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A DECISION SUPPORT SYSTEM FOR ASSESSING CONVEYANCE OPTIONS AND MODELING PASSENGER FLOW IN AIRPORT TERMINALS

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A DECISION SUPPORT SYSTEM FOR ASSESSING CONVEYANCE OPTIONS AND MODELING PASSENGER FLOW IN AIRPORT TERMINALS

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Abstract

This dissertation focuses on the use of passenger conveyance systems and modeling passenger flow in airport terminals. The successfully designed airport concourse must perform at a level that meets the needs of its users – the passengers. In this research, we propose a database design methodology that allows key conveyance statistics to be analyzed within specific locations across the airport terminal. Using passenger conveyance observations collected at five North American airports, the database enables airport planners, operators and consultants to assess passenger behavior and conveyance device performance. Results from this section of the research were in direct support of the Airport Cooperative Research Program (ACRP).

In both vertical and horizontal mode choice analysis, two logistic models are developed to serve as predictors to examine the relationship between passenger characteristics and their choice of conveyance system and analyze the probabilities of a passenger choosing different conveyance devices in airport terminals. Our analyses through logistic models show that passengers tend not to use moving walkway with increasing number of rollers.

It is important for airport planners to provide an appropriate level of service (LOS) for airport passengers. To estimate potential congestion and meet service-level requirements in a concourse, we develop a series of simulation models to estimate the occupancy of any designated area (or footprint) within a concourse. Specifically, factors such as the number of gates, flight arrivals, aircraft size and gate configuration are considered in simulation models. We identify significant factors that affect the congestion

and establish a service level design standard matrix in the footprint area. We also introduce zones inside the concourse and examine how various diversions (concessions, restaurants, etc.) within the concourse and the capacity of departure lounge in each gate affect passenger congestion in each zone.

Finally, we combine the database and mode choice models into two comprehensive concourse simulation models: (1) concourse with moving walkway (2) concourse with vertical transition devices (escalator, elevator and stairs). We use these models to estimate passenger occupancy and the resulting LOS. This research provides an understanding into how various concourse operation strategies affect when and how passenger congestion forms within the terminal.

Dedication

This dissertation is lovingly dedicated to my mother, the most beautiful and intelligent person I know …

Acknowledgments

I know this is the most difficult part of this dissertation, because I hardly know how to express my gratitude on their support throughout my five years life in CLEMSON.

I am very grateful to my advisor, Dr. Kevin Taaffe, for his patient and insightful supervision of this body of work. I always remember I cannot even speak one sentence of English in our first meeting five years ago, but he always understands what I try to say. He has shown me what a scientist and person should be. I would also like to thank Dr. Byung Rae Cho, Dr. Anne Dunning, and Dr. Scott Shappell for being on my committee and all their invaluable insightful suggestions on my way to this point.

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Chapter 1

Introduction

In recent decades, air travel has become a preferred mode of transportation for business and non-business travelers [1]. According to a Federal Aviation Administration (FAA) report, the trend of increasing demand at our nation's regional and international airports is expected to continue, reaching over 978 million passengers by the year 2020 [2]. The commercial aviation demand forecast for mainline and regional air carriers is shown in Figure 1.1. This steady growth will have a direct impact on existing airport terminals; these facilities must be ready to accommodate the increasing demand of air passengers. This, in turn, requires that airport planners and designers provide for the future within today's airport facilities and adequately prepare for additional expansion needs. Planners must be considering how passenger conveyance systems such as moving sidewalks, escalators and elevators should be introduced to reduce passengers' walking distance or the overall exertion of his or her journey through the airport. A comprehensive study of airport passenger conveyance use is needed for evaluating airport performance, and we address key issues regarding the use and capabilities of such systems in place at several international airports in the U.S.

Another important aspect in assessing airport facility design is to analyze passenger congestion and flow through the airport terminal. Passenger congestion within the airport concourse is considered a very important index of airport performance, and pedestrian spacing is a major factor that determines the breakpoints of various service levels. Thus, occupancy presents an index for the evaluation of the Level of Service (LOS) of the operational components at an airport, and occupancy presents a global index for the evaluation of LOS for the whole passenger terminal [3].

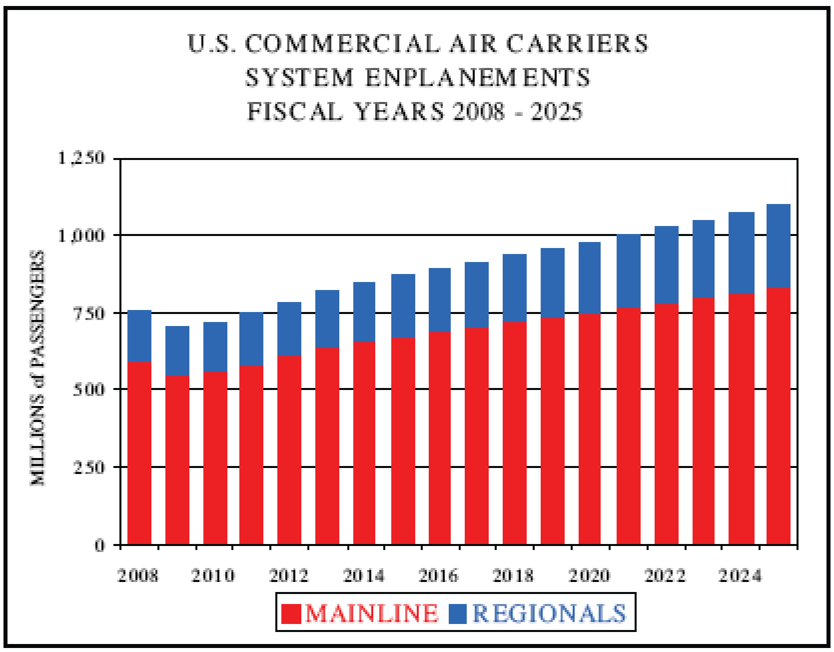


Figure 1.1 : FAA Aerospace Forecast Fiscal Years 2009–2025

This dissertation describes research focusing on the use of passenger conveyance systems in airport terminals and understanding how various concourse (or airline) operation strategies affect when and how passenger congestion forms within the terminal. Chapter 2 reviews previous work placed into five different categories: namely, passenger conveyance planning, pedestrian behavior and walking distance, LOS of pedestrian facilities, passenger conveyance systems and capacity of conveyance systems.

To prepare a comprehensive study about the use and role of passenger conveyance systems at airports, Chapter 3 presents an extensive data collection on passenger conveyance usage, throughput rates and other conveyance issues at five major airports. We then present an interactive database of information that allows a user to query based on each conveyance device in the sampled airports. The data analysis includes such items as the number of bags per passenger, passenger choice of available conveyance options and passenger walk vs. stand-on escalators and moving sidewalks. These statistics will serve as a decision-support tool for planning, designing and evaluating passenger conveyance systems at airports. To examine the relationship between a passenger's characteristics (such as the number of roller bags carried) and the mode choice, Chapter 4 presents a passenger mode choice analysis of conveyance device at airports.

Chapter 5 introduces a simulation model for estimating potential passenger congestion (or occupancy levels) within the concourse for different terminal configurations. The simulation model can help to determine the key factors that influence concourse occupancy and evaluate how the configuration of flight schedule, aircraft size and gate assignment impacts the corridor width requirements based on LOS design standards such as those recommended by Fruin [4].

In Chapter 6, the simulation model is extended to incorporate flexible zoning of a concourse, which includes the ability to place concessions, restaurants and restrooms adjacent to gates for a more accurate representation of concourse activities. Chapter 7 incorporates database information and mode choice modeling into a concourse simulation that depicts congestion levels with various conveyance devices installed. Also within Chapter 7, two scenarios (concourse with moving walkway and concourse with escalator, elevator and stairs) are simulated to estimate passenger occupancy and the resulting LOS. Finally, Chapter 8 presents our summary of this research and discusses topics for future research in this area.

Chapter 2

Literature Review

2.1. Introduction

In general, planners, designers and operators of airports face substantial challenges in how to move their passengers faster and more efficiently. To achieve acceptable passenger walking distances, within-terminal transit times (as well as aircraft-to-aircraft transfer times) and overall passenger comfort in terminals, several passenger mobility technologies are commonly used. These technologies include moving sidewalks, escalators, elevators, passenger assist vehicles, buses and automated people movers (APMs). We introduce related literature as it pertains to five main categories: passenger conveyance planning, pedestrian behavior and walking distance, LOS of pedestrian facilities, passenger conveyance systems and capacity of conveyance systems.

2.2. Planning For Passenger Conveyance Systems at Airports

There are many sources describing the process and guidelines for airport terminal planning [5-7]. In the Apron and Terminal Building Planning Manual, the Ralph M. Parsons Company [8] also provides guidance for planning airport apron-terminal complexes. They briefly discuss circulation; however, there is little mention concerning the effects of walking distances on passengers and their walking distance preferences.

The FAA [9] mentions the possibility of installing moving sidewalks, escalators and other conveyance modes to make excessive walking distances more tolerable.

In Planning and Design of Airports, Horonjeff and McKelvey [10] state that walking distance should be examined and considered in the terminal design development. As with other planning and design references, very few insights into acceptable walking distances are provided. Wells [11] and Odoni and de Neufville [12] also mention that airports should consider minimizing walking distances for passengers when designing terminal building space requirements. Another widely used planning guideline is provided by the International Air Transport Association (IATA) [13], which suggests a maximum passenger walking distance of 250-300m unaided and up to 650m with moving walkways. Delve [14] mentions that size and positioning of escalators and other people-mover systems at airports are very important to minimize the time and distance that passengers travel. He also suggests a strategy for exposing passengers to various revenue-generating sites such as stores and restaurants while proceeding through the terminal.

Design projects are not always focused on improving passenger travel time efficiency. Russell [15] reviews a project to expand the number of service stands at London’s Gatwick Airport. The focus of this article is on the use of a new passenger bridge that connects the North Terminal with the Pier 6 satellite building. While not specifically designed to reduce passenger travel times, the bridge provides passengers a direct pedestrian link to aircraft, saving an estimated 50,000 coach journeys a year. With 61m-long moving sidewalks and 10 meters between each sidewalk, it also provides an enjoyable walking experience for passengers.

When discussing optimal passenger terminal building configurations, de Neufville et al. [16] mention that moving sidewalks are a relatively inexpensive means to move people through an airport. In a comparison study, Leder [17] points out two critical reasons for using passenger mobility systems to help passenger movement within and between terminals: (1) continued vigorous growth in all categories of air travel for at least the next decade and (2) airline hubbing, which requires the transfer of large numbers of connecting passengers over long terminal distances in a short time.

2.3. Passenger Conveyance Systems

Moving walkways, courtesy carts, buses and APMs are the most frequently used mobility technologies in airport terminal. Leder [17] presents comprehensive reviews of each of the above modes. In this paper, the author also reviews the advantages, disadvantages and limitations of four airport terminal passenger mobility systems: moving sidewalks, courtesy carts, buses and APMs which are summarized in Table 2.1. Tough and O'Flaherty [18] describe the operational details of the various types of passenger conveyors. In addition, a comprehensive review of basic specifications of each installation is also included in this book. Kusumaningtyas and Lodewijks [19] provide a literature review on accelerated moving walkways (AMWs). In particular, they compare the characteristics of AMWs with other public transport systems--namely buses, light rail, APMs and Personal Rapid Transits (PRTs). They conclude that AMWs can be competitive to the other short-distance transport modes in terms of high-capacity people transport at relatively low costs. In addition, Al-Sharif [20] and Smith [21] have developed a great deal of information and comprehensive reviews of escalators in actual operations.

Table 2.1: Summary of Advantages and Disadvantages for Passenger Mobility Systems

Alternatives	Advantages	Disadvantages	Limitations
Moving sidewalks	• Moving sidewalks can be used effectively to aid passenger mobility when length does not exceed 1,000 to 1,500 ft.	• The slow tread way speed of 100 ft/min and the tendency to form barriers to cross-travel movements.	• Moving sidewalks can only provide point-to-point travel along straight lines.
Courtesy carts	• Carts offer flexibility that moving sidewalks and APMs do not. • Serve an important role in assisting handicapped passengers.	• Operate in mixed traffic with pedestrians on the aircraft boarding-de-boarding level terminal.	• Operational endurance between out-of-service periods for battery recharging varies widely depending on usage. • Practical safe operating speed is usually considerably less.
Buses	• Curbside stops are defined but can easily be changed. • Either scheduled or on-demand service is provided.	• Average speed is low. • Operation involve circuitous in relation to passengers' arrival and departure gates. • Sharing the right-of-way with other vehicles.	• Traffic congestion related origin-destination passengers occur during connecting bank.
APMs	• APMs offer a high level of schedule and trip time dependability. • Use an exclusive right-of-way.	• High infrastructure costs.	• Require careful attention to terminal architecture and structural engineering.

The conventional moving walkway is a pedestrian-carrying device where passengers may stand or walk. Moving sidewalk user safety aspects are discussed by Horonjeff and Hoch [22]. It is noted that traditional horizontal moving sidewalks are restricted to a maximum speed of 180 feet per minute, and it would be more desirable to define capacity as the rate at which users can enter the moving walk and not the rate at which they exit. This is because of a safety issue: people can easily to lose their balance, causing an injury when enter the moving walk. Thus, horizontal moving walks are normally restricted to a maximum speed.

Young [23] compares the moving walkway with other primary modes of airport terminal passenger transportation. The result shows that the average travel speed for passengers using moving walkways was only marginally higher than for those who chose to bypass the device. This is primarily due to a decrease in walking speeds ranging from 0.15 to 0.45 m/sec for passengers walking on conveyors. Moreover, Young develops a regression model to predict the travel speed and travel time of the passengers who have chosen to walk based on an empirical study of passenger conveyors at San Francisco International Airport. He considered many passenger characteristics, including gender, luggage, normal walking speed, group size, etc. In addition, discrete choice models were developed to predict the probability with which passengers will choose to use moving walkways (including the decision to walk or stand) or simply walk without assistance. The results indicated that the vast majority of passengers who used the moving walkways tended to walk instead of stand.

Joy [24] presents a historic synopsis of secure vs. non-secure travel path issues at George Bush International Airport/Houston, followed by an examination of non-secure inter-terminal passenger conveyance alternatives for the airport as a case study. The author states that the case study, George Bush International Airport/Houston, considers an existing Inter-Terminal Train (ITT), small technology APM, as a viable alternative for continuing to meet the low demand of non-secure passenger movements with a relatively high LOS. Kyle [25] conducts a study and presents a discrete-event simulation model to examine how existing and future operations would impact the mobile lounge fleets at Dulles International Airport. The author's model is flexible and data driven to show how many mobile lounge to assign for each route, number of docks for each concourse.

2.4. Capacity of Conveyance Systems

The Airport Development Reference Manual [13] indicates that the problem of traffic peaking at airports has been the subject of increasing concern by airline and airport operators around the world. An obvious focus and recommendation is to use schedule coordination to manage capacity demand. This manual gives comprehensive definitions of capacity in airports but not specific capacity numbers or estimates for conveyance systems. Researchers have attempted to gauge the practical capacity of conveyance systems, with differing results across the studies. One clear theme does emerge: manufacturer theoretical capacities can rarely be achieved in practice. This will be further explored within the analysis and data collection in Chapter 3.

Pushkarev and Zupan [26] stated that human factors play a large role in defining the maximum capacity of an escalator. They claim that a manufacturer rating of 50 persons per minute per foot of tread width (167 persons per minute per meter) cannot be achieved in practice. In this book, it suggests a maximum flow on a wide escalator (with steps designed for two people) to be about 18 persons per minute per foot (or 60 per minute per meter) with free arrivals and 27 persons per minute per foot (90 per minute per meter) under pressure from a waiting queue. Parts of their findings were based on O'Neil [27]. In his study, he found that the maximum observed flow under crush conditions in subway stations was 103 pedestrians per minute on a wide escalator. For design purposes, O'Neil recommends 90 persons per minute as the maximum value. O'Neil further emphasizes that the flow rate in the short-term is more realistic than any hourly extrapolation and should apply well whenever the flow is fed from a waiting queue. As will be shown in our analysis, another point worth noting is that adding one foot of tread width will not result in a linear increase in capacity. There is very limited data on this subject in the references cited.

Based on measurements at the Port Authority Bus Terminal, Fruin [4] found that 31 persons per foot (103 per meter) of tread width per minute to be the maximum achievable capacity. Also, Fruin calculated the maximum queue length at that rate of flow to be about 15 persons. Barney [28] conducted a comprehensive review of elevator and escalator capacity and flow. The author proposed a theoretical method of escalator capacity and found that an escalator with 1000mm nominal step width running at a rate speed of 0.5 meters per second has a theoretical handling capacity of 150 persons per minute. However, the author indicates that the practical handling capacity is about half of the theoretical (75 persons per minute) because the hesitations at boarding often result in an escalator not delivering its potential practical handling capacity. Davis and Dutta [29] estimate escalator capacity by using regression based on actual observations in the London Underground. They found that the capacity of an escalator at speed rate of 43.2 meters per minute, where passengers stood on both sides, would be approximately 108 persons per minute. The result is very similar to the findings in O'Neil [27]. Pushkarev and Zupan [26] and Davis and Dutta [29] both state that the approaches to escalator capacity and acceptable queue lengths are open issues. Based on the cited work, the maximum observed flow of an escalator is above 100 persons per minute. However, due to safety and LOS issues, a maximum flow on a wide escalator should likely be below 100 persons per minute.

In response to all of the literature presented, one point is clear. There is no consensus on the actual capacity of an escalator, and there is limited information concerning this capacity in an airport environment, where the users have bags and items on their person that will further reduce the escalator's throughput. This issue alone provides motivation for further study, and this is one of many issues investigated within this research.

2.5. Pedestrian Behavior and Walking Distance

It is well documented that pedestrian behavior (in general as well as specifically within airports) is a very important factor when considering acceptable walking distances.

Several articles provide contributions regarding the interaction between facility design and walking requirements, as well as appropriate walking speeds and distances. These articles are described next.

The ability to assess pedestrian behavior based on actual data in real systems cannot be overemphasized. Researchers often analyze the actions of other people in lab conditions for the purpose of action coordination. In order to understand whether such self-relative action perception differs from other-relative action perception, Jacobs and Shiffrar [30] conducted a design of experiments and suggest that the visual analysis of human motion during traditional laboratory studies can differ substantially from the visual analysis of human movement under more realistic conditions. In contrast, there are many examples of studies where researchers have studied existing transport systems to more accurately determine (and predict) pedestrian behavior.

Hoogendoorn and Daamen [31] introduce experimental findings of pedestrian behavior when faced with bottlenecks in flow. Essentially, pedestrians inside such bottlenecks form layers or trails, with a typical separation of approximately 45 cm. This is less than the effective width of a single pedestrian, which is around 55 cm. When quantifying pedestrian movement, Hui et al. [32] found that walking speed, step size and step frequency all followed normal distributions. Moreover, gender and age significantly affected these three measures, except for walking speed and step size of children and older pedestrians. These results were based on data collected in Beijing, China. The author found the walking speed varies due to gender and age. However, from the view of passenger flows, the most influential factor on average passenger walk speed is traffic density. Helbing [33] provided a more specific perspective by presenting a mathematical model for the movement of pedestrians.

Walking distance and walking speed are significant factors when installing APMs within airport terminals. Seneviratne [34] proposes an approach for determining critical pedestrian walking distance. Based on findings from a series of surveys in Alberta, Calgary, the author found that the critical pedestrian walking distance distribution is dependent on the classification of the pedestrian. The results show that the best walking distance distribution for most work-based trips follows a gamma distribution, and the critical distance is estimated at 796 feet (243 m). This is the same methodology first introduced by Pushkarev and Zupan [26], where they identified a critical walking distance distribution for urban areas. They report that average walking distances in central London were more than 800 meters, whereas those in midtown New York City were 524 meters. Moreover, Pushkarev and Zupan [26] state the advantages and limitations when using an escalator and a moving sidewalk. However, they leave the optimal length of a moving walkway as an open issue. In order to solve this problem, Bandara and Wirasinghe [35] and Bandara [36] develop an analytical model for optimizing pier-type terminal configurations. They consider an objective function that minimizes the sum of system operational costs and individual user costs to determine the optimal length of the moving sidewalk.

When discussing walking speed, walking distance and LOS of facilities in public, Fruin [4] conducted a series of studies on the behavior of pedestrians within transportation terminals. Two studies in particular—conducted at the Port Authority Bus

Terminal and at the Pennsylvania Train Station, both located in New York City—observed pedestrian walking speeds under free-flow conditions along with various observable pedestrian characteristics. Among the characteristics included were age, gender, trip purpose, number of bags carried, direction of travel, size of group, and final destination within the terminal. Fruin found that the mean walking speed was approximately 80.8 meters (265 ft) per minute, with a standard deviation of 15.3 meters (50 ft) per minute. Seneviratne and Wirasinghe [37] performed a cost analysis with the goal of optimizing airport terminal corridor width. This will be revisited in Chapter 5, which focuses on the relationship between concourse corridor width and passenger LOS.

It is worth noting that these research contributions are not recent, and with changes in airport design, airline schedules and the improved ability to model many alternate scenarios quickly, there is an obvious need to address passenger movements within the airport terminal in more detail.

More recently, Zacharias [38] discusses acceptable walking distances in city areas and provides suggestions for further research-based development of methods to plan effectively. In another study of urban pedestrian movement, Smith and Butcher [39] discuss the various conditions that should be taken into account to determine how far people using parking garages should be asked to walk.

APM systems in airports are known to reduce passengers' walking distance, but little is known about their effects on airport pedestrian flows. The effect of moving walkways on pedestrian walking speeds is examined by Young [40]. Through survey data, Young found that there is no significant difference in the mean free-flow walking speeds with observed pedestrians' characteristics within airport terminals. These characteristics include the pedestrian's apparent age, the presence of baggage, the direction of travel and party size. It also revealed that average free-flow walking speed is 80.5 meters (264 ft) per minute, approximately normally distributed with a standard deviation of 15.9 meters (52 ft). This result is very similar to Fruin's [4] study of 80.8 meters (265 ft) per minute.

It is well known that passengers can often be distinguished by their travel characteristics, such as business/leisure, group size, age, gender, number of bags, citizenship, etc. Moreover, a better understanding of the relationship between passenger type and passenger conveyance use would be very useful. In fact, on many attributes, Dresner [1] notes that leisure and business passengers are very similar in terms of their choice of airport, their parking requirements and the number of bags they check. However, this study does not mention the differences and similarities between leisure and business passengers when using conveyance systems in airports.

2.6. LOS of Pedestrian Facilities

Airport terminal passenger mobility systems, such as moving walkways, escalators, elevators and APM systems provide more efficient ways to help airport passengers reduce their walking distance and their walking time. However, we still need to consider the LOS of pedestrian facilities.

The LOS concept was first developed in the field of traffic engineering in recognition of the fact that capacity design actually results in a certain level of planned congestion [4]. Safety and comfort of pedestrian movement is a necessary consideration in all airports. Thus, Omer et al. [7] suggest the LOS concept should be used to assess the pedestrian's efficiency in mobility facilities and landside in airports. Research work on pedestrian LOS design has its foundation in Fruin [4], where a series of LOS design standards for walkways, stairways and pedestrian queuing was developed. Fruin [4] established measures of pedestrian effort and satisfaction based on the density of pedestrians in a corridor.

Walking speed, pedestrian spacing and the probability of conflict in various traffic concentrations are the major factors that determined the breakpoints for the various service levels. Lee and Lam [41] show LOS design standards for stairways in Hong Kong Mass Transit Railway (MTR) stations, and they compare six LOS standards in Hong Kong stairways against LOS standards proposed by Fruin [4].

Sarkar [42] defined six service levels for pedestrians according to the quality of walkways in terms of safety, security, convenience and comfort, system continuity, coherence and attractiveness. Similar to Sarkar [42], Khisty [43] found that these qualitative environment factors are just as important as the quantitative flow, speed and density factor in planning and designing pedestrian facilities. In particular, both comfort and safety receive high importance in pedestrian decision making. Seneviratne and Morrall [44] considered the perceptions of quality of service for the ranking and design of walkways. The findings of this article are based on the pedestrian studies conducted by Seneviratne [34]. Mori and Tsukaguchi [45] conducted a study for evaluating the service levels of sidewalks under different flow conditions in Osaka, Japan.

2.7. Lessons from the Literature Review

In section 2.2 and 2.3, we reviewed and identified the importance of conveyance systems in the airport environment. Conveyance systems can help passengers not only reduce their walking distance but also provide a comfortable airport travel experience. Sections 2.2 and 2.3 motivated the need for work in assessing the use of conveyance systems in airports.

When discussing the use and capacity of conveyance systems, the literature reviewed in section 2.4 provides a good contribution on conveyance systems capacity based on either a theoretical approach or actual observations. However, the use and capacity of conveyance systems may vary across different environments. This motivates this research to develop a database of information regarding each conveyance device across several major airports. In addition to conveyance capacity, the literature related to pedestrian behavior and walking distance in section 2.5, providing the motivation to further explore a passenger's choice of mode when facing either a vertical or horizontal transition.

Finally, it is well known that LOS is considered an important index when measuring airport performance. When discussing the measure of airport performance, several articles presented in section 2.6 provide contributions on the optimal passenger terminal configurations to reduce passenger walk distance and on the optimal airport terminal corridor width based on cost analysis. However, a good airport terminal is determined not only by either minimum walking distance or lower construction cost but also by a comfortable environment in terms of space requirement for passenger. Thus, a simulation model of passenger flow through an airport concourse based on various operating characteristics is needed and could be used to aid planners in the operation of airport concourses.

Chapter 3

Database Design for Planning and Evaluating Passenger Conveyance Systems at Airports

3.1. Introduction

One important airport landside performance index is the use and capacity of passenger conveyance devices in airports. Several research studies on estimating true capacity of moving walkways and escalators have been conducted at rail or subway stations, as was noted in Chapter 2 [4,28,29]. However, capacities exhibited in these environments may not translate into similar capacities within airport terminal facilities. Moreover, very little is known about passenger preferences when given a choice of modes for walking short distances in airports. While planning guidelines exist, such as the one created by IATA, there is no single reference that focuses merely on passenger behavior and the use of conveyance systems for airports. The focus of this chapter is to propose a database design that would provide such a single source of information on passenger behavior related to airport conveyance systems. This research into passenger conveyance use and capacities will provide insight to airport operators, planners and other groups and agencies.

