

    if parkingDwellTmLowerBound < ALIGHT_INTERVAL:
```

```
        maxPeriod = parkingDwellTmLowerBound * simRes
    else:
        maxPeriod = ALIGHT_INTERVAL * simRes

    scriptPeriod = CurrentScript.AttValue("Period")

    if maxPeriod == 0:
        msgString = "You need to increase the simulation resolution in
order for the script 'Generate Passengers' to run correctly. The
simulation will be stopped now."
        ctypes.windll.user32.MessageBoxA(0, msgString, "Warning", 0)
        Vissim.Simulation.Stop()
    else:
        if scriptPeriod > maxPeriod:
            msgString = "The script period of " + str(scriptPeriod) + "
for '" + currentScriptFileNoPath + "'\n"
            msgString += "is too coarse for the currently defined\n"
            msgString += "alighting interval and alighting stop time.\n"
            msgString += "Hence it is reduced to the maximum value of " +
str(maxPeriod) + "."
            ctypes.windll.user32.MessageBoxA(0, msgString, "Warning", 0)

            CurrentScript.SetAttValue("Period", maxPeriod)

#=========================================================================
=====================
# End of script
#=========================================================================
=====================
```

Appendix C: MassMotion C# Code

This code is provided as is in a best effort to present the code used to produce the model results. The code is written to be used alongside specific MassMotion scenarios and is not applicable to other MassMotion scenarios unless they are built to fit this code. Values of the code are meant to be changed depending on the conditions of each MassMotion scenario. Not all portions of the code are relevant for every MassMotion scenario as they were built to be called as needed from within the model.

```
#include <massmotion/all.h>
#include <windows.h>
#include <iostream>
#include <unordered_map>
#include <cassert>
#include <cmath>
#include <string>
#include <unordered_map>
#include <random>

using namespace massmotion;
using namespace std;


//function controlling the movement characteristics of agents while they
are on treadmills
void whileOnTreadmill (Vec3d& nextVelocity, Vec3d desiredVelocity, Vec3d&
nextPosition, Vec3d& currentPosition, double frameLength, Vec3d
currentEscalatorSpeed);


int main(int argc, char** argv)
{
    try
    {
        Sdk::Init();
```

```
        if (argc != 3)
        {
            std::cout << "Run as CustomEscalator.exe ProjectFilename.mm
OutputFilename.mmdb" << std::endl;
            return 1;
        }

        ProjectPtr pProject = Project::Open(argv[1]);

        // Get the full path to the output file
        char outputPath[1024];
        GetFullPathNameA(argv[2], 1024, outputPath, NULL);

        SimulationPtr pSimulation = Simulation::Create(pProject, "SdkRun",
outputPath);

        double frameLength = pSimulation->GetFrameLength();
        //double maxAcceleration = 3.0;
        //double maxRadius = 3.0;
        //double neighborForceScale = 10.0;


        // Variables needed to assign speeds for agents while on
escalators

        // Generating normal distribution of movement profile while on
escalator
        default_random_engine generator;
        normal_distribution<double> distribution(2.80, 0.66); //speed of
people with roller on people mover
        //the array that will hold all the speeds agents will move at
while on escalators to a max of 5000 agents
        double escalatorSpeeds[5000][2];
        Vec3d escalatorDirection[5000];
        Vec3d previousPosition[5000];
        double positionID[5000];
        //integer to keep track of if an agent's previous position has
been established
        int positionEstablished = 0;
```

```
        //integer to keep track of where values are being assigned in
position array
        int positionOrder = 1;
        //intiger to keep track of where values are being assigned in the
speed array
        int order = 1;
        // Intiger to keep track of if the speed for the agent while on an
escalator has been created
        int speedDone = 0;
        // loop variable
        int i = 1;
        int incorrectMovementCount= 0;


        /*int Escalator1 = !pProject->GetEscalator("Escalator1");
        int Escalator2 = !pProject->GetEscalator("Escalator2");
        int Escalator3 = !pProject->GetEscalator("Escalator3");
        int Escalator4 = !pProject->GetEscalator("Escalator4");
        int Escalator5 = !pProject->GetEscalator("Escalator5");
        int Escalator6 = !pProject->GetEscalator("Escalator6");*/



        while (!pSimulation->IsDone())
        {



            int currentFrame = pSimulation->GetCurrentFrame();

            std::vector<AgentPtr> createdAgents = pSimulation-
>CreateAgents();
            pSimulation->ChooseAgentTargets();





            for (const AgentPtr& pAgent : pSimulation->GetAllAgents())
            {
```

```
                Vec3d       currentPosition = pAgent->GetPosition();