As part of Airport Cooperative Research Project (ACRP) 03-14 (Airport Passenger Conveyance System Usage/Throughput), the research in this chapter was the product of a larger combined research effort between TransSolutions, LLC and its two *subconsultants Clemson University and Kimley-Horn Associates. For further information about the conveyance analysis, the database and its use, please refer to the report "Airport Passenger Conveyance System Usage/Throughput ACRP 03-14" to be published by the end of 2011. It will be available from the Transportation Research Board and the National Academy of Sciences.*

3.2. Research Question Statement

In this section, our main objective is to find the capabilities of available passenger conveyance options as well as passenger conveyance preferences within various functional areas in airports. Therefore, our research question is "Can we better understand how conveyance devices are used within the airport landside environment, and is there a limit as to how much passenger traffic and congestion a particular device can handle?" For example, when a passenger enters the terminal building (either from the curbside dropoff, parking garage or from an aircraft arrival), does the passenger choose to use a moving walkway, and does the passenger walk or stand when using the device? A series of such considerations exist as the passenger journeys through the entire landside experience. Through an extensive data collection and analysis effort using data from five major U.S. airports, answers to questions similar to this were found.

A data collection plan was created to specifically collect and compile information on passenger conveyance use. Once all data is collected, categorized and summarized, the database will be developed. All information obtained from the collected data will be inputted to the database. This database will assist airport planners and operators when considering the use of conveyance devices in airports and provide a great benefit to the industry in determining if the passenger conveyance planning guidelines standards are proper or not.

3.3. Data Collection

Specific passenger conveyance device information is required to carry out further analysis into the issues highlighted above. The ACRP 03-14 project team conducted a thorough data collection, and we briefly discuss the approach. For further information about the database and its use, please refer to the report "Airport Passenger Conveyance System Usage/Throughput ACRP 03-14" to be published by the end of 2011. It will be available from the Transportation Research Board and the National Academy of Sciences.

We have considered various airport and passenger characteristics in selecting the five airports for data collection on passenger usage/choice of conveyance systems, practical capacity and airport/terminal design characteristics. To collect meaningful data, the airport needed to have adequate sustained busy periods of passenger traffic in order to determine device capacity and passenger mode choice considerations. For this reason, the focus was mostly on larger airports; however, a medium hub airport was also included. In addition to each airport having the passenger conveyance devices installed within their terminals, the characteristics of each airport were also considered when selecting the airports to study.

The five selected airports provide a reasonable representation of airport characteristics in the U.S. Collecting data across these characteristic airport types enabled the team to understand if the different attribute types of airports have differing passenger conveyance needs. *For further information about the database and its use, please refer to the report "Airport Passenger Conveyance System Usage/Throughput ACRP 03-14" to be published by the end of 2011. It will be available from the Transportation Research Board and the National Academy of Sciences.*

At each participating facility, certain defining characteristics were recorded for each device observed: (1) location of conveyance within corridor, (2) number of elevators and escalators and (3) whether the direction is up or down. Specific data collection points can be summarized as follows:

Elevator Boarding / De-boarding Information

Within this section, descriptive information was recorded for each passenger boarding or de-boarding the elevator. In addition to denoting the boarding/de-boarding start and stop times for an elevator dwell, several individual passenger data elements were recorded: large bags, rollers (or bags with wheels), wheel chairs, carts, etc.

Escalator Board Rate

This includes recording the time between each passenger boarding the escalator. The average inter-boarding time during a sustained demand period would be the (observed) practical capacity of the escalators.

Vertical Transition Passenger Mode Choice Percentage

When a passenger is facing a vertical transition with at least an escalator available, the data to record includes: (1) percentage of each vertical conveyance mode chosen (when elevators and/or stairs are also available), (2) percentage of passengers standing vs. walking on an escalator and (3) number of rollers per passenger.

Moving Walkway Board Rate

This includes recording the time between two consecutive passengers boarding a moving walkway. The average inter-boarding time during a sustained demand period would be the (observed) practical capacity of the moving walkway.

Horizontal Transition Passenger Mode Choice Percentage

When a passenger is facing a horizontal transition where a moving walkway is available, the following information is recorded: (1) percentage of each horizontal conveyance mode chosen (moving walkway vs. corridor), (2) percentage of passengers standing vs. walking on a moving walkway and (3) number of rollers for those passengers using either the moving walkway or corridor.

Table 3.1 shows the total number of observations collected from each of the five airports for the five observational data types just described: elevator-board, escalator board rate, escalator passenger characteristics, moving walkway board rate, and moving walkway passenger characteristics.

Table 3.1 : Sample Size for Data Collected at the Study Airports

Airport	1	2	3	4	5	Total
Data Set	Sample Size					
Elevator-Board/De-board Information	1,117	None	983	40	4,388	6,528
Escalator Board Rate	26,291	1,023	10,292	1,022	3,722	42,350
Vertical Transition Passenger Mode Choice Percentage	2,146	10,671	7,819	2,912	11,525	35,073
Moving Walkway Board Rate	169	2,548	1,988	173	50	2,928
Horizontal Transition Passenger Mode Choice Percentage	6,632	11,841	19,004	2,923	4,886	45,286
Total	36,355	26,083	40,086	7,070	24,571	134,156

Once the data has been collected in five selected airports, the database will begin to be built in the next section.

3.4. Database Design and Development

There are two types of passenger flow, inbound and outbound. For inbound flow, all arriving passengers enter the concourse via gates. Once at the concourse, passengers can potentially use an APM system to move toward the main terminal to retrieve baggage or leave the airport. Alternatively, passengers may stay within the terminals and concourses to connect to outbound flights. For outbound flow, all departing passengers visit a security check point with a possible first stop at ticketing or check-in. After the check point, departing passengers move toward their concourse, again possibly via an APM system. There are several transitions (for both inbound and outbound flow) between each area where passenger conveyance options are provided for passengers to use. To allow the researchers to account for different behavior and performance of passengers and the conveyance devices within the airport, specific locations (or what we have called transitions areas) throughout the airport terminal environment were identified and considered. This will enable researchers to consider a single transition area when viewing data summarized in the database or to still summarize data across all possible transition areas. Figure 3.1 depicts the passenger flow and the possible data analysis areas in the airport. Based on this flow, several specific locations across the airport terminal were proposed where key conveyance statistics could be analyzed.

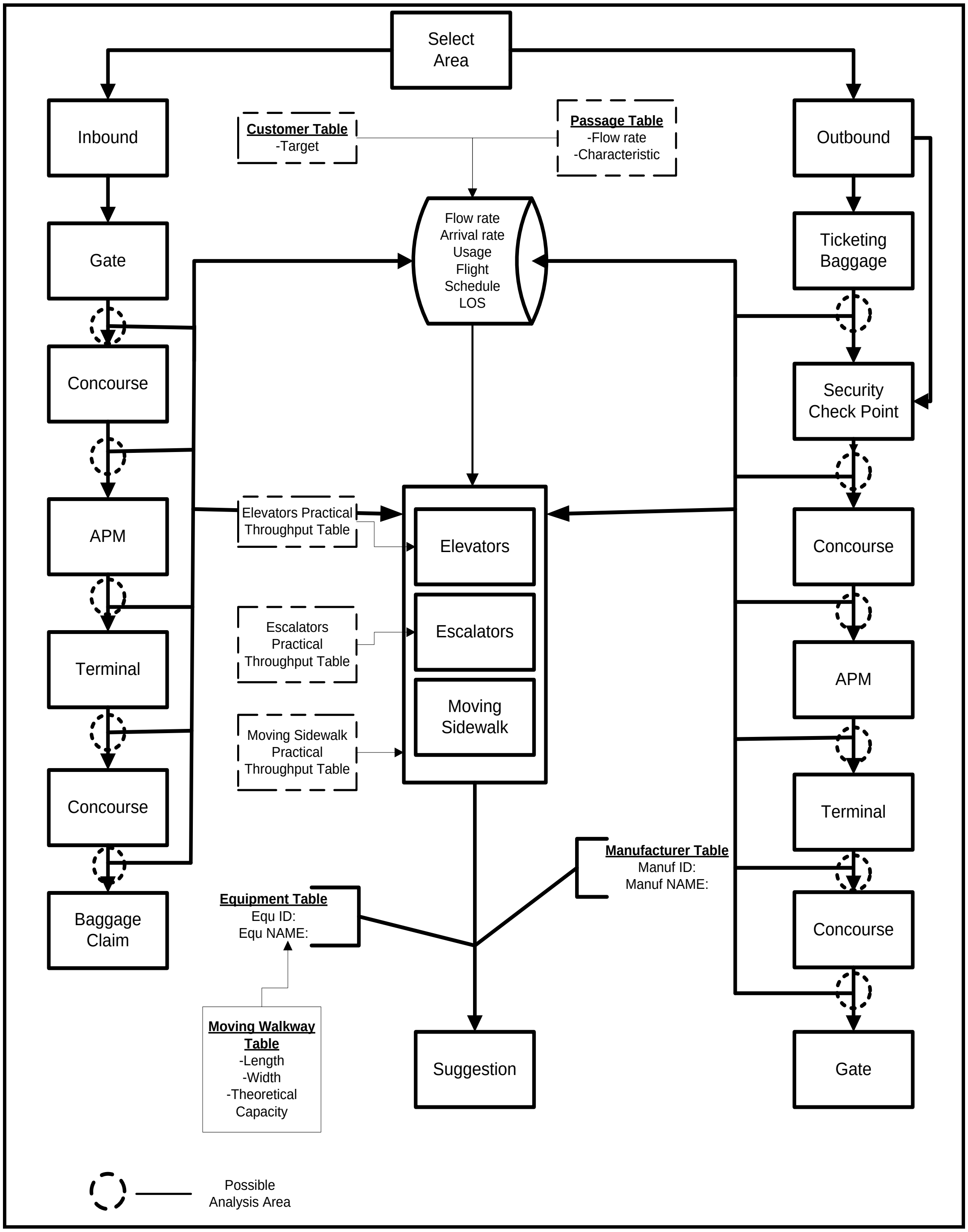


Figure 3.1 : Airport Passenger Flow and Potential Data Analysis Areas

To provide a comprehensive guide for evaluating passenger conveyance systems at airports, a database was designed in MICROSOFT ACCESS 2007 and developed with collected information from the five previously-mentioned airports. The chosen platform is a very common, easy-to-use database software tool. According to Balter [46], the term “database” means different things to different people. For many years, “database” was used to describe a collection of fields and records (this is called a table in Access). In a client/server environment, “database” refers to all the data, schema, indexes, rules, triggers and stored procedures associated with a system. In ACCESS terms, a database is a collection of all the tables, queries, forms, reports, macros and modules that compose a complete system.

Tables are the starting point for our application. The initial data information we collected from airports was stored as several unique tables by each data set. The table’s data can be displayed in a datasheet, which includes all individual records and the fields collected as part of the research. Figure 3.2 is an example of one of the many tables in the database.

Location	Area	ModeChoice	NumOfElv	NumOfEsc	Stairs	Direction	Roller
16	Post-Security	4	1	3	N	U	1
16	Post-Security	1	1	2	N	U	0
16	Post-Security	1	1	2	N	U	0
16	Post-Security	1	1	2	N	U	0
16	Post-Security	1	1	2	N	U	0
16	Post-Security	1	1	2	N	U	0
16	Post-Security	4	1	2	N	U	1
16	Post-Security	4	1	2	N	U	1
16	Post-Security	4	1	2	N	U	1
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	1
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	1
16	Post-Security	4	1	2	N	U	1
16	Post-Security	4	1	2	N	U	0
16	Post-Security	4	1	2	N	U	0

Figure 3.2 : A Datasheet View of Vertical Transition Passenger Mode Choice

After creating tables, we needed to define relationships among the tables for maintaining our data’s integrity and improving the ability to connect data across the tables. Figure 3.3 shows the relationship between tables in the database. Many of the relationships have a join line between tables with a “1” and an infinity symbol. This means a one-to-many relationship between the two tables. For example, the relationship between Manufacturer Information and Equipment_Common_Information is a one-to-many relationship. This means equipment cannot be added for manufacturers who do not exist. And if a Manufacturer ID is updated, all records containing Manufacturer ID in the Equipmnent_Common_Information table are also updated.

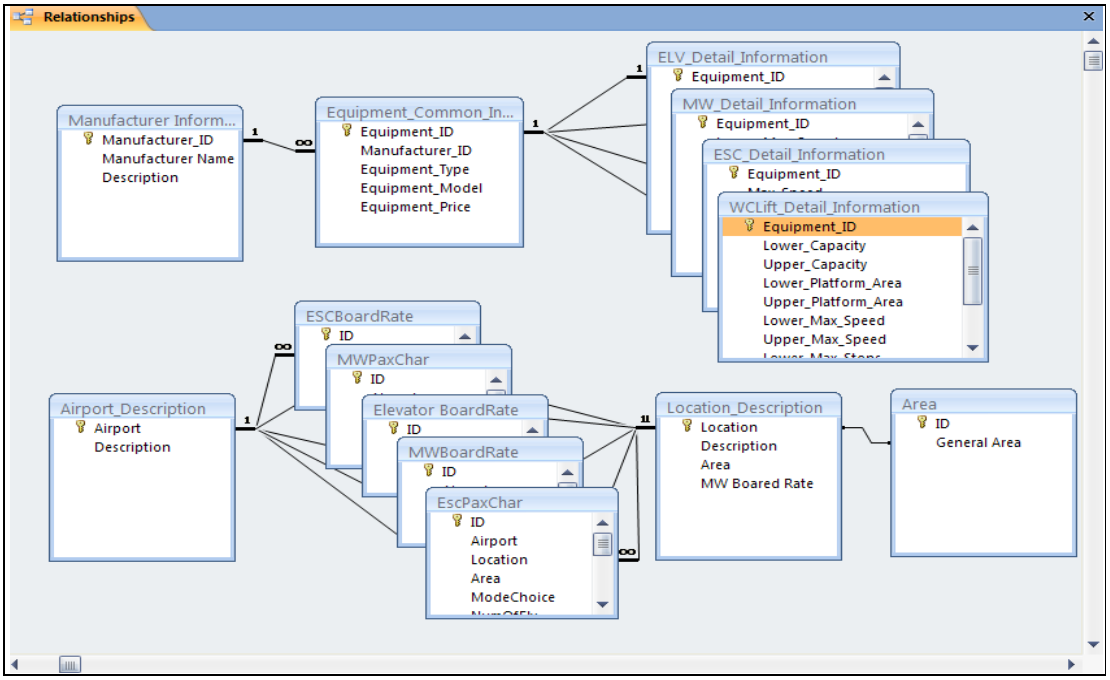


Figure 3.3 : The Entity Relationships for Database Tables

Once the tables are created and the relationships between tables are indicated, then the data can be further explored using queries, which can help the user to view, summarize and perform calculations on the data in our database. For example, Figure 3.4 shows the query design where the data source is the ESCBoardRate table. It displays the Airport, NoOfEsc, Direction and Location from ESCBoardRate table and defines the calculation of board rate. This query gives us the escalator passenger board rate by airports, number of escalators, travel direction and locations. Figure 3.5 shows an example for the output of the throughput (board rate) of the escalator by direction and escalator width by using this particular query.

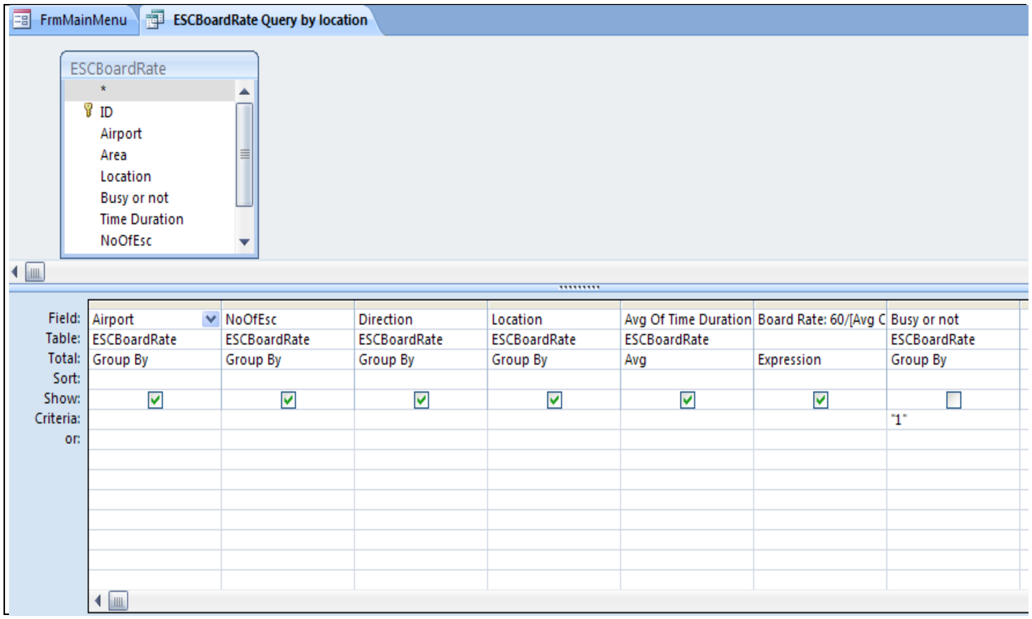
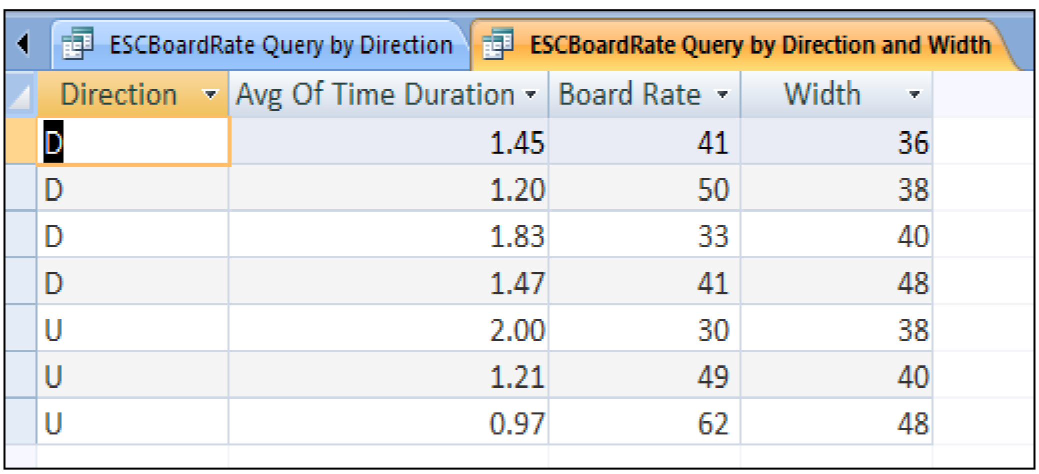


Figure 3.4 : The Query Design Window



Direction	Avg Of Time Duration	Board Rate	Width
D	1.45	41	36
D	1.20	50	38
D	1.83	33	40
D	1.47	41	48
U	2.00	30	38
U	1.21	49	40
U	0.97	62	48

Figure 3.5 : The Result of Escalator Board Rate by Query

In order to provide an overview of the functionality of the tool developed by the research team, an outline and framework of navigation options was created. The purpose of this framework is to provide users an easier way to review the data by different conditions. *For further information about the analysis, the database and its use, please refer to the report "Airport Passenger Conveyance System Usage/Throughput ACRP 03-14" to be published by the end of 2011. It will be available from the Transportation Research Board and the National Academy of Sciences.*

3.5. Passenger Conveyance Database

To provide a comprehensive guide for evaluating passenger conveyance systems at airports, a database was designed and developed in MICROSOFT OFFICE ACCESS 2007. The database contains information collected from several airports across the U.S. The database allows users to view summary forms of vertical and horizontal conveyances at the study airports, as well as a planning tool for gauging transition equipment requirements when comparing a planned transition rate against observed transition rates and equipment performance at the five airports. Reports are presented by conveyance type (elevator, escalator and moving walk), as well as being available for each transition area and across all transition areas. The database also provides conveyance equipment information. *For further information about the analysis, the database and its use, please refer to the report "Airport Passenger Conveyance System Usage/Throughput ACRP 03-14" to be published by the end of 2011. It will be available from the Transportation Research Board and the National Academy of Sciences.*

3.6. Analysis of Observed Data

Vertical Transition - Escalators and Elevators

The most striking result to come out of this initial analysis was that the escalator throughput or capacity achieved from our sample of airports was significantly lower than previous works that estimated their practical capacity based on a subway station environment (see Fruin [4], Pushkarev and Zupan [26], O'Neil [27], and Davis and Dutta [29]). (See Table 3.2)

As we can see from Table 3.2, the escalator board rate from the data collection effort was less than half of the escalator board rate presented in past studies of subway stations. One obvious explanation for this difference is that air passengers have more bags and items on their person than subway system commuters in the city.

Table 3.2 : Observed Escalator Board Rate

Study	Board Rate (Pax/Min)
From our sampled airports	
1	49
2	33
3	52
4	38
5	50
From previous studies on estimating true capacity	
Fruin (1971)	103
Pushkarev and Zupan (1975)	90
O'Neil (1974)	103
Davis and Dutta (2002)	108
Barney (2003)	75

Airport passengers have a larger footprint of space required as they travel, and it is confirmed in this comparison. There is much debate as to what this footprint of space should be, with no set standard that is used across the industry. However, it is clear that additional baggage per person would make it much more unlikely that two airport passengers would stand side-by-side. Another contributing factor to the reduced capacity is the difficulty in boarding an escalator with bags. This involves more than simply walking onto the escalator, and even though a bag can be placed right next to the passenger while riding the escalator, the bag could take up as much space as ½-1 passenger when boarding. These observations all contribute to the overall decrease in the practical escalator capacity at an airport. An interesting comparison would be to compare how travelers in an airport and travelers in a subway stand on an escalator. It would appear that subway passengers are simply willing to give up more personal space than airport passengers.

Moreover, Table 3.2 shows that the board rate at airport 2 is lower than the other four airports. There are often many influencing factors that would lead to such a result. In this case, it could be due to airport size or the fact that escalators are not located right at the entrance to the concourse. Moreover, the demand for vertical transition does not experience extreme peaking since there is no people mover system feeding demand directly to any escalator.

If we look at the average escalator board rate by airport and by up (U) and down (D) direction across all escalator at that airport, escalator board rates for passengers going up are higher than the board rates when going down. In general, it is believed that passengers may slow their board rate when going down as the entire device is not visible when boarding. The results were not consistent across all airports, but there was a definite trend. This could be due to airport configuration and which levels are generating the "peaking" effect of passenger demand. Also, observations clearly indicate an increase in board rate as the number of escalators is increased. However, this is not a linear increase, and it is dependent on the use and placement of the escalator bank.

We summarize elevator board time at those sampled airports. Table 3.3 shows the average elevator board times and passenger characteristics by airport and type of boarding (boarding or de-boarding). Across all airport locations, the average time to board an elevator is always longer than the average time to de-board an elevator.

Table 3.3 : Elevator Board Times and Passenger Characteristics by Airport

Airport	Board / Deboard	Avg. Boarding Time		Average Number of					
		Time (secs)	Per Pax (Secs/pax)	Pax	Large luggage	Back pack	Roller	Golf	Stroller
1	Board	10.04	4.12	2.44	0.05	0.44	0.62	0.00	0.30
1	Deboard	7.10	3.24	2.19	0.03	0.26	0.57	0.00	0.22
3	Board	9.60	3.85	2.50	0.50	0.72	1.33	0.08	0.09
3	Deboard	6.71	3.43	1.96	0.15	0.54	1.21	0.03	0.07
4	Board	8.58	3.27	2.63	0.04	0.08	0.25	0.00	0.13
4	Deboard	3.94	3.71	1.06	0.00	0.00	0.25	0.13	0.19
5	Board	11.01	3.00	3.67	0.15	0.89	1.84	0.03	0.17
5	Deboard	7.76	2.61	2.96	0.11	0.66	1.33	0.01	0.15

When faced with multiple vertical transition options, passengers could often choose between elevators, escalators and stairs.

Examination of vertical conveyance mode choice data revealed that a vast majority of airport passengers did use escalators for a vertical transition. For those passengers using escalators, between 85% and 90% stood on the device. The reason for this may be that most airport passengers have baggage with them, and it is not convenient to walk on an escalator. We also observed that passengers use elevators much more heavily at one airport over all others. This is directly related to the location, size and availability of the devices. Passengers are clearly presented an elevator option in two key locations: (1) entrances to the terminal from rental car return and parking lots and (2) in and around the baggage claim area.

Data were recorded to provide the average number of rollers by airport and by passenger vertical conveyance mode. While passengers regularly have a roller bag when using escalators for vertical transition, the average number of rollers for those passengers who choose to walk (over simply standing) on the device to quicken their trip is no more than 0.1. This result was consistent across all airports. The mode choice will be further discussed in Chapter 4.

For further information about the analysis, the database and its use, please refer to the report "Airport Passenger Conveyance System Usage/Throughput ACRP 03-14" to be published by the end of 2011. It will be available from the Transportation Research Board and the National Academy of Sciences.

Horizontal Transition - Moving Walkways

When a passenger walks into the airport concourse, they may have the choice to use a moving walkway to reduce the amount of walking. We summarize the data and present the passenger horizontal conveyance mode choice by airport in Table 3.4.

Table 3.4 : Moving Walkway Mode Choice by Airport

Airport	Pct Corridor	Pct Moving Walk	Pct Walk on MW	Pct Stand on Mw
1	35.62%	64.38%	91.03%	8.97%
2	47.27%	52.73%	85.35%	14.65%
3	30.36%	69.64%	85.78%	14.22%
4	45.23%	45.77%	91.32%	8.68%
5	28.71%	71.29%	70.74%	29.26%

When analyzing the use of moving walkways in airports, we can simply compare the finding from Young's study [23] shown in Table 3.5. It can be seen from Table 3.4 that more than half of all passengers will use moving walkways when given the choice. For those using the devices, a majority of the passengers choose to walk. These moving walkway findings are similar to those presented in Young [23].

Table 3.5 : Moving Walkway Mode Choice Distribution from Young (1995)

Airport	San Francisco International Airport	
Mode	#Obs	%Total
Bypass	66	25%
Use	203	75%
- Stand	57	21%
- Walk	146	54%

Moreover, one interesting finding here is that passengers who use the corridor (without using a moving walk) have more rollers than those who use moving walkway in several of the airports. Moreover, passengers who walk on moving walkways have more rollers than passengers who stand on moving walkways. This is similar to the regression result from Young [23]. A further study on mode choice will be discussed and explained in Chapter 4.

Chapter 4

Analysis of Conveyance System Use in Airport Terminal

4.1. Introduction

We can observe every day that airports are increasing and improving their facilities to keep up with the rising demand. More people are flying these days causing the airport authorities to increase the size of the airport including the number of terminals, the number of security checkpoints, the number of conveyance systems, etc. Because of the massive growth in air travel, the scale of airport terminals often exceeds acceptable walking distances for passengers. To maintain acceptable passenger walking distances, as well as maintain acceptable transit times in terminals and provide a more comfortable environment (i.e. LOS), airport operators have introduced various passenger conveyance systems including moving walkways, escalators and elevators. In particular, IATA (2004) even suggests that when the distance between the point of check-in and the point where passengers board the aircraft exceed 300 meters, consideration should be given to providing a people-moving system. As mentioned in Chapter 2, an article by Leder [17] presents comprehensive reviews of people mover systems.

Airport terminals pose unique challenges in regards to the placement and use of passenger conveyor systems. In general, there is a lack of agreeable information on passenger behavior; few studies exist concerning the use of the conveyance system in airport. A focused research of passenger conveyance actually used will provide insight to airport operators on what factors may influence whether a passenger chooses one mode over another. Such an empirical study is performed using the extensive data collection effort on passenger conveyance systems from Chapter 3. A logistic regression methodology was applied to estimate a passenger's mode choice probability and to examine the relationship between passenger characteristics and their choice of automatic conveyance system in airport terminals.

4.2. Research Question Statement

As mentioned in previous chapters, airports provide many passenger conveyances, such as moving sidewalks, elevators and escalators to reduce passenger walking distance and improve the LOS experienced by the passenger while beginning a journey, completing a journey or connecting between flights. For transitions between levels, elevators and escalators are provided to improve passenger service. And vice versa, moving sidewalks are provided for horizontally transitioning passengers.

For most research relative to demand analysis of passenger conveyance, assumptions are made as to the appropriate percentage of passengers who will take elevators vs. escalators when multiple types of vertical transitions are available. Figure 4.1 and 4.2 illustrate the mode choice for both vertical and horizontal transition. There is no comprehensive information on passenger behavior addressing how passengers make their choice on both vertical and horizontal transition in airports.

In order to evaluate how the number of rollers carried per passenger affects the passenger's choice of conveyance system, logistic regression models are developed to predict passenger mode choice. Results for the vertical transitions are described first, followed by a discussion of horizontal transitions. As part of this section, a brief comparison is drawn concerning the use of moving walkways. We will compare the findings from this empirical analysis with a similar prior study performed by Young [23].

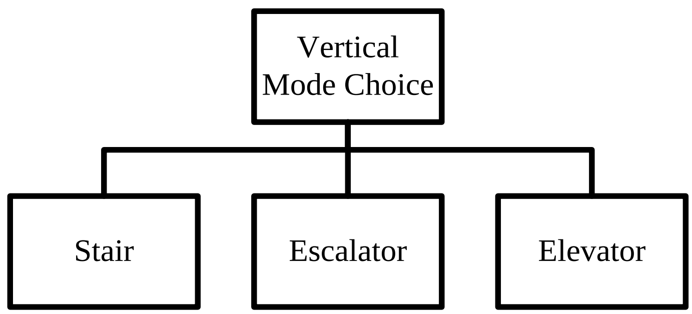


Figure 4.1 : Vertical Mode Choice

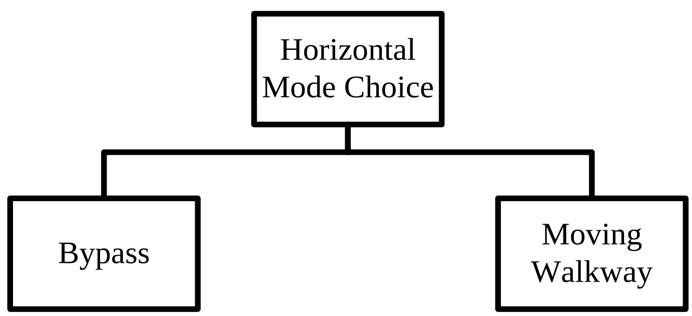


Figure 4.2 : Horizontal Mode Choice

4.3. Logistic Regression - Overview

Logistic regression methodology has been applied in many fields of research. There are several types of logistic regression, taken from "Logistic regression: a primer" by Pampel [47]:

Binary logistic regression is a form of regression which is used when the dependent is a dichotomy and the independents are of any type. Multinomial logistic regression exists to handle the case of dependents with more classes than two, though it is sometimes used for binary dependents also since it generates somewhat different output described below. When multiple classes of a multinomial dependent variable can be ranked, then ordinal logistic regression is preferred to multinomial logistic regression. Continuous variables are not used as dependents in logistic regression. Unlike logit regression, there can be only one dependent variable.

In this research, binary regression is applied to estimate passengers' mode choice probability when passengers are choosing whether or not to use moving walkways in the airport. In addition, multinomial logistic regression is used to examine the relationship between passenger characteristics and their choice of escalator, elevator and stairs in airport terminals.

An explanation of logistic regression begins with an introduction of the logit function:

$$f(z) = \frac{1}{1 + e^{-z}}$$

A graph of the function is shown in Figure 4.3. The input is z and the output is $f(z)$. The logistic function is useful because it can take as an input any value from negative infinity to positive infinity, whereas the output is confined to values between 0 and 1. The variable *z* represents the exposure to some set of independent variables, while *f*(*z*) represents the probability of a particular outcome, given that set of explanatory variables. The variable *z* is usually defined as:

$$z = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k$$

Each of the regression coefficients describes the size of the contribution of that risk factor. A positive coefficient means that that explanatory variable increases the probability of the outcome, while a negative coefficient means that variable decreases the probability of that outcome.

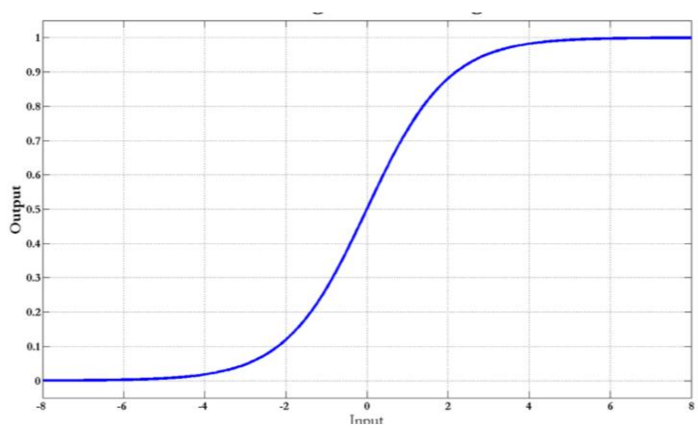


Figure 4.3 : The Logistic Function

4.4. Model Application and Data Sources

The data of passenger conveyance devices at airports is required to carry out further analysis to present the issues highlighted above. As part of the ACRP 03-14 (Airport Passenger Conveyance System Usage/Throughput), the project team conducted a careful analysis of which airports were best suited for providing the necessary data for the research; the data collection effort was a combined effort between the prime contractor TransSolutions, LLC and its two subconsultants Clemson University and Kimley-Horn Associates.

In this section, we propose specific mode choice equations based on the following data collected on vertical and horizontal transitions when choice included an escalator or a moving walkway, respectively:

- Which vertical transition mode (escalator, elevator, stair) is chosen by the passenger;
- Which horizontal transition mode (moving walkway, walk) is chosen by the passenger;
- The number of rollers carried by the passenger;
- Whether the passenger was an airport employee or not;
- Whether the direction is up or down (in the case of a vertical transition);

A total of 35,073 observations were collected for vertical transitions, while 45,286 observations were collected for horizontal transitions. The distribution of mode choice for vertical and horizontal transition is presented in Table 4.1 and Table 4.2.

To explore the mode choice made by airport passengers, two logistic regression models are developed to serve as predictors. The first model evaluates two mode choices in horizontal transition (moving walkway vs. bypass) using the independent variable "number of rollers." A second model evaluates the three mode choices in vertical transition (escalator vs. elevator vs. stairs) using the independent variables (1) number of rollers, (2) transition direction and (3) whether or not the traveler is an employee.

Table 4.1 : Vertical Transition Mode Choice Distribution

Airport	1		2		3		4		5	
Mode	#Obs	%Total	#Obs	%Total	#Obs	%Total	#Obs	%Total	#Obs	%Total
Escalator	1969	91.75%	9376	87.86%	7031	89.92%	2673	91.79%	8824	76.56%
Stair	86	4.01%	978	9.17%	659	8.43%	142	4.88%	1734	15.05%
Elevator	91	4.24%	317	2.97%	129	1.65%	97	3.33%	967	8.39%
Total	2146		10671		7819		2912		11525	
Esc Choice?										
Walk	133	6.75%	798	8.51%	889	12.64%	287	10.75%	521	5.91%
Stand	1836	93.25%	8578	91.49%	6142	87.36%	2386	89.25%	8303	94.09%

Table 4.2 : Horizontal Transition Mode Choice Distribution

Airport	1		2		3		4		5	
Mode	#Obs	%Total	#Obs	%Total	#Obs	%Total	#Obs	%Total	#Obs	%Total
Moving Walkway	4270	64.38	6244	52.73	13234	69.64	1601	54.77	3483	71.29
Bypass	2362	35.62	5597	47.27	5770	30.36	1322	45.23	1403	28.71
Total	6632		11841		19004		2923		4886	
MW Choice?										
Walk	3887	91.03%	5329	85.35%	11352	85.78%	1462	91.32%	2464	70.74%
Stand	383	8.97%	915	14.65%	1617	12.22%	139	8.68%	1019	29.26%

4.5. Horizontal Transition Mode Choice Models

In determining which factors may influence a passenger's choice of whether or not to choose a moving walkway over just walking through a corridor, the individual factors were tabulated to identify any apparent distinctions in data based on mode selected. Table 4.3 provides a comparison of the number of rollers by mode selected.

Table 4.3 : Number of Rollers (per passenger) for Each Horizontal Transition Mode

Airport	1	2	3	4	5
Mode	Average number of rollers per passenger				
Moving Walkway	0.29	0.36	0.28	0.30	0.52
Bypass	0.33	0.39	0.32	0.26	0.52

The horizontal transition logistic regression (HTLR) model was applied to predict whether airport passengers' would use moving walkways and the influence of the number of rollers per passenger on their choice. While the differences in number of rollers by mode do not appear to be large, we chose this to be our independent variable in the binary logistic regression model. Specifically, the horizontal mode choices are either to use the moving walkway or to simply walk in the corridor, and the probability function is obtained by:

$$f(z) = \frac{1}{1 + e^{-z}}$$

where:

$$z = \beta_0 + \beta_1 x_1$$

$$x_1 = \text{number of rollers}$$

Table 4.4 displays the estimated results across five airports. It corresponds to the equation:

$$ln\left(\frac{P(Use)}{P(Bypass)}\right) = b_{10} + b_{11} * Roller$$

We found that the number of rollers is a significant predictor for using or not using a moving walkway. The HTLR model is illustrated using the equation above. Consider the coefficients for the regression equation that address moving walkway mode choice. There is one predictor variable (rollers) in this model. The coefficient is used to predict the log odds (or logit) of the dependent variable, which is $ln\left(\frac{P(Use)}{P(Bypass)}\right)$. Positive coefficients of variables indicate the positive relationship between the independent and dependent variables. An increase in the independent variable will result in the increase in the logit of the dependent variable. On the other hand, a negative coefficient indicates a negative relationship between independent and dependent variables. For example, the negative coefficient for rollers (Table 4.4) implies that increasing the number of rollers will decrease the log odds of the event occurring, which means a passenger who has more rollers is more likely not to use a moving walkway when other factors are controlled.

When considering the probability of using (or not using) a moving walkway, from the result in Table 4.4, we know that β_0=0.594531 (the intercept) and β_1= -0.0976356. If there is a passenger with one roller (x_1=1), z value is 0.496895 (=0.594531-0.0976356*1) and odds value is 1.6436. The probability of choosing the moving walkway can be calculated using equation (1), which is 0.6217 or 62.2%. Carrying out this analysis for other values of the independent variable, we present the overall results in Table 4.5 and Figure 4.4.

Table 4.4 : Binary Regression Coefficients by All Airports

Predictor	Coef	SE Coef	Z	P	Odds Ratio
Constant	0.594531	0.0117801	50.47	< 0.000	
Roller	-0.0976356	0.0189630	-5.15	< 0.000	0.91
Log-Likelihood	-29664.213				
Test that all slopes are zero: G = 26.396, DF = 1, P-Value = < 0.000					

Table 4.5 : The Probability Using Moving Walkway by Rollers

Number of rollers	Prob. use MW
0	64.44%
1	62.17%
2	59.85%
3	57.48%

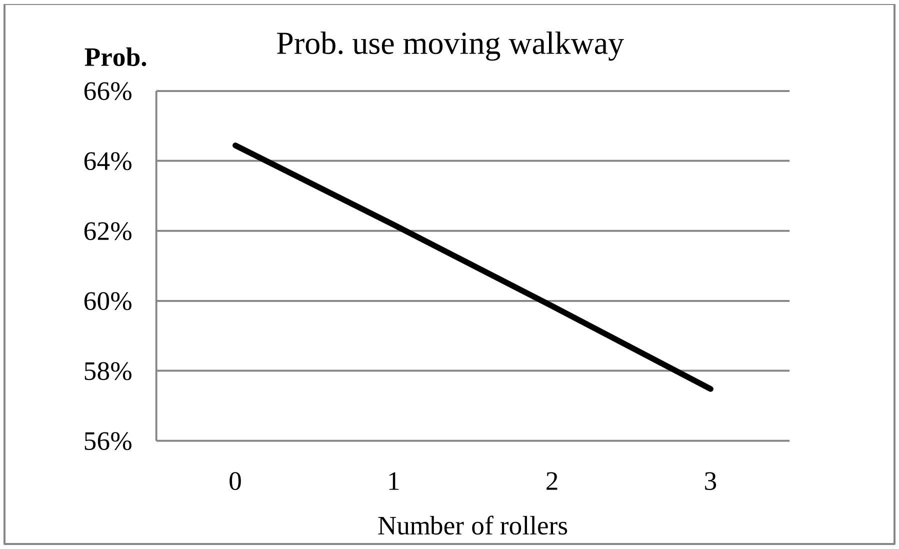


Figure 4.4 : Probability of Using Moving Walkway

Figure 4.4 illustrates that more rollers will decrease the probability of taking moving walkway. The sensitivity of each variable to this model was assessed by examining the odds ratio. If one roller increases, the odds value of use will decrease by 1.4907/1.6436 = 0.91. What we discussed above is the odds ratio shown at the right-hand side in Table 6. When we consider the strength of the relationship, the odds ratio depicts the increase (or decrease) in likelihood of selecting Mode 1 (using moving walkway) over Mode 2 (bypass) given a one unit increase in the independent variable. A ratio of 1 indicates the independent variable has no change in mode choice. From the example above, for every one unit increase in roller, the odds of use (vs. not use) will change by a factor of 0.91, or decrease by 9%.

It is interesting to note from the result that passengers tend not to use moving walkways with an increasing number of rollers. As a passenger has more baggage, they may hesitate to use the moving walkway as they become an obstruction to all passengers behind them. Another reason is that the additional baggage can make navigating the moving walkway more challenging. This supports the linear regression result in Young's (1995) work which is travel speed increases with increasing number of bags. Recall that average travel speed decreases when the moving walkway is more heavily used. This was explained by Young [23]:

"One explanation for this may be that those passengers with more baggage tended to be in more of a rush to catch their flights than were those with fewer bags."

The use of conveyance devices in different airports may vary from airport to airport due to the different characteristics of each airport. Instead of using the data across all airports, let us look at the result of each airport. The results and analysis of the five airports are shown in Table 4.6.

As we can find from the results of airports 1, 2 and 3, rollers are a significant predictor for using or not using moving walkway. The negative coefficient for rollers implies that a passenger that has more rollers is more likely not to use the moving walkway. For every one unit increase in rollers, the odds of using a moving walkway (vs. not using) are decreased by a factor of 0.86, 0.88 and 0.87. The coefficients for rollers are positive in airport 4, indicating that passengers tend to use moving walkways when more rollers were carried. Given the p – value (for testing that all slopes are zero) is 0.858 in airport 5, there is not sufficient evidence to prove a significant relationship between number of rollers and horizontal mode choice at airport 5.

Table 4.6 : Binary Regression Coefficients of Five Airports

Airport	Predictor	Coef	SE Coef	Z	P	Odds Ratio
1	Constant	0.640439	0.0305745	20.95	0.000	0.86
	Rollers	-0.155690	0.0527448	-2.95	0.003	
	Log-Likelihood = -4314.242					
	Test that all slopes are zero: G = 8.661, DF = 1, P-Value = 0.003					
2	Constant	0.156857	0.0227120	6.91	0.000	0.88
	Rollers	-0.125738	0.0354027	-3.55	0.000	
	Log-Likelihood = -8184.837					
	Test that all slopes are zero: G = 12.627, DF = 1, P-Value = 0.00					
3	Constant	0.870228	0.0185448	46.93	0.000	0.87
	Rollers	-0.133763	0.0318419	-4.20	0.000	
	Log-Likelihood = -11657.833					
	Test that all slopes are zero: G = 17.470, DF = 1, P-Value = 0.00					
4	Constant	0.138626	0.0432162	3.21	0.001	1.21
	Rollers	0.186626	0.0784554	2.38	0.017	
	Log-Likelihood = -2009.883					
	Test that all slopes are zero: G = 5.702, DF = 1, P-Value = 0.017					
5	Constant	0.904040	0.0420063	21.52	0.000	1.01
	Rollers	0.0095822	0.0535578	0.18	0.858	
	Log-Likelihood = -2929.180					
	Test that all slopes are zero: G = 0.032, DF = 1, P-Value = 0.858					

4.6. Vertical Transition Mode Choice Models

Before creating the mode choice model for vertical transitions, we again reviewed the data available for several potential factors by mode choice. Table 4.7 depicts the number of rollers per passenger by vertical mode choice and airport. Clearly, there are differences in the number of roller bags by mode selected, indicating that this could be a good independent variable to consider when creating the regression model. In addition to rollers, other variables such as travel direction, employee or not, whether the passenger uses a wheel chair or not and whether the passenger has stroller or not are also considered. However, after examining the data, only 0.35% of overall samples were with a wheel chair and 0.2% of overall samples were with a stroller. These two variables were therefore not included into models due to insufficient observations on wheel chairs and strollers.

Table 4.7 : Number of Rollers (per passenger) for Each Vertical Transition Mode

Airport	1	2	3	4	5
Mode	Average number of rollers per passenger				
Escalator	0.45	0.38	0.29	0.35	0.26
Stair	0.21	0.09	0.03	0.03	0.05
Elevator	0.62	0.36	0.72	0.44	0.51

A multinomial logistic regression is used to predict vertical transition mode choice (elevator vs. escalator vs. stair), where the independent variables are the number of rollers, transition direction and whether or not the user is an employee. The probability function is again using the equation:

$$f(z) = \frac{1}{1 + e^{-z}}$$

where:

$$z = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3$$

$$x_1 = \text{number of rollers}$$

$$x_2 = \begin{cases} 1, & \text{transition direction is up} \\ 2, & \text{transition direction is down} \end{cases}$$

$$x_3 = \begin{cases} 1, & \text{traveler is an employee} \\ 2, & \text{traveler is not an employee} \end{cases}$$

The logit model coefficient results (compare alternate modes against riding an escalator) are based on all valid data collected at the surveyed airports, and these results are shown in Table 4.8.

Table 4.8 : Multinomial Regression Coefficients by All Airports

Predictor	Coef	SE Coef	Z	P	Odds Ratio
Logit 1: (Stair/ESC)					
Constant	-1.67890	0.0202368	-117.33	< 0.001	
Roller	-1.91673	0.0719594	-26.6	< 0.001	0.15
Direction(Up)	-0.494236	0.0606146	-8.15	< 0.001	0.61
Employee	-0.314262	0.108092	-2.91	0.004	0.73
Logit 2: (ELV/ESC)					
Constant	-3.09431	0.0366201	-84.50	< 0.001	
Roller	0.651185	0.0474535	13.72	< 0.001	1.92
Direction(Up)	-0.559582	0.0868459	-6.44	< 0.001	0.57
Employee	0.157478	0.137341	1.15	0.252	1.17
Log-Likelihood	-16070.816				
Test that all slopes are zero: G = 1598.983, DF = 6, P-Value = < 0.001					

The multinomial logistic regression consists of multiple logit functions which consist of a constant and coefficients in each logit function. Consider each logit model where (Mode 1/Mode 2) denotes the two modes being compared. There are two logit equations estimated since there are two modes other than choosing an escalator. Each set of models—logit 1 and logit 2—estimate the change in logits of stair and elevator relative to the reference event, that of the escalator. The two equations are:

$$Log\left(\frac{P(Stair)}{P(Esc)}\right) = b_{10} + b_{11} * Roller + b_{12} * Up + b_{13} * employee$$

$$Log\left(\frac{P(Elv)}{P(Esc)}\right) = b_{20} + b_{21} * Roller + b_{22} * Up + b_{23} * employee$$

The ratio of the probability of choosing one outcome category over the probability of choosing the reference category is often referred to as the relative risk (and it is also referred to as odds). The relative risk or odds ratios are displayed in the last column of Table 4.8. The results show that "rollers" is a significant variable in both logit 1 and 2 model, where the odds ratio is 0.15 in logit 1, and 1.92 in logit 2. When all other variables are controlled, we can make the following assertion: a one unit increase in rollers causes an 85% decrease in the odds of choosing stairs over an escalator; a one unit increase in rollers also causes a 92% increase in the odds of choosing an elevator over an escalator. Both trends are very consistent with what logic would tell us about passenger behavior. However, the magnitude of the change is quite intriguing. For variable direction, up is predicted, and down is the reference. Given that the travel direction is up, the odds of choosing stairs over an escalator decreases by 39% when the travel direction is down. This implies that passengers are more likely to use escalators when the travel direction is going up. A similar trend is observed for the comparison of an elevator and escalator. The odds of choosing an elevator over an escalator will decrease by 43% as compared to when going in the down direction. When considering whether the subject is an airport employee, we see a split trend (as was observed for the rollers variable). The odds of choosing stairs over an escalator decreases by 73% for those being employees rather than passengers. The employee variable did not figure into logit 2 as it was not considered a significant variable.

By looking at the probability of choosing the escalator over stairs through different conditions in Table 4.9 and Figure 4.5, it was found that, in general, the more rollers a passenger has, the higher probability that passenger will prefer an escalator over stairs. Passengers have a higher probability of using an escalator over stairs when the travel direction is up. The probability of choosing an escalator for employees is higher than airport passengers.

Table 4.9 : Probability of Using Escalator Compare to Stair

	Passenger		Employee	
Rollers	Up	Down	Up	Down
0	89.78%	84.28%	92.33%	88.01%
1	98.35%	97.33%	98.79%	98.04%
2	99.75%	99.60%	99.82%	99.71%
3	99.96%	99.94%	99.97%	99.96%

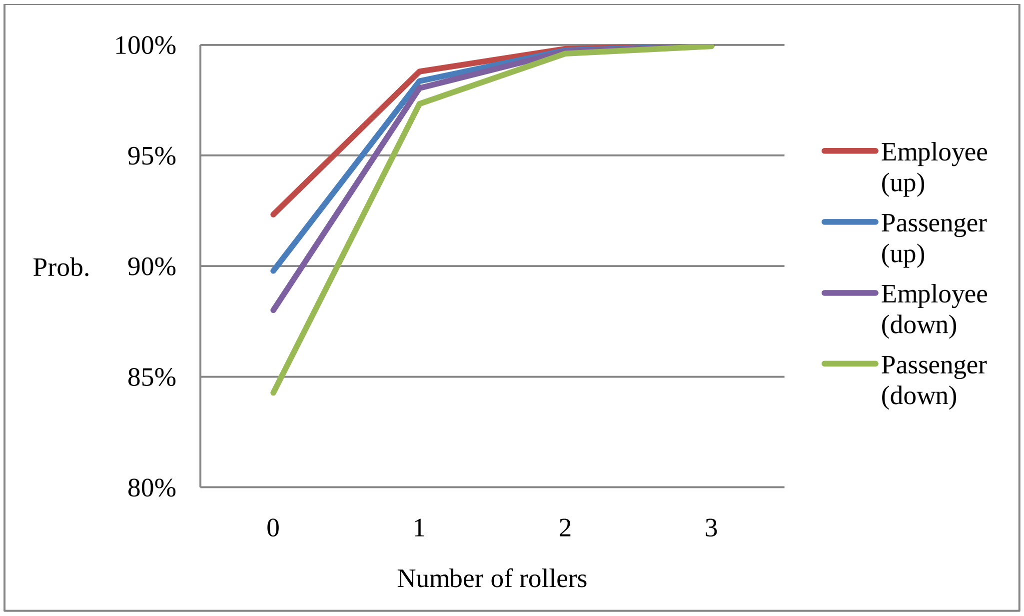


Figure 4.5 : Probability of Using Escalator over Stair

Consider the probability of choosing an escalator over an elevator based on various conditions as shown in Table 4.10. An increase in the number of rollers will decrease the probability of using the escalator compared to the elevator. This means a passenger who has more rollers is more likely to use the elevator as opposed to the escalator. This result also indicates that people have a higher probability of using escalators when the travel direction is up. Passengers also have a higher probability of choosing escalators than employees do. Figure 4.6 depicts these same trends graphically based on number of rollers, passenger direction and employee.

Table 4.10 : Probability Use Escalator Compare to Elevator

	Passenger		Employee	
Rollers	Up	Down	Up	Down
0	97.48%	95.67%	97.06%	94.96%
1	95.27%	92.01%	94.51%	90.77%
2	91.31%	85.72%	89.97%	83.68%
3	84.56%	75.78%	82.39%	72.78%

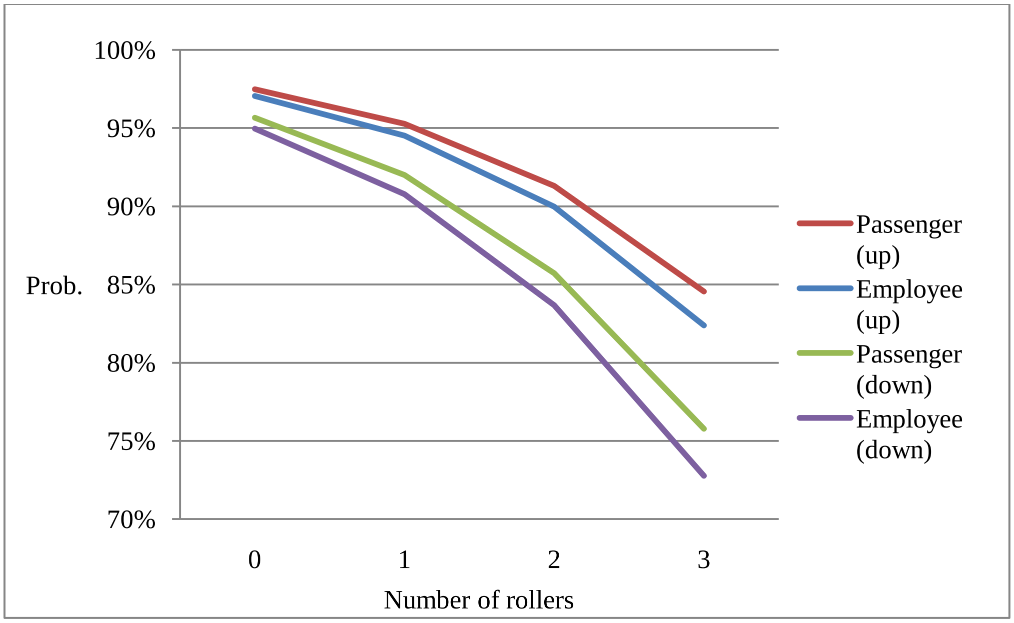


Figure 4.6 : Probability of Using Escalator over Elevator

Instead of using aggregate data across all airports, we now consider the behavior experienced at each airport individually. These results are shown in Table 4.11. Two regression models were created for each airport to explore the mode choice decision.