                Vec3d       currentVelocity = pAgent->GetVelocity();
                GlobalId    currentFloor = pAgent->GetCurrentFloorId();
                //GlobalId currentEscalator = pAgent-
>GetCurrentEscalatorId();




                int id = pAgent->GetId();

                //pAgent->AssumeControl();
                //pAgent->ReleaseControl();

                try
                {

                    if (!pAgent->HasPathToTargetWaypoint())
                    {

                        // Agent must have been bumped off floor - move
them back
                        //GetClosestPointWithPathToTargetWaypoint(double
dSearchRadius);
                        //Vec3d closestPoint = pAgent-
>GetOpenPointClosestTo(currentPosition, 1.0);
                        // Agent must have been bumped off floor - move
them back
                        pAgent->AssumeControl();

                        try
                        {
                            Vec3d closestPoint = pAgent-
>GetClosestPointWithPathToTargetWaypoint(1.0);
                            //std::cout << "Agent " << pAgent->GetId() <<
" is off floor in frame " << currentFrame << ", moving to " <<
closestPoint << std::endl;
```

```
                            pAgent->MoveTo(closestPoint);
                            //currentPosition = closestPoint;
                        }
                        // Agent is not on any special floor type
                        catch (const Exception& exception)
                        {

                            // Releasing control of the agent back to
massmotion
                            pAgent->ReleaseControl();


                        }

                    }
                    else
                    {
                        if (pAgent->HasTargetWaypoint())
                        {


                            // Initiallizing movement variables
                            Vec3d nextVelocity = currentVelocity;
                            Vec3d nextPosition = currentPosition;





                            Vec3d goalDirection = pAgent-
>GetDirectionToTargetWaypoint();
                            Vec3d desiredVelocity = currentVelocity;
                            //Vec3d goalForce = (desiredVelocity -
currentVelocity) / frameLength;
```

```
                            // Checking if the agent is on people mover
(classified as an escalator) but keeping them from being affected if they
are on an actual escalator
                            try
                            {
                                if (pProject->GetEscalator(currentFloor)
&& !(pProject->GetEscalator(currentFloor) == pProject-
>GetEscalator("Escalator1") || pProject->GetEscalator(currentFloor) ==
pProject->GetEscalator("Escalator2") || pProject-
>GetEscalator(currentFloor) == pProject->GetEscalator("Escalator3") ||
pProject->GetEscalator(currentFloor) == pProject-
>GetEscalator("Escalator4") || pProject->GetEscalator(currentFloor) ==
pProject->GetEscalator("Escalator5") || pProject-
>GetEscalator(currentFloor) == pProject->GetEscalator("Escalator6")))
                                {



                                    // This has the code take control of
all the agents
                                    pAgent->AssumeControl();
                                    //AllowAdjustment to let massmotion
help keep agents from walking into eachother
                                    // DisallowAdjustment keeps massmotion
from adjusting agent behaviour from walking into eachother (agents can
overlap and walk through eachother)
                                    pAgent->AllowAdjustment();
                                    // Make the agent look like they are
walking, purely for visual purposes
                                    pAgent->SetNextMovementType(WALKING);


                                    //going through the list of created
agent speeds on escalators and checking if the current agent has been
given a speed while on an escalator, limited to a max of 5000 agents
created in total
                                    i = 1;
                                    for (i = 1; i < 5000; ++i)
                                    {
                                        if (pAgent->GetId() ==
escalatorSpeeds[i][1])
```

```
                                        {
                                            //Agents speed on escalators
has already been created, exit the loop
                                            speedDone = 1;
                                            break;

                                        }



                                    }

                                    // Checking to see if it was found
that the agent has not been given a speed while on an escalator
                                    if (speedDone == 0)
                                    {
                                        //Agent's speed on escalators has
not been created

                                        // Assigning a speed
                                        escalatorSpeeds[order][1] =
pAgent->GetId();
                                        escalatorSpeeds[order][2] =
distribution(generator);
                                        //escalatorDirection[order] =
pAgent->GetDirectionToTargetWaypoint();
                                        order = order + 1;

                                    }





                                    // Telling the program what the
agent's desired speed on the escalator is
                                    if (speedDone == 1)
                                    {
                                        // Agent was found to already have
a speed saved at the i position in the array
```