There are different observations to be made from the results. As we can find in logit 1 equation from all the airports, if the number of rollers increased, then the passengers prefer the escalator over stairs. For a one unit increased in roller in logit 1 equation, the odds of choosing stairs over the escalator decreased by a factor of 0.47 in airport 1, 0.17 in airport 2, 0.09 in airport 3, 0.006 in airport 4 and 0.15 in airport 5. The variable “rollers” is the most influential factor when comparing stairs to the escalator in airport 4 since the odds ratio is the farthest from one. In logit 2 equation, the positive coefficient in airports 3 and 4 for rollers implies that a passenger that has more rollers is more likely to use the elevator as compared to the escalator. However, the preference of elevator over escalator is not significant in airports 1, 2 and 4. For every one unit increase in rollers in logit 2 equation, the odds of using the elevator over the escalator increase by a factor of 2.98 in airport 3 and 2.48 in airport 5.

The effect of the main dichotomized variables used in the model, positive coefficient of direction in logit 1 equation indicates that passengers tend to use stairs instead of the escalator when travel direction is going up in airports 1, 2 and 4. When we compare the elevator with the escalator, logit 2 equation, passengers tend to take an elevator if the direction is up in airport 3. However, it is reversed in airports 2 and 4. Based on these results, we do begin to see certain layouts and characteristics of individual airports dominating the results derived from the modeling. The technique is still well served for representing passenger behavior within various areas of the passenger terminal.

For the final significant variable (i.e., employee), the results indicate that employees prefer an escalator over stairs in airport 2, and an escalator over an elevator in airport 1. However, in airport 3, the odds ratio of coefficient of employee is extremely small. Garson [48] has explained that the reason for this is that the algorithm estimating the logistic coefficient (and hence also exp (b), the odds ratio) is unstable, failing to converge while attempting to move iteratively toward positive infinity (or negative infinity). This situation may also appear from the limitation of the number sample points in the data (21 out of 7819 data points).

Table 4.11 : Multinomial Regression Coefficients of Five Airports

Airport	Predictor	Coef	SE Coef	Z	P	Odds Ratio
	Logit 1: (STA/ESC)					
	Constant	-4.0114	0.260440	-15.4	<0.001	
	Rollers	-0.744538	0.271392	-2.74	0.006	0.47
	Direction (Up)	1.7227	0.266063	0.266063	<0.001	5.60
	Employee (Yes)	0.49906	0.49906	0.49906	0.064	1.65
1	Logit 2: (ELV/ESC)					
	Constant	-3.16855	0.189916	-16.68	<0.001	
	Rollers	0.306778	0.182842	1.68	0.093	1.36
	Direction (Up)	0.150674	0.221804	0.68	0.497	1.16
	Employee (Yes)	-1.90754	0.725369	-2.63	0.009	0.15
	Log-Likelihood = -687.702 Test that all slopes are zero: G = 92.116, DF = 6, P-Value = 0.000					
	Logit 1: (STA/ESC)					
	Constant	-1.95195	0.0417487	-46.75	<0.001	
	Rollers	-1.77796	0.112014	-15.87	<0.001	0.17
	Direction (Up)	0.400974	0.0776194	5.17	<0.001	1.49
	Employee (Yes)	-0.639918	0.195793	-3.27	0.001	0.53
2	Logit 2: (ELV/ESC)					
	Constant	-3.24822	0.0748673	-43.39	<0.001	
	Rollers	-0.0769224	0.116923	-0.66	0.511	0.93
	Direction (Up)	-0.939744	0.19363	-4.85	<0.001	0.39
	Employee	0.399535	0.209913	1.90	0.057	1.49
	Log-Likelihood = -4436.375 Test that all slopes are zero: G = 457.106, DF = 6, P-Value = 0.000					
	Logit 1: (STA/ESC)					
	Constant	-1.81660	0.0426804	-42.56	<0.001	
	Rollers	-2.41613	0.223686	-10.80	<0.001	0.09
	Direction(Up)	-19.7916	868.126	-0.02	0.982	0.00
	Employee	-2.571E+12	218218	-1.178E+7	<0.001	0.00
3	Logit 2: (ELV/ESC)					
	Constant	-5.40724	0.179613	-30.10	<0.001	
	Rollers	1.0906	0.128637	8.48	<0.001	2.98
	Direction(Up)	1.93161	0.198044	9.75	<0.001	6.90
	Employee	-5.665E+11	218218	-2596093	<0.001	0.00
	Log-Likelihood = -2584.591 Test that all slopes are zero: G = 643.743, DF = 6, P-Value = 0.000					
	Logit 1: (STA/ESC)					
	Constant	-3.04137	0.156889	-19.39	<0.001	
	Rollers	-2.88059	0.508897	-5.66	<0.001	0.006
	Direction(Up)	0.847899	0.188455	4.50	<0.001	2.33
4	Logit 2: (ELV/ESC)					
	Constant	-3.03541	0.149851	-20.26	<0.001	
	Rollers	0.319427	0.206066	1.55	0.121	1.38
	Direction(Up)	-1.19777	0.249785	-4.80	<0.001	0.30
	Log-Likelihood = -916.121 Test that all slopes are zero: G = 143.446, DF = 4, P-Value = 0.000					
	Logit 1: (STA/ESC)					
	Constant	-1.38842	0.02788	-49.80	<0.001	
	Rollers	-1.91125	0.115764	-16.51	<0.001	0.15
	Employee	0.308629	0.168653	1.83	0.067	1.36
5	Logit 2: (ELV/ESC)					
	Constant	-2.56892	0.0455132	-56.44	<0.001	
	Rollers	0.906745	0.0615002	14.74	<0.001	2.48
	Employee	0.736500	0.211215	3.49	<0.001	2.09
	Log-Likelihood = -7649.872 Test that all slopes are zero: G = 767.337, DF = 4, P-Value = 0.000					

4.7. Conclusion

This empirical study analyzes the use of passenger conveyance systems in airports and passenger mode choice for both horizontal and vertical transitions. The researchers observed and collected data from five airports across the U.S., and the mode choice modeling uses these data for determining relationships between significant factors for horizontal and vertical transitions, respectively.

Overall, a large percentage of passengers tend to use and walk on moving walkways. For vertical transitions, a vast majority of passengers use escalators, but those who use escalators tend to stand on the device rather than walk on it. The logistic regression analysis suggests that the number of rollers has an impact on a passenger's mode choice in both horizontal and vertical transitions. More rollers will decrease the probability of using moving walkways. Airport passengers tend to use escalators as compared to stairs, and elevators over escalators—when they have more rollers with them. Escalators are a highly preferable mode for both employees and passengers as compared to stairs or elevators in airports. Also, when the transit direction is up, passengers are more likely to prefer escalators over stairs and elevators.

To effectively meet future increases in airline passenger demand, this information can be used to help airport planners in studying the use of passenger conveyances in airport construction and expansion projects.

Chapter 5

Determining Influential Factors on Corridor Congestion in Airport Concourse Operations

5.1. Introduction

Airport improvements require major infrastructure investment, which implies that airport planners and designers must provide for the future within today's airport facilities. In addition to meeting increasing passenger enplanements, the introduction of the Airbus A380 has posed new requirements in terminal planning [49], which transferred the airport capacity problem from the runway to the passenger processing terminal [50]. As airports become larger, the operation of airport terminals/concourses becomes more important. Well [11] indicated that the pedestrian walkway to aircraft is an important factor to consider for airport planners. Horonjeff and Mckelvey [10] discuss characteristics of terminals based on four existing classifications: (1) linear, (2) pier or finger, (3) satellite and (4) transporter. The optimal passenger terminal configurations and gate requirement problem was analyzed by de Barros et al. [51, 52], who proposed an analytical methodology for accommodating new large aircrafts, like the A380. Research by de Neufville et al. [16, 53] also defined the optimal configuration of the airport passenger building using a novel two-phase analysis. After first defining or choosing a terminal configuration, an operational concept is selected that provides the desired LOS for the passenger.

For airport operation planners and designers, one important aspect in assessing airport facility design is to analyze passenger occupancy in the airport terminal. This chapter presents a simulation model of passenger flow through an airport concourse based on various operating characteristics. The main theme of this chapter will focus on identifying influential factors and their impact on concourse corridor width.

5.2. Problem Statement

It is well-known that an airport must provide enough space for its passengers to meet a standard LOS. This leads to our research question: "Which factors have the most influence on passenger occupancy of any designated area (or footprint) within a concourse?" To this point, there is limited research exploring this particular question.

5.3. Concourse Operation Simulation

In airport planning, it is important to develop a model for determining the capacity of an airport which takes into account the LOS. Our framework for estimating potential corridor congestion is based on the pedestrian density by using the general purpose simulation software package, ARENA. We consider different combinations of factors and set incremental levels of each factor in our model to assess LOS at each test instance and determine the configurations that can achieve a high LOS. Moreover, the simulation model will provide an appropriate tool for airport designers and planners to determine the airport corridor width.

The model in Figure 5.1 represents a typical concourse operation, showing the passenger occupancy in the Measure Area (Footprint). The operation of the airport concourse starts from an aircraft's arrival to a passenger's leaving the concourse. The gate area was identified as G in the figure below.

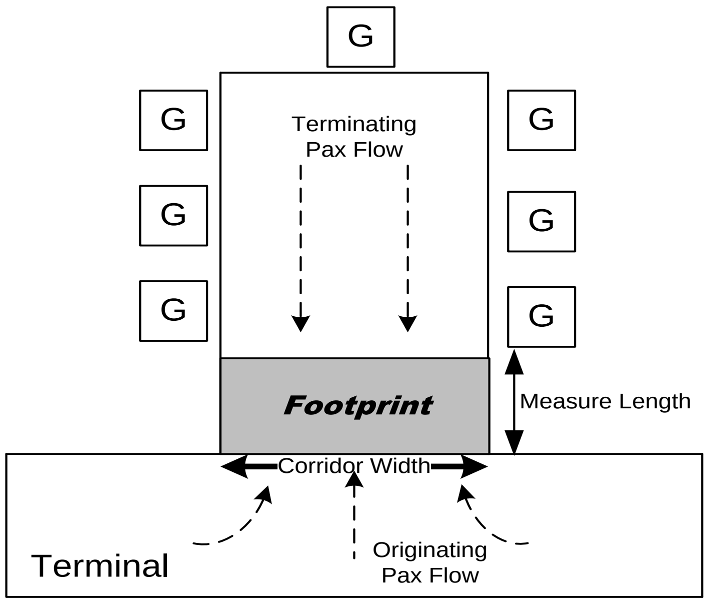


Figure 5.1 : The Scenario of Concourse Simulation

To be clear, the process of our simulation model is described as follows (and shown in Figure 5.2). Once the aircraft arrives to a gate based on different flight schedules and different aircraft sizes, the passenger will de-board the aircraft based on a chosen de-board time and then enter the concourse. If the passenger has a connecting flight, they will stay in the concourse and will not cross the Footprint. Otherwise, terminating passengers will cross the Footprint. Note that for this research, we assume connections are within the concourse only. By adjusting the connection percentage, we can easily account for airports that operate multiple terminals and concourses.

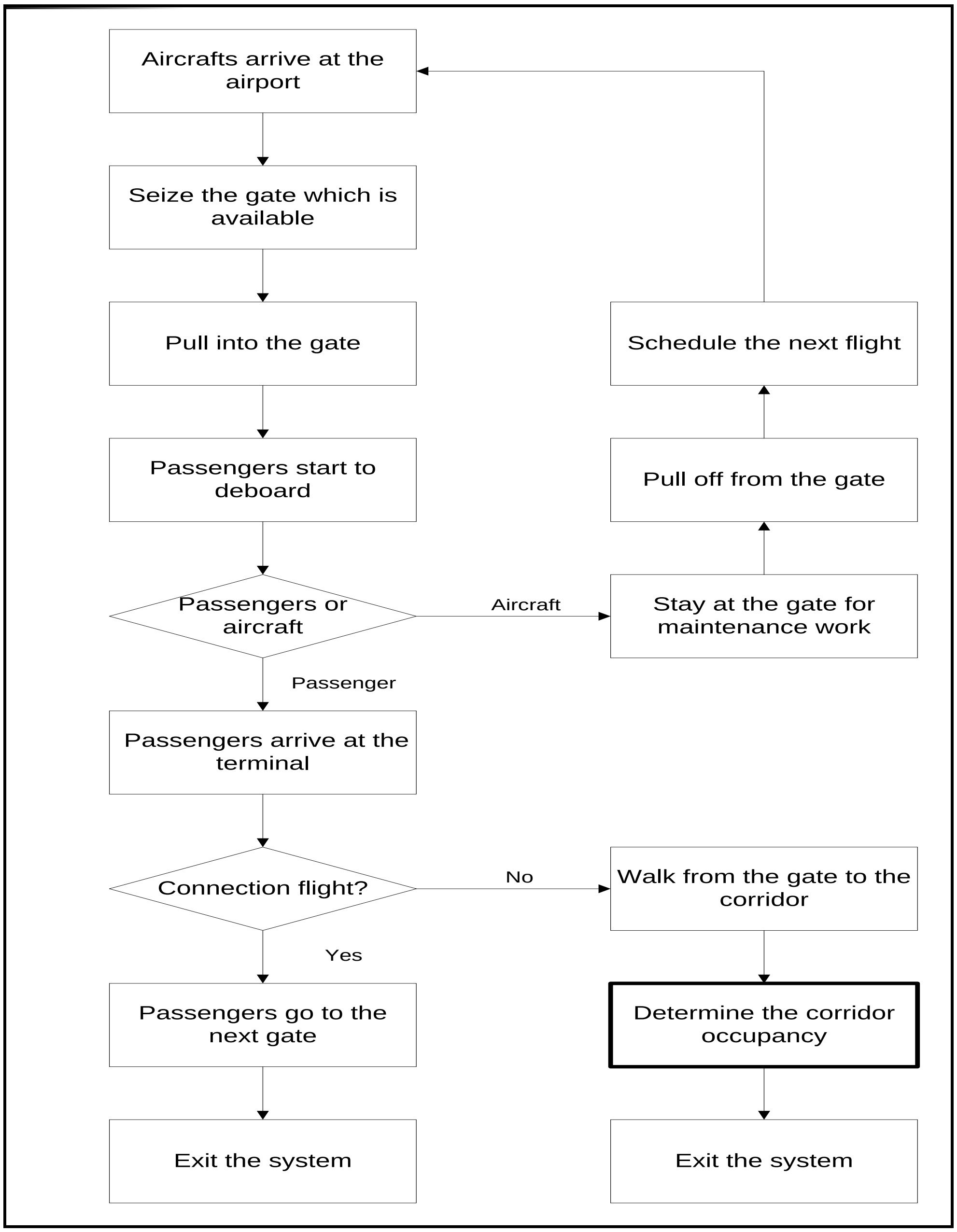


Figure 5.2 : Concept Description of Aircraft and Passenger Arrival Flow in Simulation Model

The purpose of defining the aircraft and passenger arrival flow is to determine the maximum passenger occupancy at the airport terminal given the different airport parameters. Our objective is to estimate the number of passengers who dwell in or pass through the Footprint in a unit of time. For each configuration, the model will simulate the system though a day and provide the number of passengers present in the corridor and Footprint throughout the day. The passenger density can be used by an airport planner as a basis for design.

5.4. Factors Affecting Passenger Occupancy

In order to plan corridor width in terms of passenger occupancy at a specific LOS, it is necessary to clearly understand the various factors which affect corridor occupancy. For representing an actual airport concourse, several factors—like number of gates, aircraft size, percentage of passengers taking connecting flights, passenger de-board time, passenger walk speed and flight arrival frequency—were considered in the model. Using simulation, each factor's influence on LOS, in terms of corridor occupancy, was assessed. Intuitively, corridor occupancy could be most influenced by the number of gates, size of aircraft and percentage of connecting passengers within the concourse. However, a more complete understanding of how each factor influences corridor occupancy is desired.

In order to test each factor's impact on passenger corridor occupancy, a two-level full factorial design / design of experiments (DOE) approach is applied to simulate the different scenarios. An ANOVA statistics are generated to identify the significance of each of the factors and their interactions that affect the planning of airport operations.

Note that in this section, only a subset of factors was included in the DOE analysis. We also investigate additional factors in Chapter 6. The factors used in this section and their levels are summarized in Table 5.1.

We consider two concourse sizes—10 gates and 25 gates. Flights arrive at each gate according to an exponential distribution with mean 20 minutes. There are two sizes of aircraft—150 seats and 250 seats. The aircraft size factor denotes the percentage of small aircraft arriving to each gate. Once the flights arrive at the gates, the passengers de-board according to an exponential distribution with a mean of two (2) seconds. After all passengers exit the aircraft, aircraft remains at the gate for a designated ground time (clean and boarding for next flight). The aircraft ground time is assumed to follow a uniform distribution between 20 and 25 minutes. Once the passengers arrive at the terminal, they have an option to connect to another flight or leave the airport. A connection is considered to be "within the concourse," which implies they will not cross the Footprint or threshold measurement area. Otherwise, the passenger will travel though the corridor and then cross that area with a walk speed following a uniform distribution between 60 and 80 feet per minute (for Level 1) or between 90 and 110 feet per minute (for Level 2). In subsequent sections, a walking speed reflective of the research done by Young [40], Furin [4] and Older [59] is used. All input parameters mentioned above are based on personal experience and knowledge. All subsequent research (Chapter 6) has additional reliable sources as the literature review was completed at that time.

Table 5.1 : The Level of Each Factor

Factors	Level 1	Level 2
Number of Gates	10	25
Percentage of small aircraft	10%	40%
% of passengers connecting within the concourse	10%	30%
Walking speed of the passengers	70 feet/minute	100 feet/minute

In order to track how many passengers are dwelling in the Footprint, two assign modules in the model were used to track passengers entering and leaving the Footprint. Here, we can use the time for the passenger to walk through the measure area as the service rate, and it will be measure area length divided by passenger walk speed. This value will be used to calculate the number of passengers who leave from this system.

Table 5.2 provides a summary of the simulation results based on 80 observations of the response variable (corridor occupancy).

Table 5.2 : The Simulation Result for Each Scenario

Scenario	Reps	Number of gates	Percentage of passenger connection	Distribution of the size of the aircraft	Walking speed	Corridor occupancy
Scenario 1	5	10	10	0.4	70	9.4
Scenario 2	5	10	30	0.4	70	9.2
Scenario 3	5	25	30	0.1	70	30.8
Scenario 4	5	10	10	0.4	100	12.8
Scenario 5	5	25	30	0.4	100	22
Scenario 6	5	25	30	0.4	70	17
Scenario 7	5	25	10	0.4	70	38
Scenario 8	5	25	10	0.1	100	58
Scenario 9	5	10	30	0.1	70	11.2
Scenario 10	5	10	10	0.1	70	15.2
Scenario 11	5	10	30	0.1	100	8.6
Scenario 12	5	25	10	0.1	70	54
Scenario 13	5	25	30	0.1	100	35.4
Scenario 14	5	10	30	0.4	100	8.6
Scenario 15	5	10	10	0.1	100	12.6
Scenario 16	5	25	10	0.4	100	17

In each model replication, corridor occupancy is recorded as the average of 5 replications. In the model, each replication denotes one day with a length of 16 hours. After running the simulation for 5 days (or 5 replications), the output reports the average of any statistic measured. The model records the maximum number of passengers who dwell in the measure area for each replication. The average of those 5 replications is 9.4. So it should read “maximum mean corridor occupancy”.

Table 5.3 provides the results of the F-test taken from the ANOVA statistics, which identifies all of the factors (number of gates, percentage of passenger connection, distribution of the size of the aircraft and walking speed of the passengers) as significant factors affecting corridor occupancy. Thus, all factors studied influence the design of the airport concourse operations.

Table 5.3 : ANOVA Statistics Result

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	9214.63	9214.63	2303.66	66350.79	0.00
2-Way Interactions	6	233.68	233.68	38.95	1121.75	0.00
3-Way Interactions	4	30.46	30.46	7.62	219.35	0.00
4-Way Interactions	1	9.52	9.52	9.52	274.06	0.00
Residual Error	64	2.22	2.22	0.03		
Total	79	9490.51				

Figure 5.3 provides a Pareto chart, which identifies the number of gates as the factor with the most influence on corridor occupancy. As the quantity of gates increases, the quantity of flights arriving to the system increases, which increases the occupancy of the corridors. This is clearly the dominating relationship between a factor and corridor occupancy. It is no surprise that the first topic of discussion when planning a terminal is to identify an appropriate number of gates to meet the needs of both airlines and passengers.

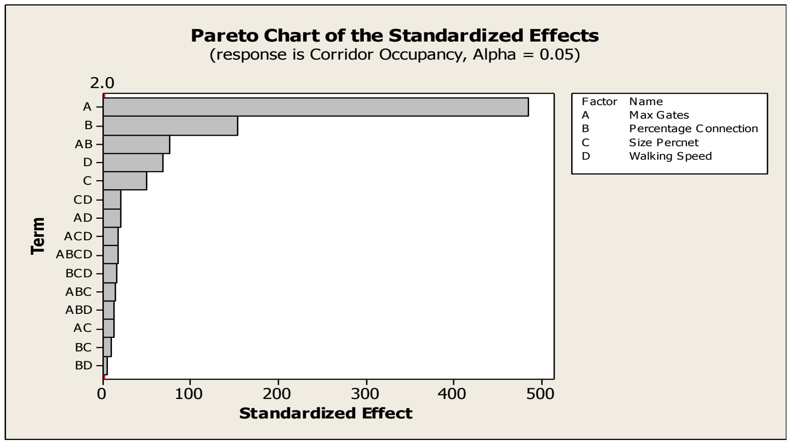


Figure 5.3 : Pareto Chart

To provide further detail for specific sources of variability, the General Linear Model (GLM) procedure can be used to construct the ANOVA table for factorial experiments and calculate a P-value of each factor and interaction. The result for this model is shown in Table 5.4. By examining the P-value of each main factor, it can be seen that there is sufficient statistical evidence that each main factor (Max Number of Gates, Percentage Connection, Percentage of Small Aircraft and Walking Speed) has a significant effect on corridor occupancy. Thus, all of these factors influence the design of the airport concourse operation. Moreover, the P-value for every interaction term is less than 0.05. Thus, the interactions by 2-way factors (AB, AC...), 3-way factors (ABC, ABD…) and 4-way factors (ABCD) are significant, implying that any combination of factors can also play a role in corridor occupancy.

Table 5.4 : General Linear Model

Source	DF	Seq SS	Seq MS	F	P
Max Gates	1	8151.31	8151.31	234776.94	0.000
Percentage Connection	1	819.78	819.78	23611.49	0.000
Size Percent	1	84.36	84.36	2429.70	0.000
Walking Speed	1	159.19	159.19	4585.02	0.000
Max Gates*Percentage Connection	1	196.22	196.22	5651.59	0.000
Max Gates*Size Percent	1	4.68	4.68	134.80	0.000
Max Gates*Walking Speed	1	14.05	14.05	404.77	0.000
Percentage Connection*Size Percent	1	2.91	2.91	83.73	0.000
Percentage Connection*Walking Speed	1	0.97	0.97	27.82	0.000
Size Percent*Walking Speed	1	14.85	14.85	427.78	0.000
Max Gates*Percentage Connection*Size Percent	1	6.14	6.14	176.96	0.000
Max Gates*Percentage Connection*Walking Speed	1	5.08	5.08	164.18	0.000
Max Gates*Size Percent*Walking Speed	1	10.25	10.25	295.11	0.000
Percentage Connection*Size Percent* Walking Speed	1	9.00	9.00	259.17	0.000
Max Gates*Percentage Connection* Size Percent*Walking Speed	1	9.52	9.52	274.06	0.000
Error	64	2.22	0.03		
Total	79	9490.51			
S = 0.186331 R-Sq = 99.98% R-Sq(adj) = 99.97%					

Next, we explore the average effects of each factor and interaction based on the results in Table 5.5 (shown below) as well as the main effect plots for corridor occupancy shown in Figure 5.4 (shown below). First, as previously stated, Max Gates has the greatest effect on corridor occupancy. The more gates, the more flights arrive to the system and increase the occupancy of the corridor. Second, Percentage Connection has the second greatest effect on corridor occupancy. A negatively correlated relationship exists, indicating that higher connection percentages result in lower corridor occupancy. This is easily explained: connecting passengers will go to the next gate without leaving the concourse. Third, the Size Percent (or Percentage of Small Aircraft) factor also has a negative effect on corridor occupancy. In other words, assigning smaller aircraft to each gate will cause fewer passengers to cross the footprint threshold. Fourth, the walking speed has a negative effect on corridor occupancy. This means that if walking speed of passengers is faster, there will be fewer passengers who dwell on the footprint area.

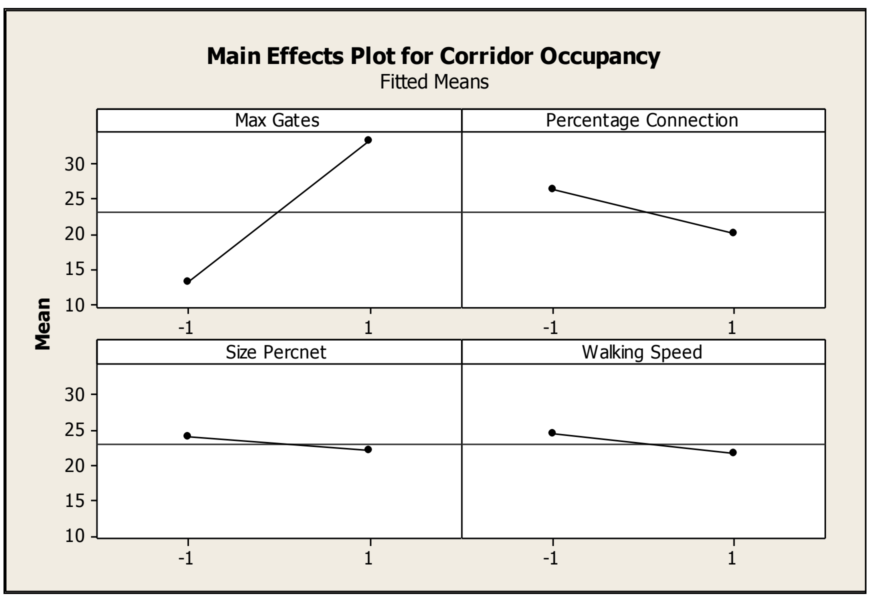


Figure 5.4 : Main effect plot for corridor occupancy

Table 5.5 : The effect of each factor and interaction

Term	Effect	Coef.	T	P
Constant		23.081	1107.92	0.000
Max Gates	20.188	10.094	484.54	0.000
Percentage Connection	-6.402	-3.201	-153.66	0.000
Size Percent	-2.054	-1.027	-49.29	0.000
Walking Speed	-2.821	-1.411	-67.71	0.000
Max Gates*Percentage Connection	-3.132	-1.566	-75.18	0.000
Max Gates*Size Percent	-0.484	-0.242	-11.61	0.000
Max Gates*Walking Speed	-0.838	-0.419	-20.12	0.000
Percentage Connection*Size Percent	-0.381	-0.191	-9.15	0.000
Percentage Connection*Walking Speed	-0.220	-0.110	-5.27	0.000
Size Percent*Walking Speed	0.862	0.431	20.68	0.000
Max Gates*Percentage Connection*Size Percent	-0.554	-0.277	-13.30	0.000
Max Gates*Percentage Connection*Walking Speed	-0.504	-0.252	-12.09	0.000
Max Gates*Size Percent*Walking Speed	0.716	0.358	17.18	0.000
Percentage Connection*Size Percent* Walking Speed	-0.671	-0.335	-16.10	0.000
Max Gates*Percentage Connection* Size Percent*Walking Speed	-0.690	-0.345	-16.55	0.000

Finally, as can be seen from the result above, all 2-way, 3-way, and 4-way interaction have a negative effect on corridor occupancy except Max Gates*Size Percent*Walking Speed. Also, all of interaction effects are significant. This indicates that airport planners should be careful about the interaction effects and not just consider the main effects on corridor occupancy.

5.5. Conclusion

Based on real-life airport conditions, we consider many factors such as number of gates, aircraft size, percentage of people who take a connection flight, flight arrival pattern, etc. For each of the factors considered, we tested two levels. We simulated the model for 16-hour days and did many replications to reduce the variance in the model. In total, we have 4 factors and 2 levels each constituting 16 scenarios. We did a full factorial DOE design to determine the most significant factor affecting the response variable (corridor occupancy). From our results, we know that all four factors have significance in determining the corridor occupancy.

Chapter 6

Estimating Potential Congestion and Meeting Service-level Requirements in Airport Concourses

6.1. Introduction

A good airport terminal is determined not only by the optimal configuration but also by providing a comfortable environment (and meeting certain spacing requirements) for the passenger. The LOS is considered an important index, and Chapter 2 introduced a number of studies which use either simulation or analytical methodology to address space requirement issues in airport terminal facilities [54-56, 56, 57]. Most of this research focuses on sizing individual areas such as check-in, wait/circulate, departure lounge and baggage claim. However, there is very little information related to the flow within the concourse or the concourse width. The work by Seneviratne and Wirasinghe [37] presented a calculus-based methodology to determine the optimal corridor width, and the result showed that facility and operating costs are an essential part of the overall design concept and should be considered simultaneously in order to achieve an optimal design. However, their findings did not address the impact that each contributing airport/passenger characteristic has on overall flow. The IATA [13] has established a complete set of space requirement that presents a LOS classification according to a scale with measures ranging from “A” to “F.” However, this standard does not include walkways. In general, a concourse’s effective width requirement is not taken sufficiently into account and is often determined empirically. This chapter extends the simulation model of passenger flow through an airport concourse in Chapter 5. In this chapter, we will still focus on one performance measure—the occupancy of a designated area of the concourse and establish a service level design standard matrix to assist in airport design and development.

6.2. Problem Statement

Traveler congestion in airport corridors, expressed in units of space per passenger and passenger flow, is used to determine the LOS. However, with a given number of gates and a particular gate configuration within a concourse, passenger flow volume may vary based on different flight schedules, aircraft size, passenger arrival patterns and passenger walk speed. In order to evaluate the impact of the combination of different factors on corridor occupancy, a simulation of all concourse operations will be performed. We can determine the width of the airport concourse necessary to achieve a desired minimum LOS and use the appropriate value of pedestrian flow volume to obtain the width of airport concourse.

6.3. LOS in the Airport Concourse

According to the literature, the LOS concept was originally established for appropriately determining highway capacities. In addition, Fruin [4] proposed a pedestrian LOS that assisted in the development a series of LOS design standards for walkways, stairways and pedestrian queuing. Pedestrian spacing is a major factor that determines the breakpoints of various service levels. Correia and Wirasinghe [58] illustrated a methodology to analyze the LOS at departure lounges using only user perceptions. A terminal building is designed to account for the passengers' needs and wants. As such, terminal designers aim not only to keep passengers moving through the system in a smooth flow but also to meet the designed LOS for passengers' spacing. However, the number of gates in a concourse, the connecting flight options and opportunities, and individual walking speed may affect the occupancy level in a concourse, so the airport design should account for these (and possibly other) factors. Pushkarev and Zupan [26] also defined a number of LOS for walking with open flow.

Although pedestrians may have unique walking speeds due to such factors as time of day, gender and trip purpose, the most significant factor is traffic volume [4]. As traffic density increases, pedestrian speed is decreased, due to the reduction in available area for continued flow. Time-lapse photography analysis of pedestrian flow has been used to establish the flow-volume relationship (Figure 6.1) for various categories of pedestrian traffic by Fruin [4]. LOS design standards have been established for different flow volumes and are expressed in terms of pedestrian area occupancy and average flow volume. Table 6.1 lists LOS design standards for walkways.

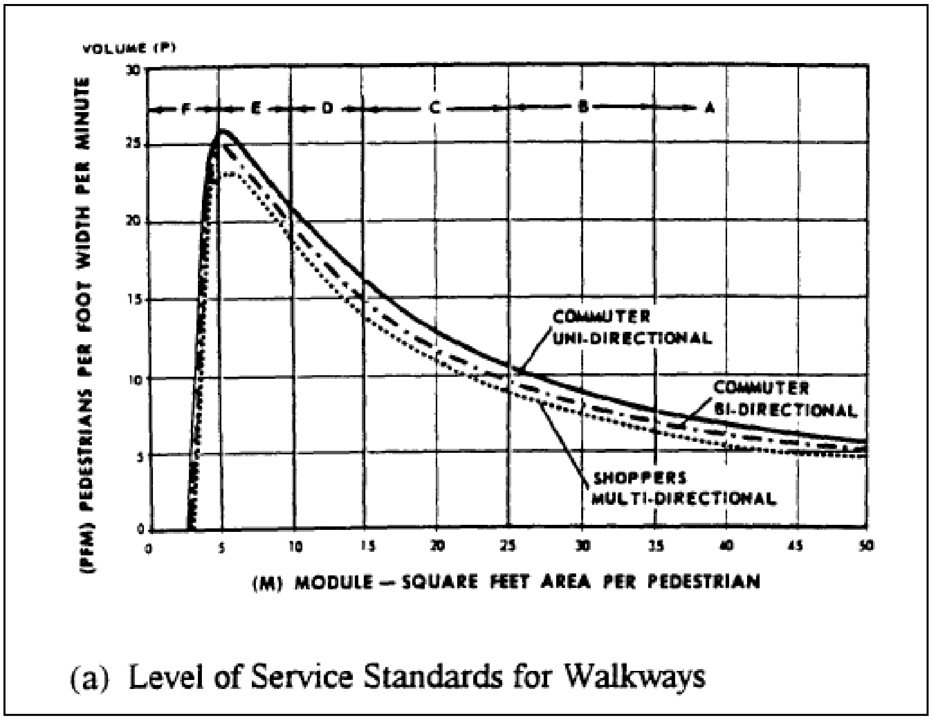


Figure 6.1 : Flow-Volume Relationship for Walkways (Fruin 1971)

Table 6.1 : LOS Standards for Walkways (Fruin 1971)

Level of Service	Avg. Pedestrian Occupancy (Square ft/person)	Avg. flow Volume (PFM)
A	>35	<7
B	25-35	7-10
C	15-25	10-15
D	10-15	15-20
E	5-10	20-25
F	<5	>25

6.4. Determining Potential Corridor Congestion in the Footprint

In order to investigate the percent of time during a day when the facility can achieve a desired LOS (LOS B is used in this section), expressed in terms of average passenger area occupancy (square ft/passenger) in the designated footprint (see Figure 5.1), a variety of factors and different combinations of gate configurations were considered.

There is no consensus as to which LOS is the most appropriate for planning airport concourse operations. However, given a choice, airport authorities always want to design for LOS "A." This is not always feasible, given the additional facility size, cost and materials required to achieve such a service. There are examples of researchers selecting various LOS, and we were able to find multiple researchers selecting LOS "B" as a critical level. Here is an excerpt from Svrcek's research [59]:

The Milan Airport Authority made extensive use of the IATA level of service parameters in the design of the new terminal of Malpensa Airport. This new terminal is expected to service 16-20 million passengers per year, and was designed to provide a "B"-level of service during peak periods. [p.213]

Thus, a "B"-LOS is selected as a standard, and a single-pier airport concourse with a 20-foot corridor width and 12 gates has been used as an example. The following factors have been included to be investigated in this model.

1. Gate configuration: Similar to aircraft size shown in Chapter 5, the mix of aircraft to accommodate at individual gates should have an impact on passenger flow and

corridor occupancy. Since it is not a variable that would have a high/low setting, it was not specifically tested in Chapter 5. The first, second and third number in parentheses represent the number for small, medium and large gates respectively. For example, the symbol, (2, 2, 8), represents 2 gates for small aircraft, 2 gates for medium aircraft and 8 gates for large aircraft. In our model, the number of passengers on small, medium and large aircraft is 75, 150 and 225, respectively.

2. Average flight frequency: (minutes between successive flights) to each gate (small, medium and large) is another factor we consider in the model. We also use 3 numbers in parentheses to represent average minutes between successive flights to different of gates. For example, (50, 60, 70) denotes that, on average, a small aircraft arrives every 50 minutes, a medium aircraft arrives every 60 minutes, and a large aircraft arrives every 70 minutes, respectively. A 10-minute range in actual inter-arrival times is considered for each setting, to simulate the effect that each flight might be delayed or arrive early to the gate. We assume a uniform distribution applies across each range.

3. Walk speed: Although several studies have shown that a passenger's average walking speed may vary due to such factors as gender, age and trip purpose, Fruin states that the average walking speed was approximately 265 ft per minute with a standard deviation of 50 ft per minute in free-flow conditions. However, the most influential determinant factor on passenger walking speed is traffic density [4]. Passenger walking speed decreases as traffic density increases: the faster the movement, the more space is required. We monitor the total number of passengers in the system at each instant of time and modify the walking speed to reflect the real world more closely. The relationship

between density and walking speed has been studied by Fruin [4] and Older [60]; it can be represented as a linear function. It takes the form of equation:

$$speed = A - B \times density$$

In the equation above, A represents the intercept on the y axis and B represents the slope of a straight line. The two coefficients, A and B, can be interpreted as follows: A represents the theoretical walking speed under free flow; B is an impedance coefficient that decreases walking speed. The constants A and B for the equation are given in Table 6.2. These constants were first proposed by Older [60].

Table 6.2 : Coefficients of Pedestrian flow Equation

Type of flow and source	A (theoretical maximum speed at free flow)		B	B/A (theoretical minimum space per pax at zero speed)	
	(ft/min)	(m/min)		(sq ft)	(m^2)
Shoppers, Olders	258	78.6	714	2.77	0.257
Commuters, Fruin	267	81.4	722	2.70	0.251

4. De-board time: When modeling passengers de-board from an aircraft, we need to make an assumption about the speed at which they can deplane. There are no standards across the industry; however, a transportation-related consulting firm provided the ranges of de-boarding rates that have often been used for different sizes of aircraft. The most-generally used average de-boarding rates are: 1) 25 passengers per minute for dual-aisle aircraft (large aircraft), 2) 19 passengers per minute for single-aisle aircraft (medium aircraft) and 3) 12 passengers per minute for commuter aircraft (small aircraft). In the

model, we convert the de-boarding rate into seconds per passenger, and assume it follows an exponential distribution. Our notation denotes the average de-board time for small, medium and large aircraft, respectively. For example, (5.5, 3.6, 2.9) represents 5.5 seconds per passenger for small aircraft, 3.6 seconds per passenger for medium aircraft and 2.9 seconds per passenger for large aircraft. We use ± 20% from basic case to test the impact of de-board time on corridor occupancy.

5. Size of aircraft: As we know, the size of aircraft is one of the influential factors on passenger flow. The common small size commercial aircraft serving in the airports is conventional jets like CRJ and ERJ with 50 seats, and the common big size commercial aircraft is similar to B747-400 with 260 seats. So the capacity (number of passengers) of small, medium and large we use in the model is 75, 150 and 225 respectively.

Other basic inputs in the simulation model are listed in Table 6.3.

Table 6.3 : Basic Inputs in the Simulation Model

Item	Input
Total gates	12
Aircraft load factor	0.8
Delay time for aircraft open door	2 minute
Aircraft ground time for aircraft	25 minute
Distance between gate	20 ft
Measure length of footprint	30 ft
Corridor width	20 ft

In each factor, a different reasonable level is set up to test passenger density in the measure area under each combination. Then we calculate the percent of time during the day when LOS B or better is attained for each factor combination. Table 6.4 summarizes the initial set of test scenarios and LOS outcomes.

Table 6.4 : Percentage Time of Day at or above LOS B for a 20-foot Width

De-board Time: +40% [7.7, 5.0, 4.0]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	97%	96%	96%	96%	95%
	(2,5,5)	99%	98%	98%	98%	97%
	(3,4,5)	99%	99%	98%	98%	98%
	(4,4,4)	99%	99%	99%	99%	99%
	(8,2,2)	99%	99%	99%	99%	99%
De-board Time: +20% [6.6, 4.3, 3.4]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	98%	98%	97%	97%	96%
	(2,5,5)	99%	98%	98%	98%	97%
	(3,4,5)	99%	99%	98%	98%	98%
	(4,4,4)	99%	99%	99%	99%	99%
	(8,2,2)	99%	99%	99%	99%	99%
De-board Time: [5.5, 3.6, 2.9]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	98%	98%	97%	97%	96%
	(2,5,5)	99%	98%	97%	97%	97%
	(3,4,5)	99%	99%	98%	98%	98%
	(4,4,4)	99%	99%	99%	99%	99%
	(8,2,2)	99%	99%	99%	99%	99%
De-board Time: -20% [4.4, 2.8, 2.3]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	99%	98%	98%	98%	97%
	(2,5,5)	99%	98%	98%	98%	98%
	(3,4,5)	99%	99%	99%	99%	99%
	(4,4,4)	99%	99%	99%	99%	99%
	(8,2,2)	99%	99%	99%	99%	99%
De-board Time:-40% [3.3, 2.1, 1.7]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	99%	99%	99%	99%	99%
	(2,5,5)	99%	99%	99%	99%	99%
	(3,4,5)	99%	99%	99%	99%	99%
	(4,4,4)	99%	99%	99%	99%	99%
	(8,2,2)	99%	99%	99%	99%	99%

Table 6.4 presents the simulation results for a 20-foot corridor width. The results indicate that this corridor width can support 12 gates and achieve an LOS B or better 95% of the day. Note that this 20-foot actual corridor width can have impedances that may reduce the physical space for entering or exiting a concourse. The reason is that there are services and concessions occupying the space along each side of corridor. Such items that influence the effective corridor "walking" width may include concessions, restaurants, departure lounges and bathrooms. In addition, kiosks and temporary construction may also reduce this corridor width, and the percent of time in LOS B or better will decrease. We can easily see from Figure 6.2 and 6.3 that the effective corridor width is the total corridor width less obstacles like telephones, flight information display system (FIDS), wastebaskets, seats and gate waiting area. Moreover, people will normally maintain a certain clearance between corridor walls.

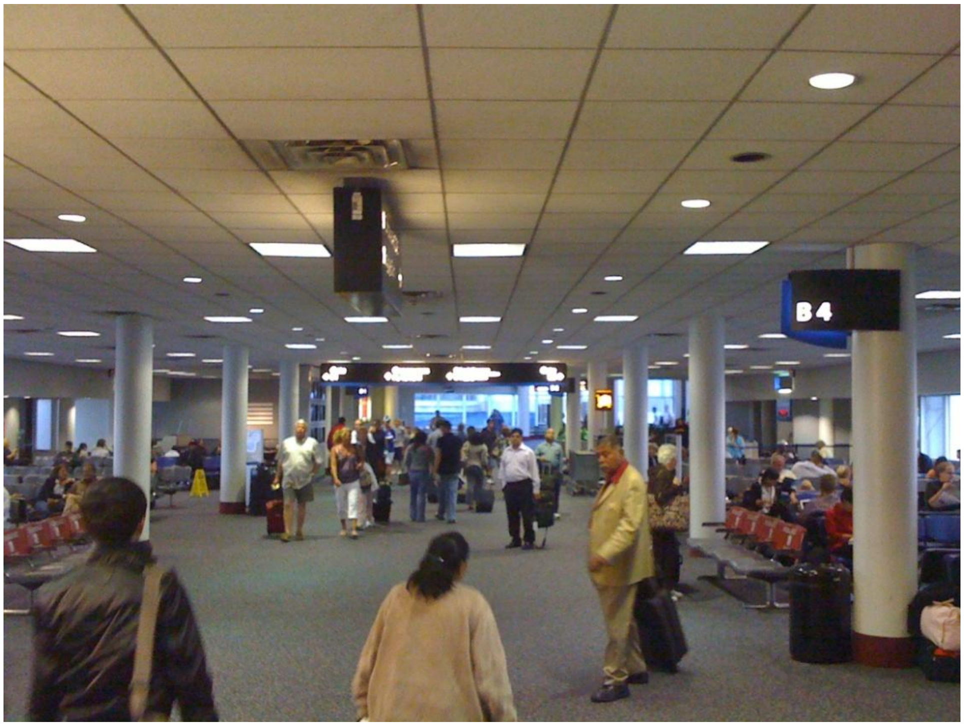


Figure 6.2 : Corridor Walking Width (1)

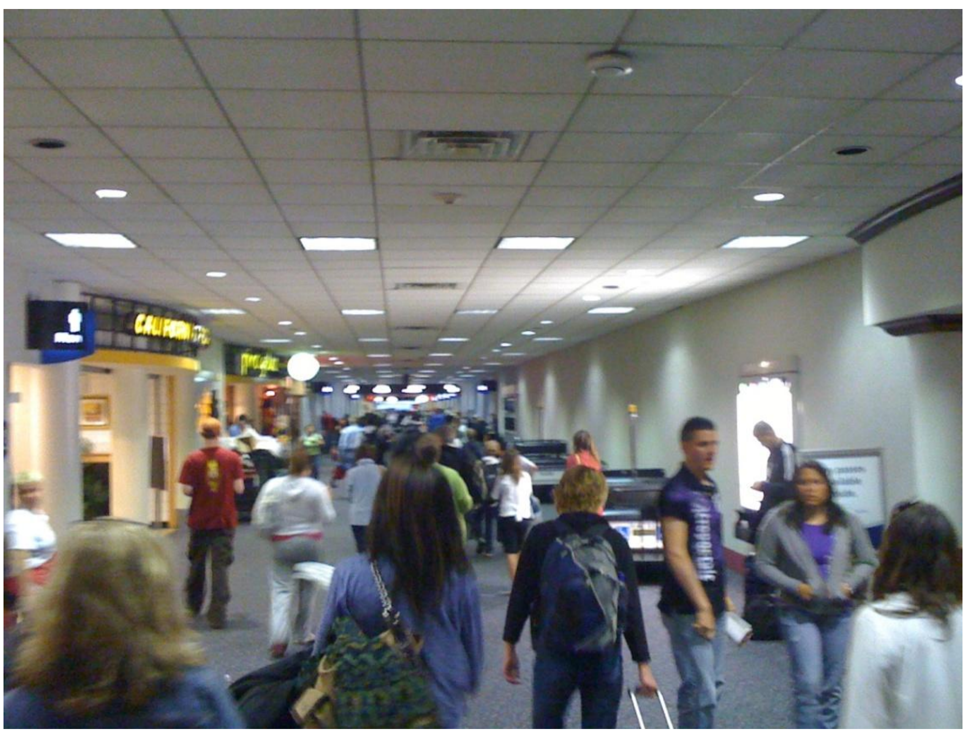


Figure 6.3 : Corridor Walking Width (2)

Consider the case in which only 10 feet is available at the entry/exit point for the corridor. For specific configurations with 12 gates, the result of performance profile and passenger corridor occupancy in the footprint area is shown in Table 6.5. Figure 6.4 shows the cyclical pattern of passenger occupancy on footprint area over simulation time. The graph tracks the occupancy in terms of square ft/passenger in footprint area over the course of the simulation run. When a flight arrives, the passenger occupancy increases, thereby reducing the square feet available per passenger. When all passengers from the flight clear the footprint area, the square ft/passenger goes back up again. And this cyclical pattern is repeated on the arrival and departure of each flight over the course of the simulation. Depending on the different flight schedules and the corridor width, the length of the pattern in the graph will change. Keeping the flight schedule constant, the relationship between corridor occupancy and corridor width is discussed in section 6.5.

From the results in Table 6.5, we find that as more gates are devoted to small aircraft, passenger density decreases and the percentage of time operating at LOS B or better increases. Notice that the percentage of time in LOS B or better increases from top to bottom for gate configurations with predominantly small aircraft, while the percentage decreases from left to right for flight frequency with predominantly high intense flight schedules.

From Table 6.5, we have illustrated the results of two cases in Figure 6.5 and Figure 6.6. The two cases that we considered are de-board time [7.7, 5.0, 4.0] and [5.5, 3.6, 2.9]. Figure 6.5 and 6.6 chart different gate configurations across percentage of time for each de-board time. Whereas Figure 6.7 charts the same gate configuration for different de-board times across the percentage of time for the flight frequency of [65, 75, 85] minutes. And each line in Figure 6.5, 6.6 and 6.7 represents the potential performance, percentage of time a day that LOS B or better is attained. From Figure 6.5, we can indicate that in each case, the percentage of time in a day to reach LOS B or better increases as we distribute additional smaller aircrafts to the gates. Moreover, the percentage of time in a day to reach LOS B or better decreases when the inter-arrival time between successive flights is more intensive as in Figure 6.6. Also, from Figure 6.7, we show that the percentage decreases by a small extent or remains the same in the footprint area with predominantly faster passenger de-board times. This indicates that passenger de-board time has very little impact on corridor occupancy. But, faster de-board time will still result in higher passenger occupancy in the corridor.