```
                                        //desiredVelocity =
escalatorDirection[i]*escalatorSpeeds[i][2] ;
                                        desiredVelocity = goalDirection *
escalatorSpeeds[i][2];
                                    }
                                    else
                                    {
                                        // First time the agent was
assigned a speed so the speed was just saved at the order position in the
array
                                        //desiredVelocity =
escalatorDirection[order-1]*escalatorSpeeds[order - 1][2];
                                        desiredVelocity = goalDirection *
escalatorSpeeds[order - 1][2];
                                    }

                                    // Resetting the speed check so the
next agent will be given a speed if they are not found to already be saved
in escalatorSpeeds
                                    speedDone = 0;




                                    //Vec3d currentEscalatorSpeed =
goalDirection * pProject->GetEscalator(currentFloor)-
>GetTreadSpeedAlongIncline();
                                    //cout << "Current Escalator Speed ="
<< currentEscalatorSpeed << endl;
                                    nextVelocity = desiredVelocity;
                                    //nextPosition = currentPosition +
desiredVelocity * frameLength;
                                    nextPosition = currentPosition +
nextVelocity * frameLength;
                                    //whileOnTreadmill(nextVelocity,
desiredVelocity, nextPosition, currentPosition, frameLength,
currentEscalatorSpeed);

                                    if (!pAgent-
>IsInOpenSpace(nextPosition))
                                    {
```

```
                                        // Agent would move into an
obstacle or off a floor - aim for the closest open point instead
                                        pAgent->MoveTo(pAgent-
>GetOpenPointClosestTo(nextPosition + nextPosition * .1, 0.1));
                                        pAgent->SetColor(Color(100, 0,
0));
                                        //cout << "incorrect movement" <<
endl;

                                    }
                                    else
                                    {

                                        // Move is valid - go ahead and
apply
                                        pAgent->MoveTo(nextPosition,
nextVelocity);
                                        //pAgent->MoveTo(nextPosition);









                                    }

                                    //checking to see if the agent moved
at all and is potentially stuck on the escalators

                                    //going through the list of created
agent speeds on escalators and checking if the current agent has been
given a speed while on an escalator, limited to a max of 5000 agents
created in total
```

```
                                }

                            }

                            // Agent is not on any special floor type
                            catch (const Exception& exception)
                            {

                                // Releasing control of the agent back to
massmotion
                                pAgent->ReleaseControl();

                            }
                            i = 1;
                            for (i = 1; i < 5000; ++i)
                            {
                                if (pAgent->GetId() == positionID[i])
                                {
                                    //Agents position on escalators has
already been created, exit the loop
                                    positionEstablished = 1;
                                    break;

                                }



                            }
                            //if the agent has had  a previous position
established then check if it has moved and otherwise remove it if it is
stationary
                            if (positionEstablished == 1 &&
currentPosition == previousPosition[i])
                            {
                                pAgent->ExitSimulation();
```

```
                            }
                            //position has been established but the agent
is moving so the previous position can be updated
                            else if (positionEstablished == 1)
                            {
                                previousPosition[i] = currentPosition;

                            }

                            // Checking to see if it was found that the
agent has not been given a position while on an escalator and giving it
one if it has
                            if (positionEstablished == 0)
                            {
                                //Agent's position on escalators has not
been created

                                // Assigning a position
                                previousPosition[positionOrder] =
currentPosition;
                                positionID[positionOrder] = pAgent-
>GetId();


                                positionOrder = positionOrder + 1;

                            }
                            //resetting position check
                            positionEstablished == 0;
                        }
                    }
                }
                //agent does not have a path to target waypoint
                catch (const Exception& exception)
                {
                    pAgent->ExitSimulation();
                }
            }

            // Advance the simulation by one frame
            pSimulation->MoveAgents();
```

```
        }

        Sdk::Fini();

        //cout << "Total incorrect movements " << incorrectMovementCount
<< endl;



    }
    catch (const Exception& exception)
    {
        std::cout << "ERROR: " << exception.what() << std::endl;
    }
}



void whileOnTreadmill(Vec3d& nextVelocity, Vec3d desiredVelocity, Vec3d&
nextPosition, Vec3d& currentPosition, double frameLength, Vec3d
currentEscalatorSpeed)
{

    // Move agent the speed of the treadmill + their base speed

    nextVelocity = currentEscalatorSpeed + desiredVelocity;
    nextPosition = currentPosition + nextVelocity * frameLength;



}
```