Table 6.5 : Percentage Time of Day at or Above LOS B for a 10-foot Width

De-board Time: +40% [7.7, 5.0, 4.0]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	81%	77%	73%	70%	65%
	(2,5,5)	84%	80%	76%	73%	68%
	(3,4,5)	86%	82%	78%	74%	71%
	(4,4,4)	89%	85%	82%	79%	74%
	(8,2,2)	95%	93%	92%	89%	86%
De-board Time: +20% [6.6, 4.3, 3.4]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	80%	76%	74%	70%	66%
	(2,5,5)	83%	79%	76%	72%	68%
	(3,4,5)	85%	81%	79%	74%	69%
	(4,4,4)	87%	84%	81%	77%	73%
	(8,2,2)	94%	92%	90%	88%	85%
De-board Time: [5.5, 3.6, 2.9]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	81%	76%	73%	69%	64%
	(2,5,5)	84%	78%	75%	72%	66%
	(3,4,5)	85%	81%	78%	73%	68%
	(4,4,4)	87%	83%	80%	77%	72%
	(8,2,2)	94%	91%	89%	88%	83%
De-board Time: -20% [4.4, 2.8, 2.3]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	80%	77%	72%	68%	63%
	(2,5,5)	83%	78%	75%	71%	66%
	(3,4,5)	84%	79%	77%	74%	68%
	(4,4,4)	87%	83%	79%	76%	70%
	(8,2,2)	93%	90%	89%	86%	82%
De-board Time:-40% [3.3, 2.1, 1.7]						
Avg. Flight Freq.		(65,75,85)	(55,65,75)	(50,60,70)	(45,55,65)	(40,50,60)
Gate Configuration	(2,2,8)	79%	75%	72%	67%	63%
	(2,5,5)	81%	76%	74%	71%	65%
	(3,4,5)	83%	77%	74%	73%	67%
	(4,4,4)	86%	82%	77%	75%	69%
	(8,2,2)	91%	90%	87%	85%	81%

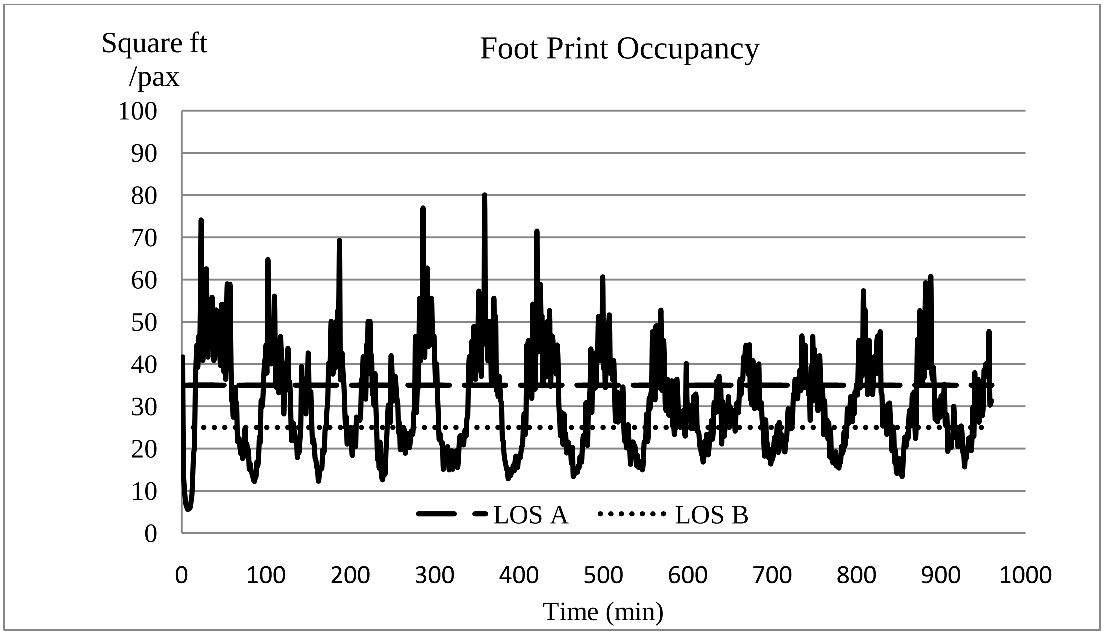


Figure 6.4 : Cyclical Pattern of Passenger Occupancy

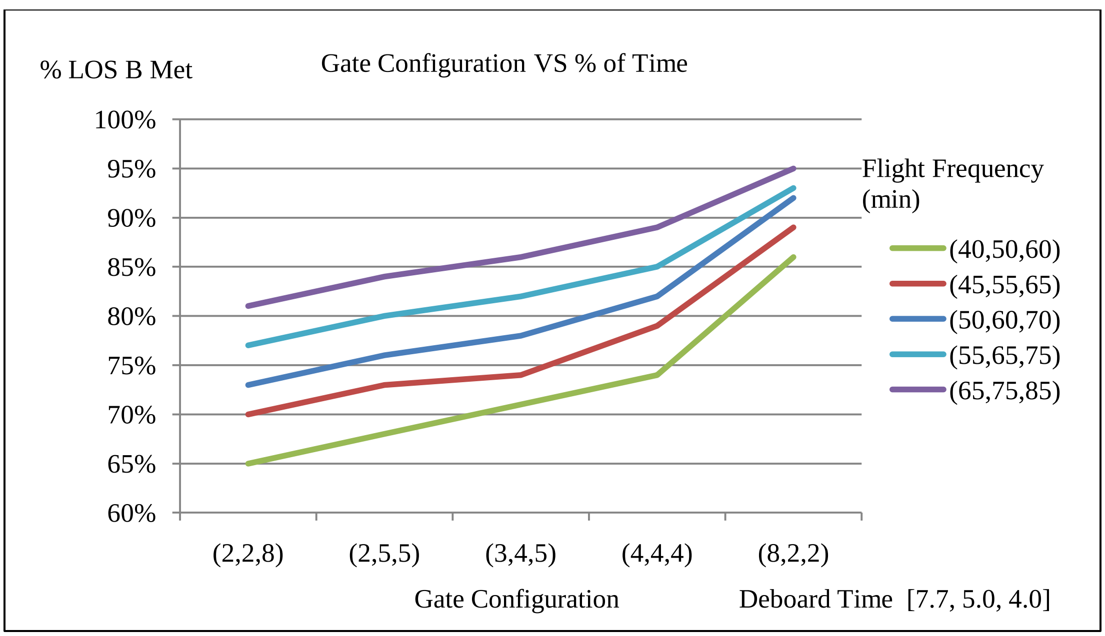


Figure 6.5 : Gate Configuration vs. % of Time

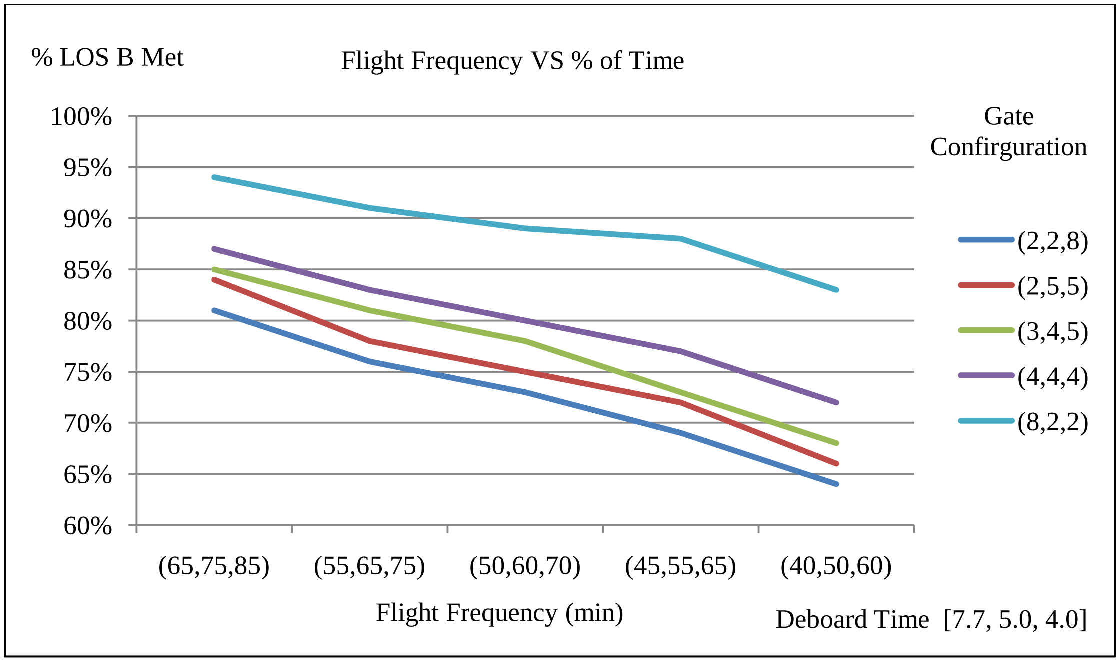


Figure 6.6 : Flight Arrival Frequency vs. % of Time

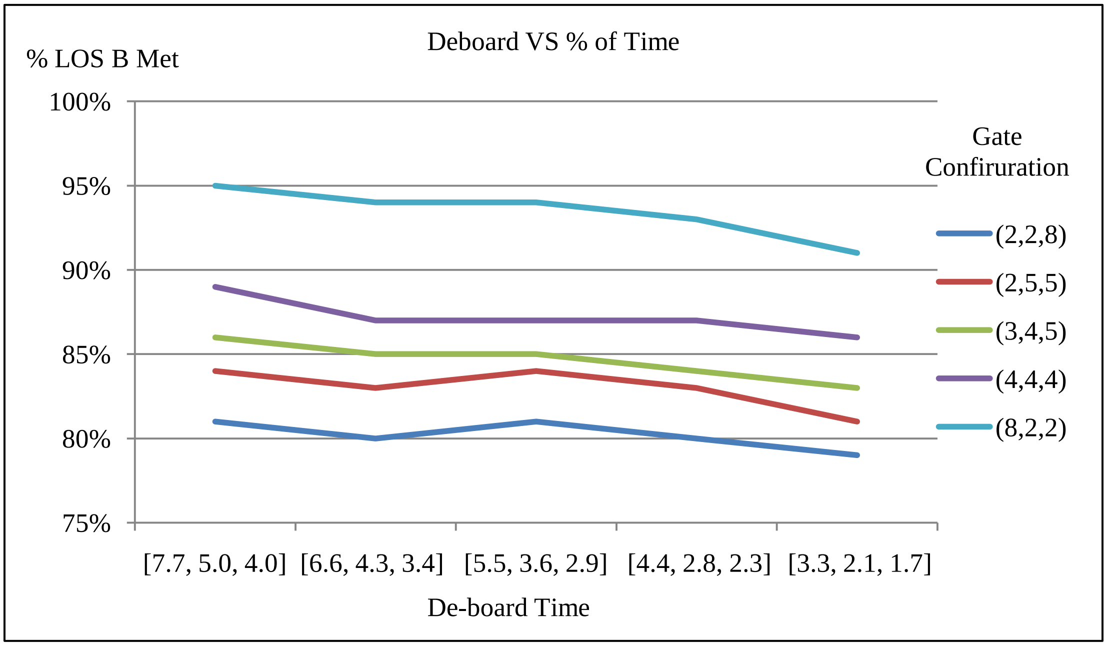


Figure 6.7 : De-board Time vs. % of Time

6.5. Numerical Example of Corridor Width Application

Besides all of the factors related to the amount of traffic generated within the concourse, the physical width of the corridor ultimately restricts the LOS that can be achieved within the facility. An inadequate width restricts flow, resulting in passenger inconvenience [4]. Besides understanding the different combination of factors that impact the percentage of time that the desired LOS can be maintained, the relationship between passenger density and the width of the corridor can be found. In terms of density, the average occupancy (O) can be easily expressed as:

$$O = \frac{L * W}{P}$$

where:

$O = Occupancy\ in\ square\ feet\ per\ passenger$

$L = Length\ of\ measure\ in\ feet$

$W = Required\ corridor\ width$

$P = Number\ of\ passengers\ in\ measure\ area$

By applying the equation above, the model can obtain the minimum corridor width under different combinations of factors. As an example, assume that for an airport with a single-pier concourse, the value of L = 30 ft, and the observed average occupancy in the footprint area is 40.62 passengers. The value of O in term of the required width W is

$$O = \frac{30 * W}{40.62} = 0.739W$$

In general, the average corridor occupancy can be expressed graphically as linearly proportional to the width, as illustrated below (Figure 6.8).

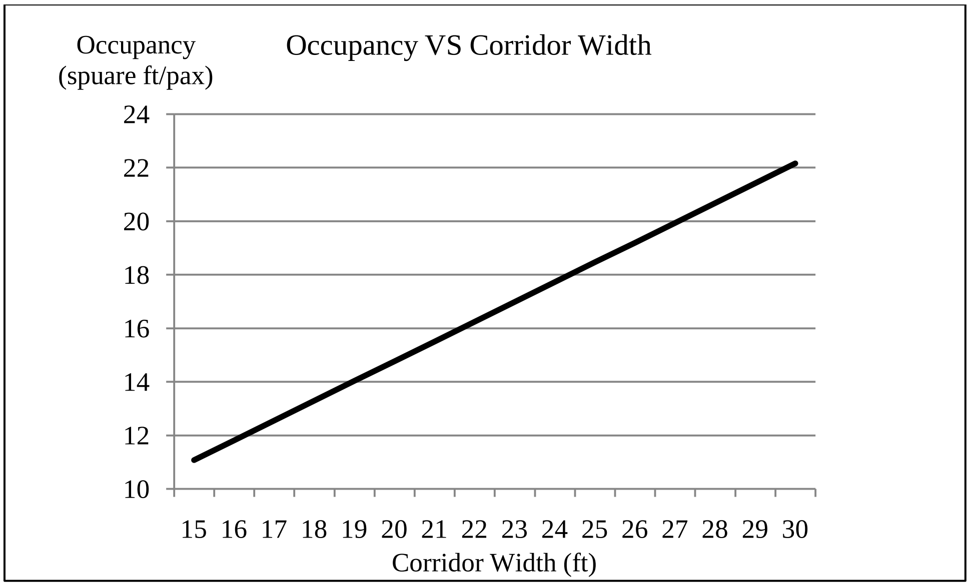


Figure 6.8 : Corridor Occupancy vs. Corridor Width

To determine the width of corridor necessary to achieve a desired minimum LOS, we can simply read the value from the left column in Table 6.1 corresponding to the desired standard (A-F), and use the appropriate value of O to obtain W.

The corridor width intuitively increases while distributing more large aircraft at a given number of gates. This guide could tell the airport planner how to arrange the gate configuration based on various combinations of factors (flight and passenger attribution) in order to maintain at least a certain percentage of time in LOS B or better.

6.6. Corridor Occupancy by Zone with Temporary Stops

In the previous section, all of the passengers that come out of the aircraft either connect to another flight or leave the airport. But in reality, there are several activities that impact passenger flow in the corridor like well-placed fast-food restaurants, restrooms and flight arrival/departure boards. In this section, we model these dwell points within the airport corridor area. The model is flexible enough to accommodate additional dwell points within the corridor area before the terminating passengers exit the airport, and originating passengers reach the gates.

6.6.1. Concourse with Dwell Points and Departure Lounges

Section 6.3 described how the simulation model estimates passenger congestion in the footprint area of an airport concourse. Such information is useful when determining the allocation of different sizes of gates and the appropriate/required corridor width needed to provide a wanted/given LOS. In addition to the footprint area, the entry/exit point for the corridor, all sections within the concourse are now considered when evaluating passenger congestion. This section extends our model to include possible passenger stops inside the concourse and departure lounges (identified as DL in Figure 6.9) for each gate.

All the possible stops and distractions inside the airport concourse—like fast food restaurants, restroom, shopping and flight information displays (FIDs)—could be considered as temporary stops in the model for some of the passengers in the airport concourse. Whereas the other passengers could move through the corridor without any stops and go to their destinations. These temporary stops could be considered service stations within the corridor. When there is a service involved, there is always a queue. So, when a passenger stops at one of these dwell points, he waits in line, receives the service and then moves towards his destination. Most of these temporary stops like restrooms, restaurants and FIDs do not take up any corridor space. They are built as extensions from the corridor; therefore, those concession areas will definitely affect the length of the corridor but not the width. On the same note, these temporary stops will have an effect on the passenger flow inside the airport, thereby affecting the corridor occupancy.

When discussing potential congestion inside the concourse, the size of the departure lounge is considered an important parameter. Inadequate size of the departure lounge may cause higher passenger congestion within the concourse. The departure lounges serve as holding areas for passengers accessing the gates. All the departing passengers access the gate area before boarding the flight. When the passengers arrive to the departure lounge, they try to get a seat in the area. If the area is full, they take up some space in the corridor. This could definitely increase the corridor occupancy. In order to accommodate the gate area in our model, we can have the departure lounge as one of the factors in the model. The gate area could be treated as a holding area for the passengers arriving at gates, and when the area is full, the passengers could be forced to move into the measure area, zones.

The visual representation of the zones within the airport concourse is shown in Figure 6.9. Whenever the flight departs, the passengers can move out of the departure lounge to board the flights, and all the passengers waiting in the measure area for the particular flight clear the area and board the flight.

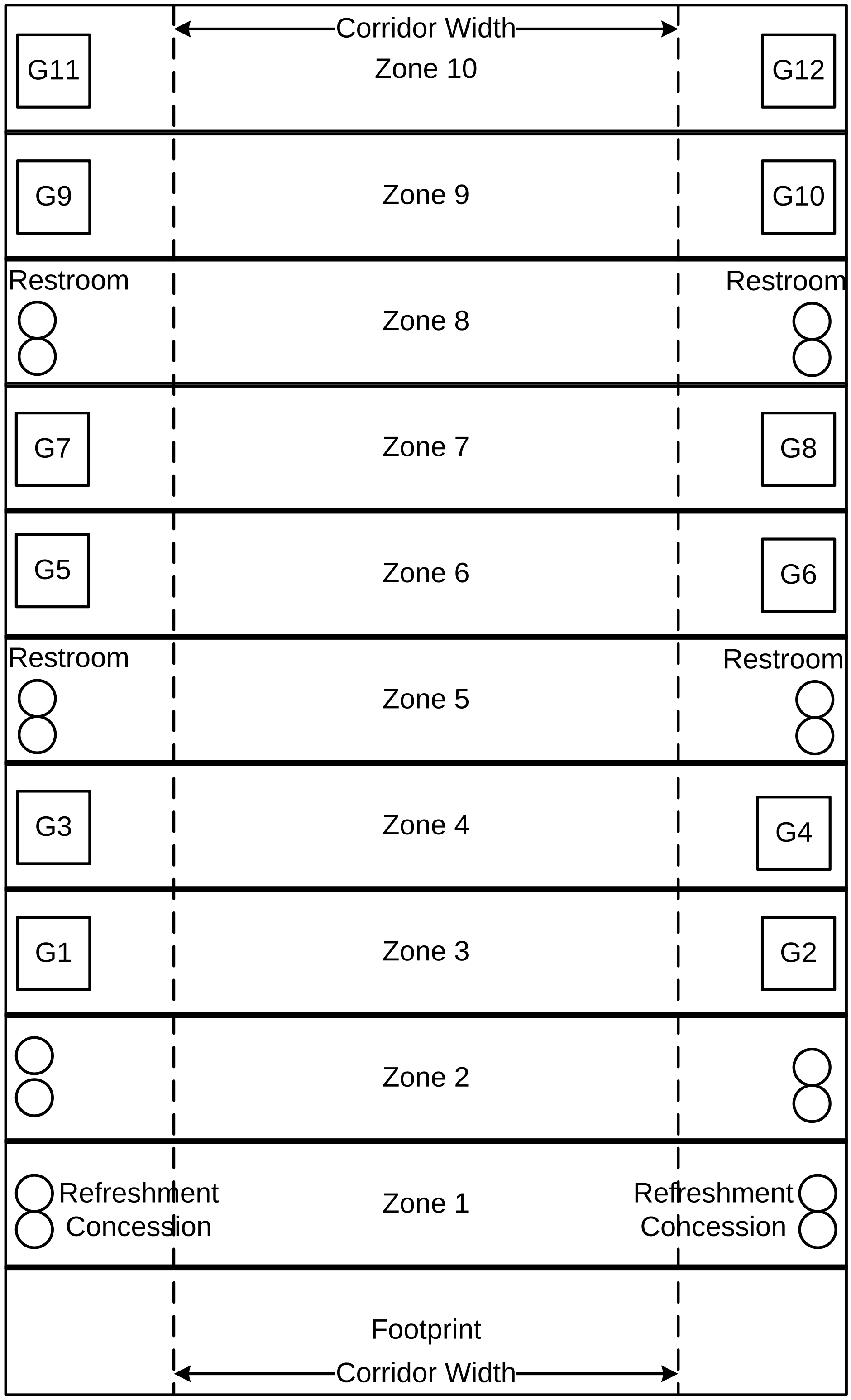


Figure 6.9 : Concourse Simulation by Zones

6.6.2. Simulation Process Flow of Zoned Concourse

We have considered the same airport concourse design as in Section 6.4. Taking that airport concourse design, we introduced zones inside the concourse. We considered one zone per two gates in the concourse. Then we introduced temporary stops such as restrooms and concession stands between gates. The width of the zone is the same as the corridor width. The length of the zones is considered to be a parameter, and it's changeable in the model. Each gate in the concourse is assigned to a particular zone; therefore, when passengers arrive at each gate, they arrive in the model at their assigned zone.

All the arriving passengers that come into their respective zone j move to the next zone j-1 and so on until they reach the footprint and leave the airport. When the passengers move from j to j-1 to j-2 etc, they have a probability in the model to choose to stop at any one of the temporary stops in that zone. Once they get serviced, they move down the zone towards the footprint. When the passengers move from one zone to another, they increase the zone occupancy while they are in that zone and decrease the occupancy when they leave that zone. Please refer to Figure 6.10 for arriving passengers flow.

The same procedure happens for departing passengers as well but in the reverse order. They move from j to j+1 to j+2 etc, until they reach their respective gate. When departing passengers reaches their gate, they try to access the departure lounge if available. If not, they stay in respective gate zone. They also can access the temporary stops in particular zones with a probability. Please refer to Figure 6.11 for departing passengers flow.

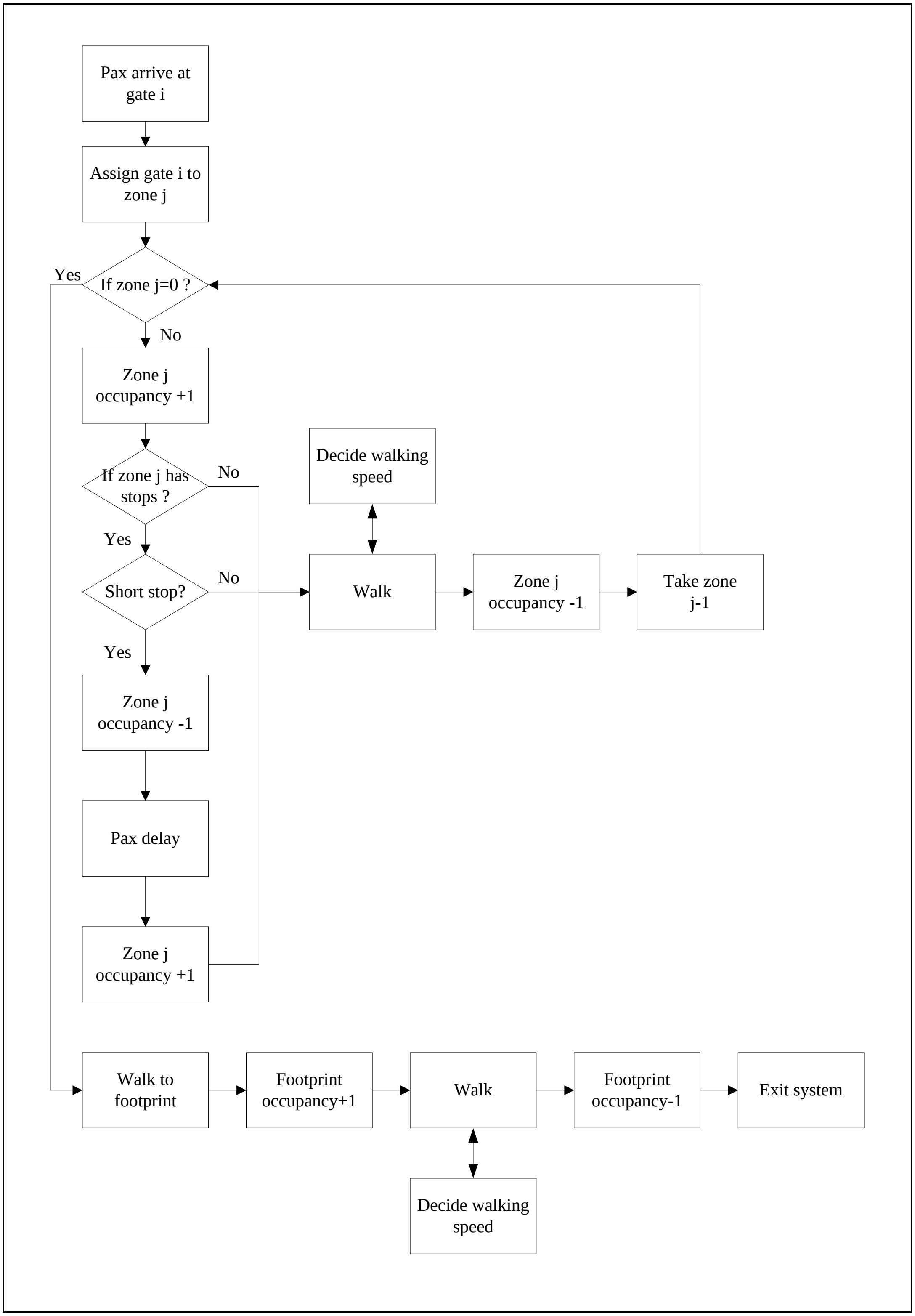


Figure 6.10 : Arrival Passenger Flow of Zoned Concourse

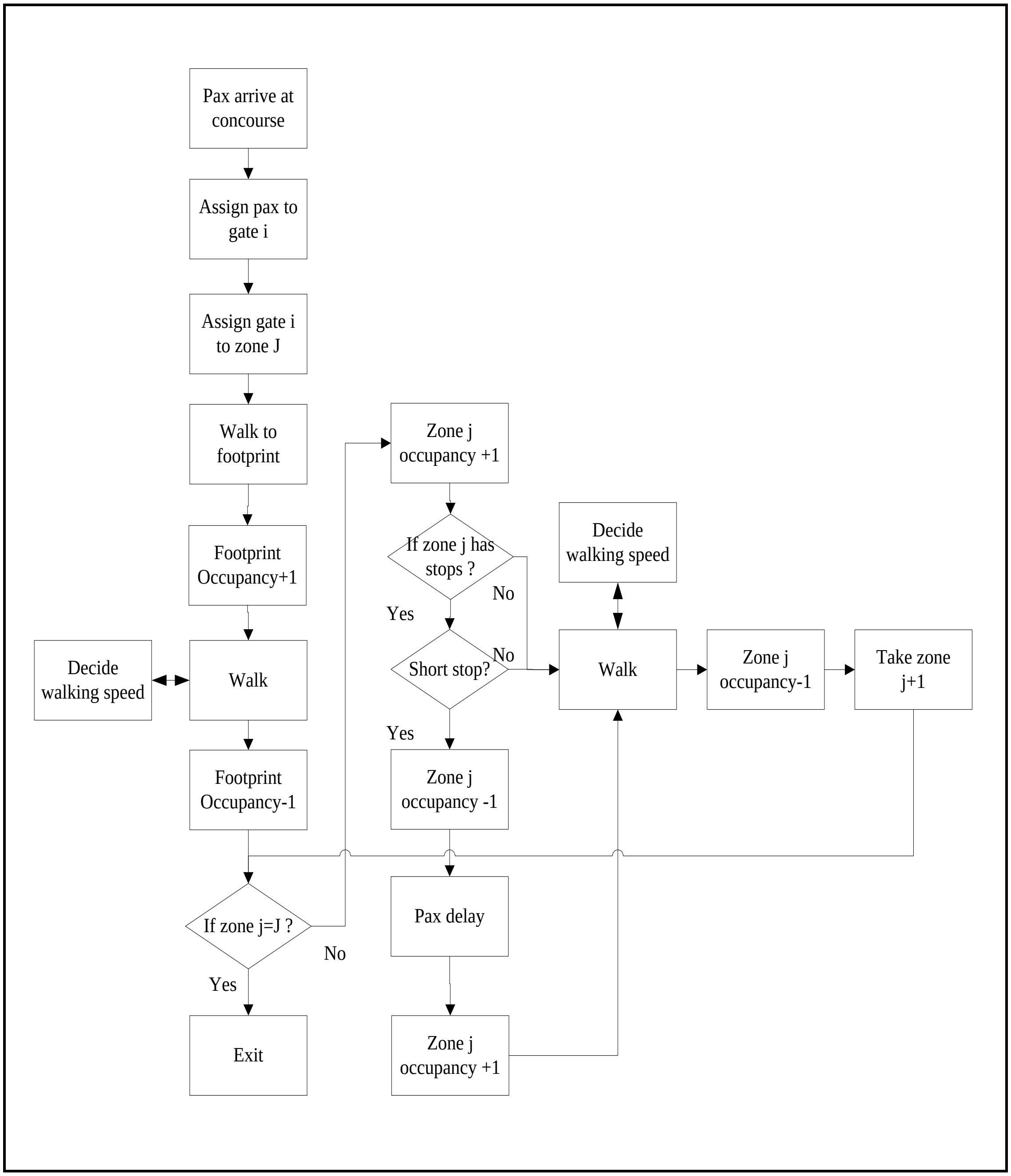


Figure 6.11 : Departure Passenger Flow of Zoned Concourse

6.6.3. Determining Corridor Congestion in a Zoned Operation

When we consider the airport concourse with zones, we are still investigating the percentage of time during a day when the facility can achieve a desired LOS. We use LOS B or better; this is the same as in Section 6.4. LOS B is expressed in terms of average passenger area occupancy (square ft/passenger) in the each zone along with footprint area. For this section, we considered all the factors such as de-board time, walking speed, gate configuration, flight frequency and size of the aircraft and combinations from the previous section. In this case (refer to Figure 6.9), Zone 1 and 2 are considered to be concession areas; Zone 3 and 4 are considered to be small gate zones (Gate 1 – 4); Zone 6 and 7 are considered to be medium gate zones (Gate 5 – 8); Zone 9 and 10 are considered to be big gate zones; Zone 5 and 8 are considered to be restroom areas in the model. We also considered additional flexibility in the model by adding a few parameters. All the basic inputs in the simulation model are listed in Table 6.6.

Table 6.6 : Input Items

Item	Input
Total gates	12
Gate allocation	(4, 4, 4)
Flight frequency (min)	(65, 75, 85)
De-board rate	EXPO (5.5, 3.6, 2.9)
Aircraft load factor	0.8
Distance between gate (ft)	20
Measure length of footprint (ft)	30
Zone length (ft)	20
Corridor width (ft)	20
% of arriving pax stopping at stops	35%
% of departing pax stopping at stops	30%
Number of service stations	8
Service time at concession stand (min)	UNIF (1, 3)
Number of restrooms	8
Service time at restrooms (min)	UNIF (2, 4)

By using this simulation model, we can investigate how the capacity of the departure lounge changes zone occupancy. We use ± 20% from basic case—50 passengers for small gates, 100 passengers for medium gates and 150 for large gates—to test the impact of departure lounge size on corridor occupancy. The first number in the bracket represents the capacity of the departure lounge for small gates; the second for medium gates; and the third for large gates. For example, (50, 100, 150) basic case, means 50 passengers could be held in the small gate departure lounge, 100 passengers for the medium gate lounge and 150 passengers for the big gate departure lounge. The percentage of time during the day was collected when LOS B or better is attained in each zone for different capacity of gate departure lounge combination. Table 6.7 summarizes the set of test scenarios and LOS outcomes by zones.

Table 6.7 : Percentage Time of Day by zones above LOS B for a 20-foot width

Gate Departure Lounge Capacity		(30,60,90)	(40,80,120)	(50,100,150)	(60,120,180)	(70,140,210)
Zones	Footprint	99	99	99	99	99
	Zone 1	71	72	71	69	69
	Zone 2	71	72	72	70	70
	Zone 3	8	19	53	71	84
	Zone 4	8	20	53	71	85
	Zone 5	70	70	72	70	71
	Zone 6	7	17	95	96	99
	Zone 7	7	17	95	99	99
	Zone 8	94	92	94	93	93
	Zone 9	8	15	78	100	100
	Zone 10	8	16	79	100	100

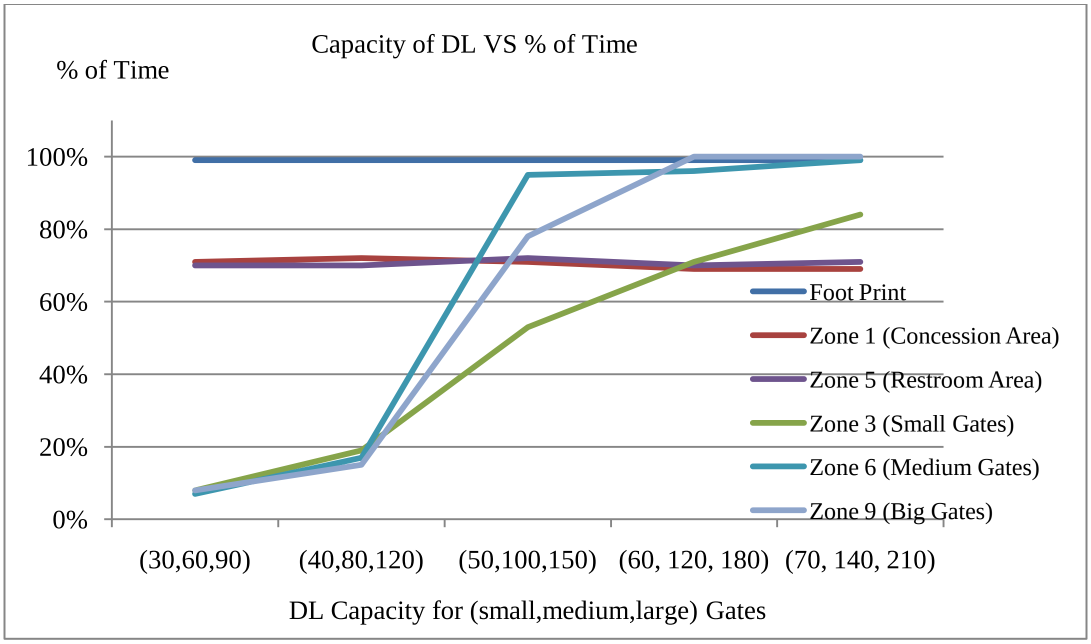


Figure 6.12: Departure Lounge vs. % of Time

Figure 6.12 illustrates the change in percentage of time on different zones under different test capacity scenarios. It indicates that the different capacities for each size of gate do not affect the passenger occupancy on the footprint, concession area or restroom area. When we only consider footprint area, the result from section 6.4 shows that a 20-foot corridor width can support 12 gates and achieve an LOS B or better 95% of the day. But when we consider the short stops and departure lounge for an airport passenger, the LOS inside concourse will not be as high as at the entry/exit point. Based on this result, we find that it is very important for an airport to provide passengers a nice environment and a decent departure lounge capacity for maintaining a good LOS in the airport concourse.

Moreover, we can see that the capacity of the departure lounge has an influential impact on zone occupancy where different sizes of gates are considered. Also, the capacity of the departure lounge is very sensitive to passenger occupancy on each gate zone.

6.7. Conclusion

LOS in terms of passenger occupancy in the airport corridor has been addressed in this paper. It is important for airport planners and operators to provide an appropriate LOS and set a planning guidance which is suitable for most airport concourse operations. The proposed model can be used as an effective decision-making reference for airport planners and operators to organize concourse operations under a desired LOS of passenger congestion.

Chapter 7

Analyzing Concourse Congestion and Incorporating Horizontal and Vertical Passenger Transitions

7.1. Introduction

The analysis of corridor occupancy under two scenarios has been introduced in Chapter 6, one focusing on the footprint area occupancy and the other scenario including zones with dwell points in the airport concourse. However, passenger conveyance devices such as moving walkways, escalator, stairs and elevators are provided for horizontal and vertical transitions. When considering corridor congestion, the conveyance device system is needed to be included in the concourse. Using research contributions from several previous chapters, we combined data analysis, mode choice modeling and simulation to address congestion in the airport terminal. Figure 7.1 shows the relationship of different studies. A database has been created in Chapter 3 which is helpful in providing information for the use of passenger conveyance systems. The information about the distribution of the number of rollers per passenger and percentage of passengers walking/standing on the conveyance device will be provided from the database. Also, mode choice models were employed to determine the probabilities of passenger choices of different conveyance systems in Chapter 4.

In this chapter, two scenarios (concourse with moving walkway and concourse with escalator, elevator and stairs) are simulated to estimate passenger occupancy and the resulting LOS. Both of these models could help in the effort to understand the effect of airport passenger conveyance devices on corridor occupancy.

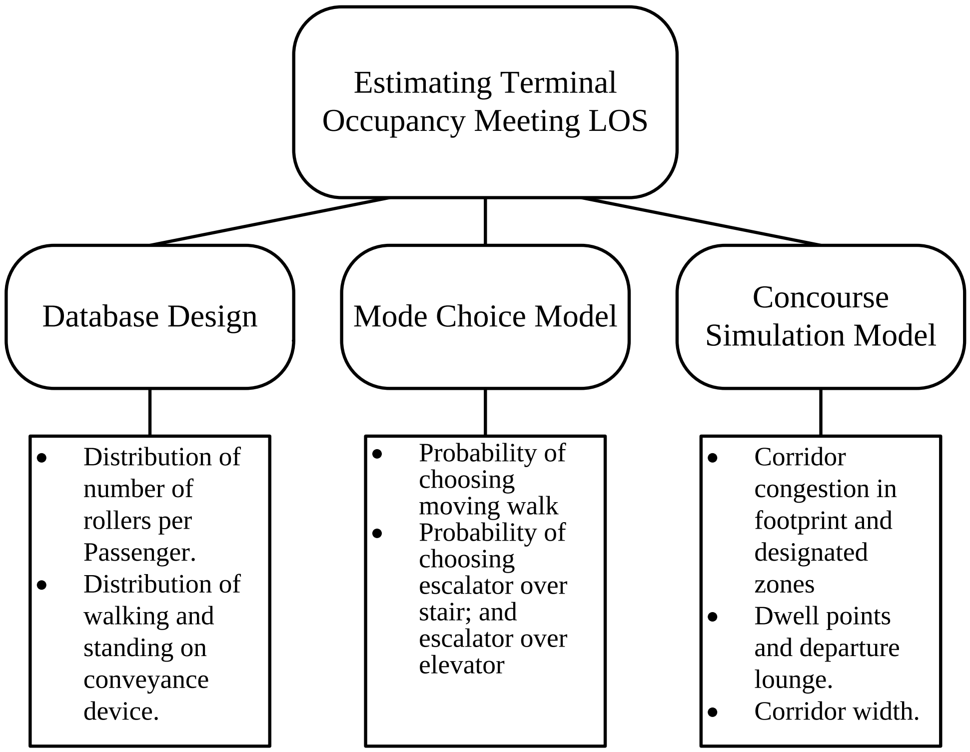


Figure 7.1 : Relationship of Different Studies

7.2. Concourses with Horizontal Transitions – Moving Walkways

When consider corridor congestion with moving walkways, the simulation model from section 6.6 is applied and expanded with the presence of moving walkways. Figure 7.2 depicts a finger-pier concourse with twelve gates along its perimeter. There are four sets of moving walkways named as MW1, MW2, MW3 and MW4 paralleled alongside the corridor. Both MW1 and MW2 are for those departing passengers who walk away from the footprint area and further out on the pier concourse towards their gate. MW1 starts from zone 2 and ends in zone 5; MW2 starts from zone 6 and ends in zone 9. In contrast, both MW3 and MW4 are for those arriving and departing passengers who walk towards the footprint and either leave the concourse or arrive at their connecting gate. MW3 starts from zone 9 and ends in zone 6, while MW4 starts from zone 5 and ends in zone 2. Note that the installing of moving walkways reduces the effective corridor width.

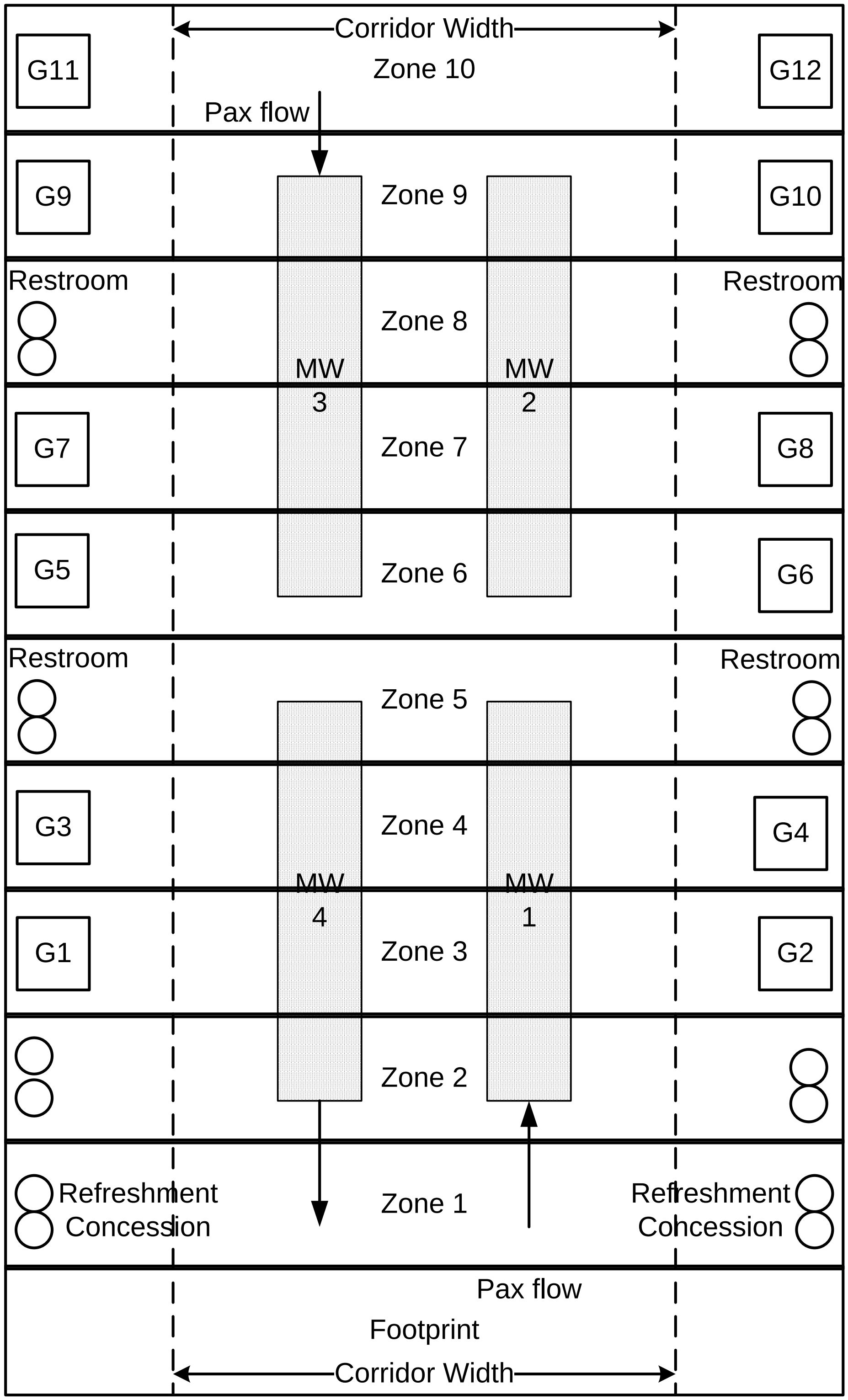


Figure 7.2 : Concourse Simulation with Moving Walkway

To track corridor congestion with moving walkways in the concourse by using a simulation model, a key measurement is still the percentage of time during a day when LOS B can be achieved. In addition to the input items which have been considered in section 6.6, the following parameters have been included in this model:

1. Number of rollers per passenger: The result of Chapter 4 concluded that a significant factor influencing passengers to use moving walkways is the number of rollers carried by passenger. Table 7.1 shows the percentage of passengers with a number of rollers from 0 to 3 (based on data from five representative U.S. airports).

Table 7.1 : Percentage of Passengers with a Different Number of Rollers

Number of rollers	Percentage
0	67.49%
1	31.35%
2	0.81%
3	0.35%

2. Probability of choosing moving walkway by rollers: In the simulation model, each passenger has his/her probability of choosing a moving walkway determined based on the number of rollers carried. Revisiting Table 4.5, the results of the mode choice model will be used in the simulation model.

Table 7.2 : The Probability of Using Moving Walkway by Rollers

Number of rollers	Percent using MW
0	64.44%
1	62.17%
2	59.85%
3	57.48%

3. Percentage of walking and standing on moving walkway: Passengers using the moving walkway will either stand or walk on the device. From the database, we see that that 85% and 15% of all moving walkway users stand and walk on the device, respectively.

4. Travel speed for those passengers who stand on moving walkway: In congested-flow conditions, passengers are often obstructed by downstream pedestrians and forced to stand on the moving walkway. The travel speed will equal to belt speed in such conditions. A speed of 98 feet per minute was applied in the model.

5. Travel speed for those passengers who walk on moving walkway: In free-flow conditions, passenger travel speed on the moving walkway could be expressed as walking speed plus belt speed. Passenger's walking speed has been discussed by Fruin [4] and Older [60] in section 6.4. However, the walking speed of airport passengers on a moving walkway may be varied from walking on the floor. A study by Young [40] has indicated that a passenger's walking speed on a moving walkway is slower than those who chose to bypass. This study shows that passengers tended to travel with a lower walking speed, averaging 204 ft per minute with a standard deviation of 92 ft per minute. A speed (feet

per minute) of normal distribution with an average of 204 and a standard deviation of 92 plus moving walkway speed of 98 is applied in the simulation model.

To incorporate the effects of moving walkways into our estimation of corridor congestion, two cases of simulation models were built and tested if moving walkway congestion level affects concourse occupancy:

1. Wide moving walkway: The wide moving walkways (60”+) are able to transport a large number of passengers in the airport concourse. These wide moving walkways allow up to three people to walk/stand abreast. In this case, the model will reflect the larger belt width by allowing more passengers to continue walking during congested times and not negatively affect traffic flow.

2. Narrow moving walkway: The narrow moving walkways (36-40”) have less capacity and allow up to two people abreast. This will lead to many more occasions in which people may not able to pass a downstream obstruction and be forced to stand on the belt. In particular, passengers are forced to stand on the belt when the congestion level is LOS D or below.

7.2.1. Simulated Process Flow with Horizontal Transitions

Zones with dwell points inside the concourse have been introduced in section 6.6. Four sets of moving walkways are introduced into the concourse in this section. When modeling passenger flow in the concourse with moving walkway, the zoned-concourse simulation model is still applied and extended by adding moving walkways in the concourse. Both arriving and departing passengers are considered in the model.

When an aircraft reaches its assigned gate, all arriving passengers with an assigned number of rollers start to de-board and enter their respective zone j. Arriving passengers then move toward the footprint to the next zone, j-1 and so on until they reach the footprint. When passengers move toward the footprint from zone j where a moving walkway is available for passengers, they have a probability (by the number of rollers each passenger carries) to step on the moving walkway or bypass it.

For those passengers who choose to bypass, they walk at a walking speed depending on the passenger density toward zone j-1 until the footprint or a zone where another moving walkway is available for passengers. Then passengers again have a probability to use the moving walkway or bypass it. For those passengers who choose to step on the moving walkway in the concourse, as mentioned in section 7.2, the two situation cases are considered in the model.

In the free-flow case in the simulation model, the passenger has his/her probability of standing/walking on belt. A passenger on the moving walkway will either stand or walk until the zone where the end of the moving walkway is. After the moving walkway, passengers move to next zone (j-1) until the footprint or the zone where another moving walkway is available. The process of arriving passenger flow in free-flow case is shown in Figure 7.3.

The difference in the congested-flow case from the free-flow case in the simulation model is passengers' movement on the moving walkway. In the free-flow case, passengers have their probability to stand and walk on the moving walkway without affecting traffic flow. But in the congested-flow case, a decision module is built into the model to check if congestion level is LOS D or below. If LOS of a zone is below D, the passenger is forced to stand on the moving walkway until the next zone. Once the LOS of the next zone is above D, the passenger is back to his/her probability of standing or walking on the moving walkway. The simulation process flow is shown in Figure 7.4.

The same procedure happens for departing passengers as well but in the reverse order in both free-flow and congested-flow cases. All departing passengers move from the footprint toward zone j+1 and j+2 etc, until they reach their respective gate. Again, when a departing passenger reaches a zone where a moving walkway is available for passengers, he/she again has a probability to use the moving walkway or bypass it. Figure 7.5 and Figure 7.6 illustrate departure passenger flow for both free-flow and congested-flow cases, respectively.

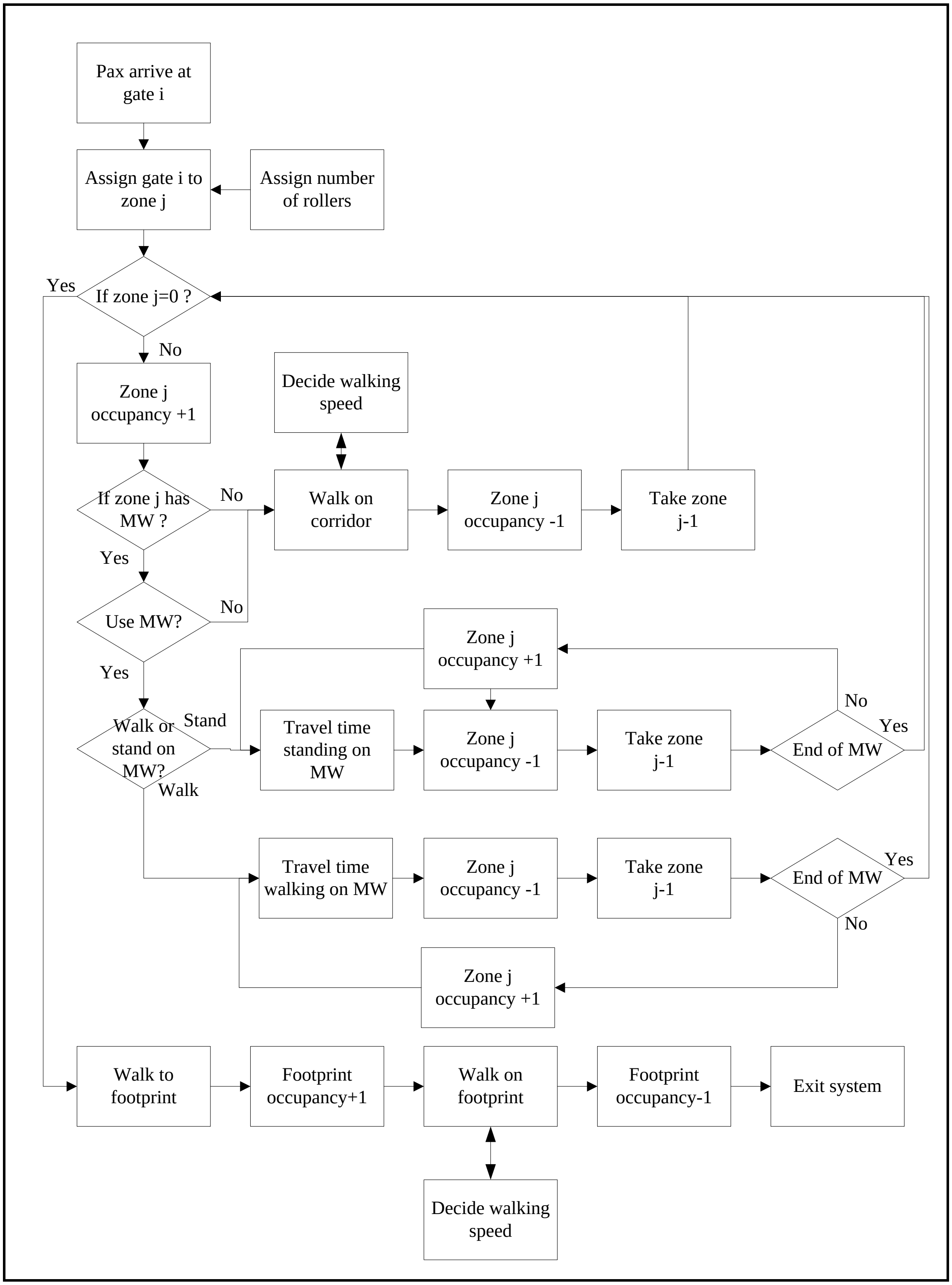


Figure 7.3 : Arrival Passenger Flow with Wide Moving Walkway

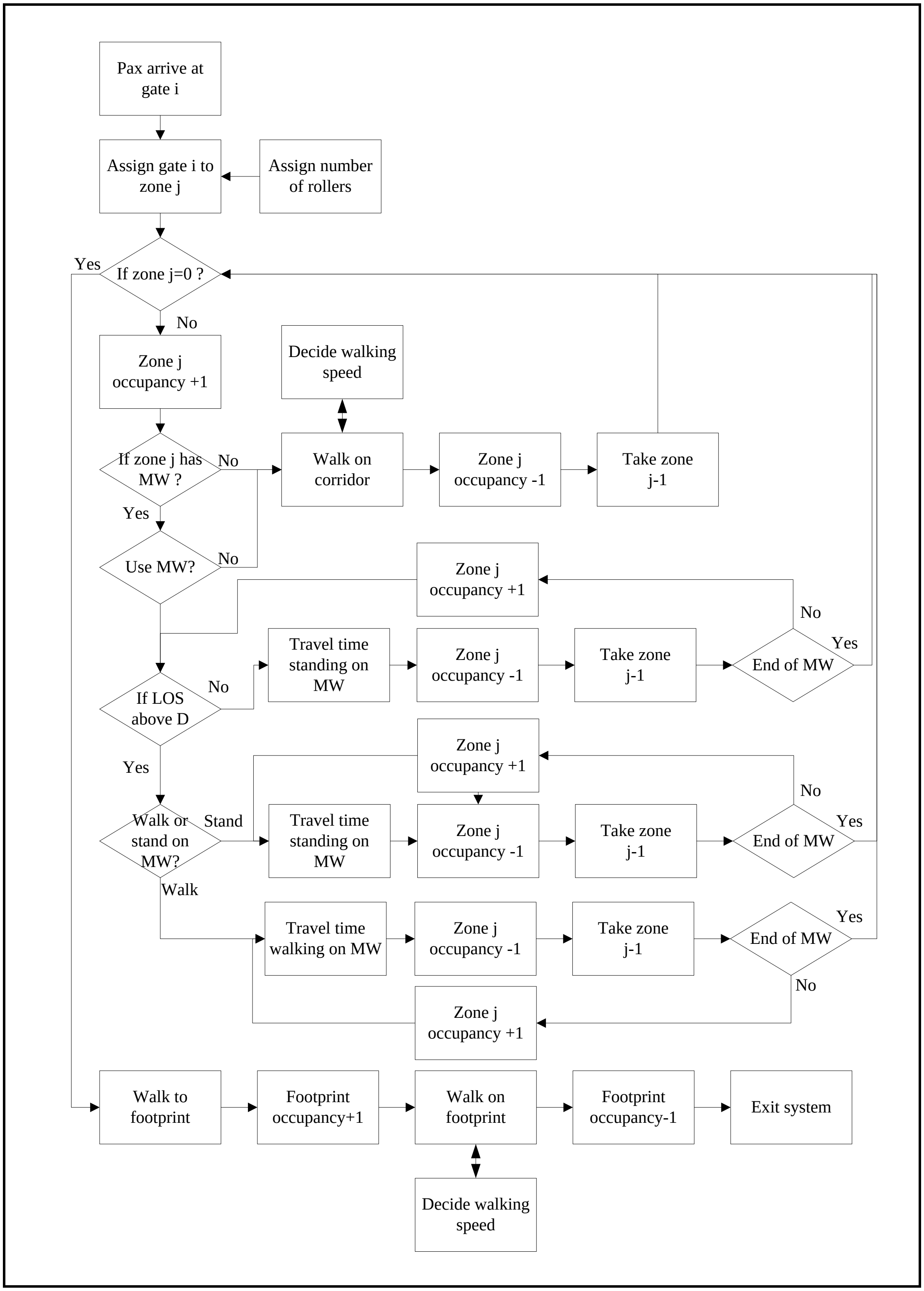


Figure 7.4 : Arrival Passenger Flow with Narrow Moving Walkway

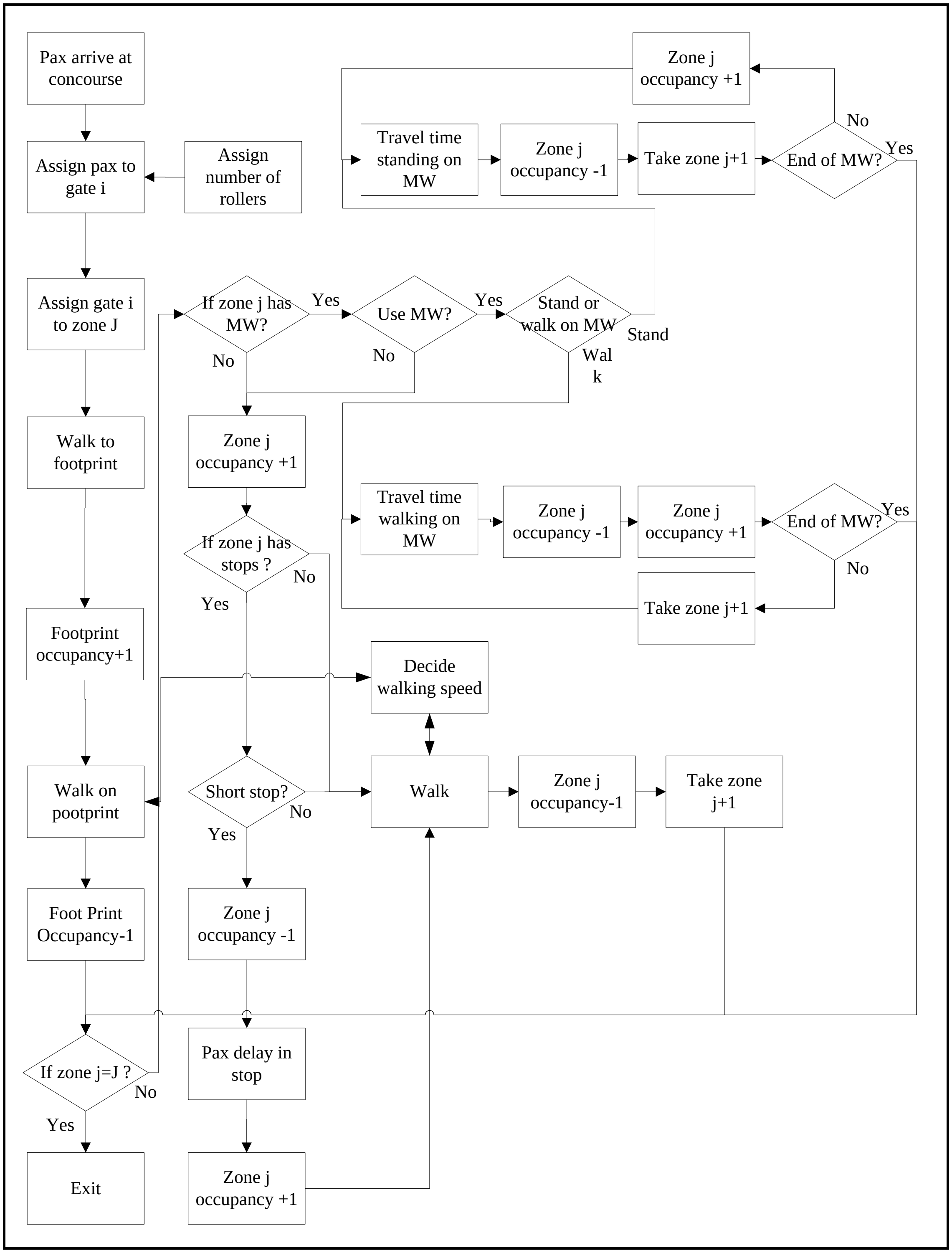


Figure 7.5 : Departure Passenger Flow with Wide Moving Walkway

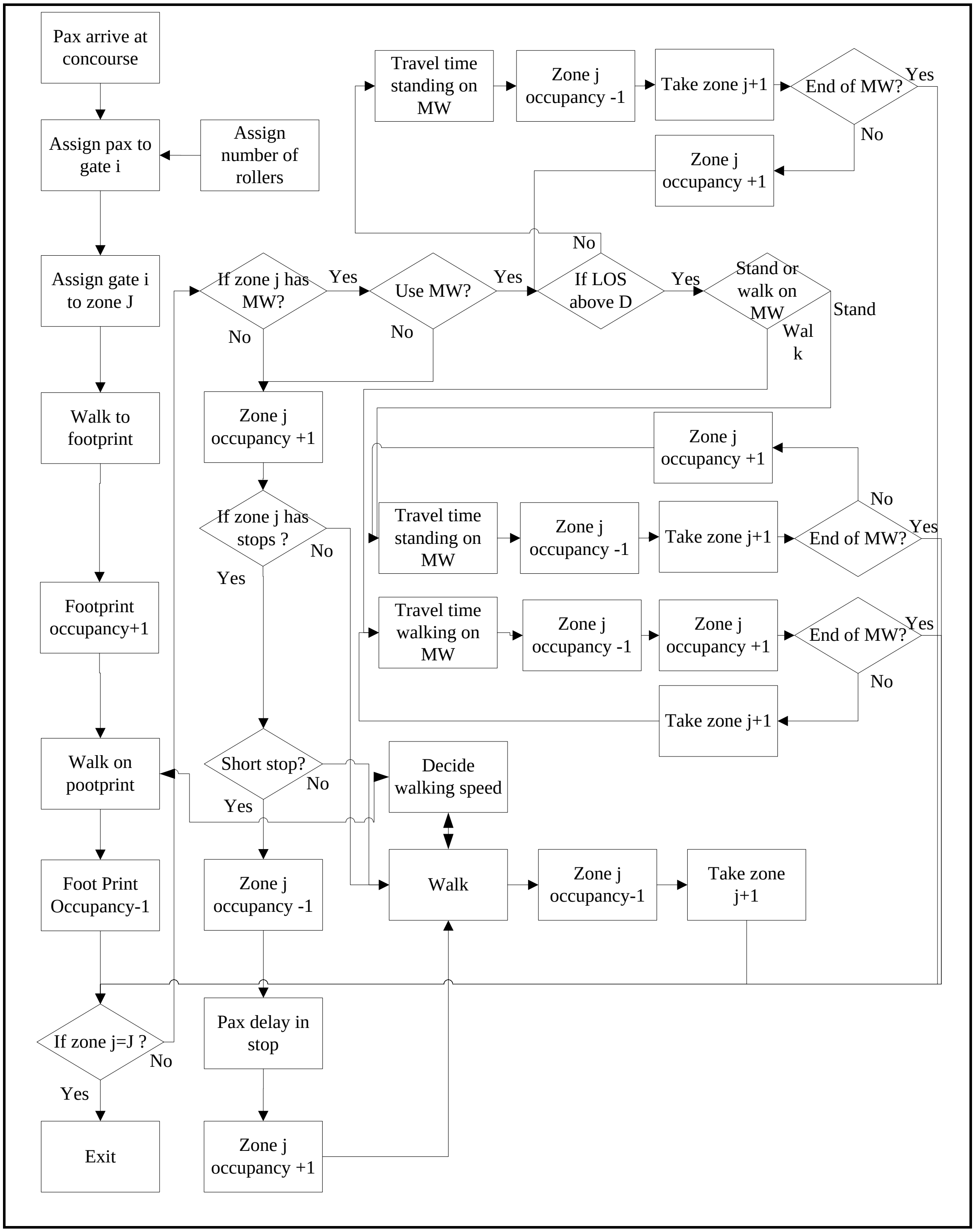


Figure 7.6 : Departure Passenger Flow with Narrow Moving Walkway

7.2.2. Estimating Corridor Congestion with Horizontal Transitions

Consider again the finger-pier concourse with four sets of moving walkways illustrated in Figure 7.2. Using the same layout of the given location (gates, concessions and restrooms) described in section 7.2, it is possible to obtain the percentage of time a day it meets LOS B or better described in Chapter 6. Note that this concourse simulation model is flexible enough to accommodate different layouts of moving walkways allocating for both the originating and terminating passenger's movement.

Based on the sampled finger-pier concourse (Figure 7.2) with 12 gates and four moving walkways allocated along both sides of concourse illustrated in section 7.2, we may wish to use following rules for passengers using moving walkways:

1) Passengers will bypass MW 1 if their gate-to-go is gate 2 and gate 4.
2) Passengers will bypass MW2 if their gate-to-go is gate 8.
3) A passenger with gate-to-go 8 will choose MW2 to the end of zone 9 and then travel one gate distance back to gate 9.

Here we focus on the zones with moving walkways and test how the moving walkways affect corridor occupancy by using different capacities of departure lounges and flight frequency. Table 7.3 summarizes the basic input data associated with the concourse and moving walkways. The percentage of time during a day it meets LOS B is obtained for three cases: 1) concourse without moving walkway, 2) wide moving walkway and 3) narrow moving walkway. The results of three cases are compared and shown in Table 7.4 and 7.5.

Table 7.3 : Model Basic Input for Concourse with Moving Walkway

Items	Input
Total gates	12
Gate allocation	(4, 4, 4)
Size of aircraft	(75, 150, 225)
De-board time (sec)	EXPO (5.5, 3.6, 2.9)
Aircraft load factor	0.8
Distance between gate (ft)	30
Zone Length (ft)	30
Corridor Width (ft)	20
Belt speed (ft per min)	98
Travel speed on MW (ft per min)	NORM (204, 92) + 98
% of arriving pax stopping at stops	35%
% of departing pax stopping at stops	30%
Number of service stations	8
Service time at concession stand (min)	UNIF (1, 3)
Number of restrooms	8
Service time at Restrooms (min)	UNIF (2, 4)

Table 7.4 and Figure 7.7 illustrate the simulation results of 20 replications for the concourse with and without moving walkways. In Table 7.4, the percentage of time during the day it meets LOS B or better in each zone is investigated under three different test capacities of departure lounges (small, medium and large). Again, as same as in the previous chapter, the size of the departure lounge is expressed by using three numbers in a bracket. The first number in the bracket represents the capacity of the departure lounge for small gates, the second for medium gates and the third for large gates. All demands

are based on an average of 45 minutes frequency for small aircraft, 55 minutes for medium aircraft and 65 minutes for large aircraft.

Table 7.4 : Percent of Time Meets LOS B or Better

Departure Lounge Capacity	Small (30, 60, 90)			Medium (50, 100, 150)			Large (70, 140, 210)		
Moving Walk?	No	Wide case	Narrow case	No	Wide case	Narrow case	No	Wide case	Narrow case
Zone 1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Zone 2	0.3	32.8	24	0.3	32	27.5	0.3	35.5	33.1
Zone 3	5.1	4.8	4.9	38.7	39.8	30.7	59.6	64.1	61.3
Zone 4	9	8.2	8.5	62.2	58.4	53.4	88.5	92.1	90.8
Zone 5	4.8	93.1	92.1	6.1	93.3	92.1	5.3	92.4	92.3
Zone 6	7	5.4	5.4	13.1	13.1	12.9	99.2	99.5	99.7
Zone 7	7.1	5.5	5.5	13.1	13.4	13.5	99.2	99.7	99.8
Zone 8	88.3	100	100	89.6	100	100	89	100	100
Zone 9	7.5	5.8	5.9	16.3	15.7	15.8	99.6	100	99.9
Zone 10	7.6	5.9	5.9	16.4	15.9	15.9	99.7	100	99.9

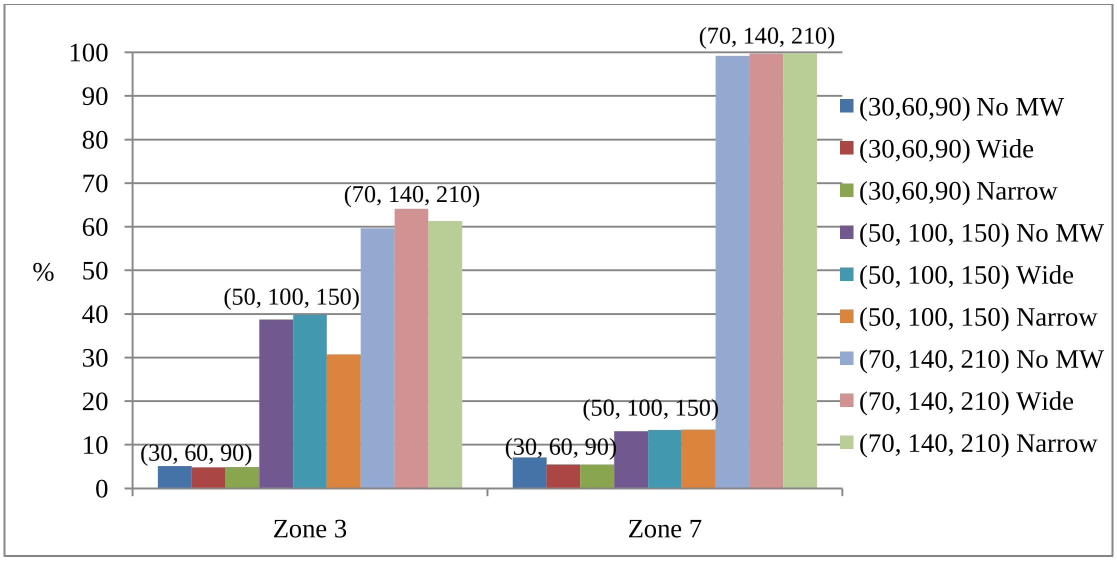


Figure 7.7 : Percent of Time Meets LOS B or Better for Zone 3 and 7

From Table 7.4, as expected in Chapter 6, the percentage of time during the day it meets LOS B or better is increased in each zone when the capacity of the departure lounge in each individual gate is increased. We use zone 3 and zone 7 as examples (Figure 7.7). For small departure lounges, moving walkways potentially introduce congestion because they take space within the corridor. Moreover, during a period of time prior to departure, passengers' spillover will block the corridor between the moving walkway and the gate departure lounge area when waiting area is full. If the waiting area in each gate is increased to prevent spillover from the departure lounge, the congestion level of the concourse with the moving walkway is close to the concourse without the moving walkway.

The presence of a moving walkway in an airport concourse occupies the space of the concourse and reduces the effective corridor width. Thus pedestrian density may increase which in turn decreases passenger walking speed. When considering enough walking width in a concourse, the physical corridor width was increased in the simulation model to maintain a 20-feet effective corridor width, and the result is shown in Table 7.5 and Figure 7.8.

From Table 7.5, we again use zone 3 and zone 7 as our example (Figure 7.8). As mentioned previously, the effective corridor width is maintained as 20 feet. This model demonstrates the effects of moving walkways on potential congestion. The corridor congestion of zones is reduced where moving walkways are available due to the faster travel speed. However, the narrow moving walkways do not improve as much as wide moving walkways do on reducing corridor occupancy due to the congested traffic flow on a narrow moving walkway.

Table 7.5 : Percent of Time Meets LOS B or Better (20-feet effective corridor width)

Departure Lounge Capacity	Small (30, 60, 90)			Medium (50, 100, 150)			Large (70, 140, 210)		
Moving Walk?	No	Wide case	Narrow case	No	Wide case	Narrow case	No	Wide case	Narrow case
Zone 1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Zone 2	0.3	38.9	38.4	0.3	37.6	30	0.3	41.2	36.4
Zone 3	5.1	5.3	4.9	38.7	42.9	32.3	59.6	65.9	62.7
Zone 4	9	9	8.8	62.2	61.2	54.7	88.5	93.5	91.5
Zone 5	4.8	96.1	93.8	6.1	95.8	94	5.3	95.4	94.1
Zone 6	7	6	5.8	13.1	13.9	13.4	99.2	99.8	99.9
Zone 7	7.1	6	5.8	13.1	14.9	14	99.2	99.9	99.9
Zone 8	88.3	100	100	89.6	100	100	89	100	100
Zone 9	7.5	6.2	6.1	16.3	16.5	16.1	99.6	100	100
Zone 10	7.6	6.2	6.2	16.4	16.7	16.3	99.7	100	100

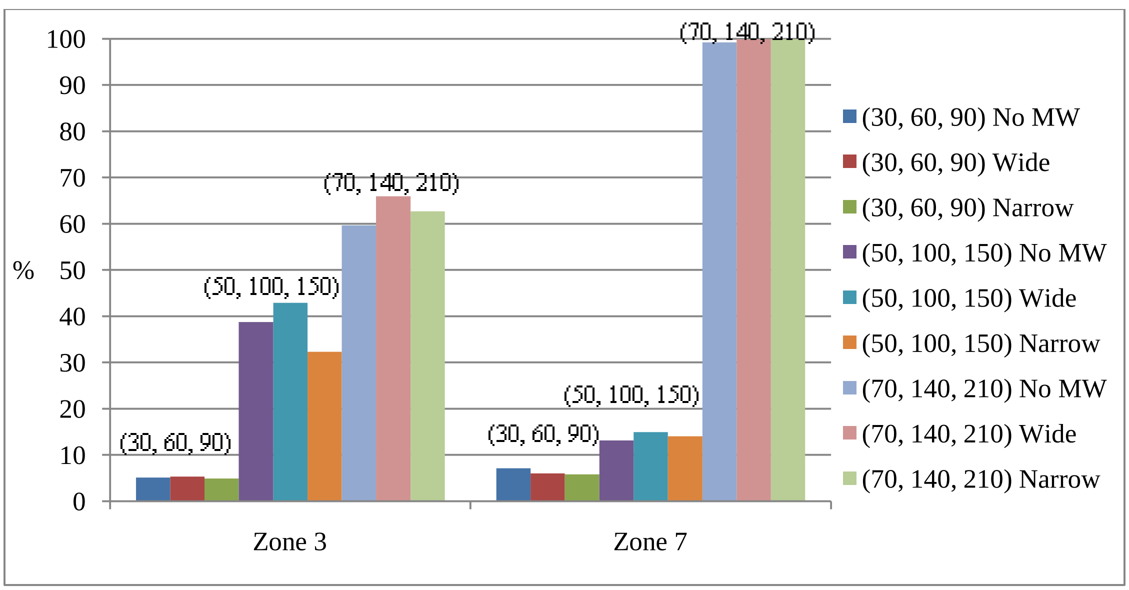


Figure 7.8 : Percent of Time Meets LOS B or Better for Zone 3 and 7
(20-feet effective corridor width)

7.3. Concourses with Vertical Transitions

As mentioned before, airports become bigger due to the increased demand. Therefore, airport passengers need to travel between different levels inside concourse. The most common vertical transition inside the airport is between the train level and gate level. A midfield design concept configuration airport, like Atlanta's Hartsfield Airport and Denver International Airport, normally use an APM system to connect individual passenger building to the concourse and avoid long walking distances. Originating passengers need an underground train that takes them to their departure concourse, then leave from the lower level (train level) to the upper level (gate level). Vice versa, terminating passengers need to go down one level to the train level and then take a train to the main terminal for their baggage.

For a concourse with a vertical transition simulation, a midfield configuration airport is used as an example where a set of vertical transition devices, including escalators, elevators and stairs, is located in the middle of concourse. In this case, originating passengers will only show up in the concourse from a vertical transition device. Terminating passengers who arrive from their gate can only go one level down to the train level through a vertical transition device.

In this section, we only focus on a measure zone where a set of vertical conveyance devices is only available for both departing and arriving passengers traveling between the lower and upper level. The same concept as the previous section, the percentage of time during the day when LOS B is attained is investigated by different aircraft arrival intervals and capacity of a set of vertical transition device. This simulation model includes the following parameters.

1 Number of rollers per passenger: The distribution of different number of rollers is shown in Table 7.6.

Table 7.6 : Distribution of Rollers for Vertical Transition

Number of rollers	Percentage
0	65.11%
1	33.82%
2	1.01%
3	0.06%

2 Percentage for passenger choosing escalator, stairs and elevator by different number of rollers: This information could be provided from database, and the percentage of mode choice for passengers is shown in Table 7.7.

Table 7.7 : Probability of Mode Choice by Rollers for Passengers

Mode	Number of rollers			
	0	1	2	3
Escalator	89.73%	97.36%	59.77%	25.93%
Stair	5.51%	0.62%	0.75%	3.7%
Elevator	4.67%	8.02%	39.49%	70.37%

3 Probability for an airport employee choosing escalator, stairs and elevator by different number of rollers: The percentage of mode choice for employees is shown in Table 7.8.

Table 7.8 : Probability of Mode Choice by Rollers for Employees

Mode	Number of rollers			
	0	1	2	3
Escalator	81.78%	88.14%	0%	0%
Stair	6.94%	0.64%	20%	0%
Elevator	11.28%	11.22%	80%	100%

4 Distribution of standing and walking on escalator: When passengers step on the escalator, they either stand or walk on the device. This information could be provided from database, and it shows that only 7.74% of all people who use the escalator walk on the device.

Others basic input data associated with vertical transition in the concourse are summarized in Table 7.9.

Table 7.9 : Model Basic Input for Vertical Transition in Concourse

Items	Input
Measure zone width (ft)	20
Measure zone length (ft)	30
Percent of airport employee	1%
Escalator boarding times (sec)	EXPO (1.05)
Travel time stand on Escalator (sec)	UNIF (20,30)
Travel time walk on Escalator (sec)	UNIF (10,20)
Stair travel time(sec)	UNIF (20,40)
Elevator travel time(sec)	UNIF (10,30) + 9

5 Capacity of a set of vertical conveyance device: There are an escalator, a stair and an elevator in a set of vertical conveyance devices. The capacity of the escalator and stairs is 50 people; the capacity of the elevator is 15 people.

7.3.1. Simulated Process Flow with Vertical Transitions

When aircrafts reach assigned gates, all arriving passengers with an assigned number of rollers start to de-board and move toward the measure zone where access is only available for terminating passengers go down to train level. When passengers are in the measure zone, they have a probability of taking the escalator, stairs or elevator by the number of rollers each passenger carried to go to the lower level. For those passengers who choose escalator, they can either stand or walk on the device.

The same procedure happens for departing passengers as well but in the reverse order. Departing passengers with assigned rollers move from train level up to gate level through a vertical conveyance device. Again, each departing passenger has a probability of taking the escalator, stairs or elevator by the number of rollers he/she carried.

7.3.2. Estimating Corridor Congestion with Vertical Transitions

When considering a zone with vertical transition devices, percentage of time during the day when LOS B is attained is investigated by different aircraft arrival intervals and capacity of a set of vertical transition devices. Again, three numbers in a bracket, for example (75, 85, 95), are used to represent average minutes between successive flights for small, medium and large aircraft. Also, a 10-minute range in actual inter-arrival times is considered for each setting. The simulation result is summarized in Table 7.10.

Table 7.10 : Simulation Result for a Measure Zone with Vertical Transition Device

# of set of vertical transition devices	Flight interval (min)			
	(85,95,105)	(75,85,95)	(65,75,85)	(55,65,75)
3	62.7	47.02	20	0.3
2	63.76	47.55	21.2	0.3
1	61.43	45.07	18.9	0.3

From the result in Table 7.10, it can be shown that the number of sets of vertical transition devices do not affect the corridor occupancy in particular zones. This is because a higher capacity of a vertical conveyance device can transport more terminating passengers from gate level, but it also brings up more originating passengers from train level to gate level. Meanwhile, the percentage of time during the day it meets LOS B decreases from left to right for flight frequency with predominantly a high intense flight schedule.

7.4. Summary

The simulation models incorporating both horizontal and vertical transitions (as well as passenger input characteristics derived from the historical database and mode choice models) have been built and simulated in this chapter. The key performance measure for estimating corridor congestion is monitoring the percentage of time each day that the concourse (or individual zones) can meet an LOS B or better. From the results, moving walkways have been observed to reduce corridor congestion while the airport concourse corridor has sufficient available width, not including moving walkways, for passengers to walk in the concourse.

In addition to improving the comfort of a passenger's journey, a benefit of moving walkways is to reduce corridor congestion and move passengers more quickly. However, under certain situations, moving walkways also introduce congestion since they effectively reduce the available space to freely traverse the concourse. In this situation, reducing the effective corridor width results in slower passenger walking speeds. In contrast, a concourse with sufficient corridor width could further benefit from installing moving walkways which can assist passengers in moving through the concourse more rapidly. At the same time, they increase passenger comfort by allowing passengers to choose to stand and reduce their physical exertion during their trip.

In addition to sufficient corridor width in a concourse, departure lounge capacity plays a key role in the effective corridor width (and the available space for passenger conveyances). Larger departure lounges can prevent passenger spillover into the corridor, thus allowing the corridor to provide more flow than queuing space. This could be explained from the simulation result in Table 7.4. For departure lounge capacities, the percentage of time during the day it meets LOS B or better in a concourse without moving walkways is higher than in a concourse with the presence of moving walkways. Congestion due to this spillover effect is not as pronounced when moving walkways are not present.

Even though the Chapter 7 results (in particular, Table 7.10) show that vertical transition devices do not affect passengers' occupancy within a zone, we still need to consider the space and location of such devices in order to maintain a certain LOS by zone. The focus of this research was on measuring the occupancy level in the entire zone. If we shift our focus to passenger queuing, providing appropriate capacity in and around vertical transition facilities is necessary for moving passengers adequately between different levels. The proposed simulation model in this chapter could be used as a reference for estimating corridor congestion in terms of LOS in the concourse with both vertical and horizontal conveyance devices.

Chapter 8

Conclusions

In this dissertation, we contribute to the field of airport terminals performance measure by presenting the database and mode choice models for assessing the use of conveyance options in airports. To estimate potential congestion and meet service-level requirements in a concourse, we develop a series of simulation models to help airport planners when estimating concourse occupancy of any designated area in an airport concourse.

To evaluate and analyze the use of conveyance systems in an airport terminal, database design methodology was proposed and allows key conveyance statistics to be analyzed within specific locations across the airport terminal. This database will assist airport planners and operations when considering the use of conveyance devices in airports and provide a great benefit to the industry in determining if the passenger conveyance planning guideline standards are proper or not. Again, results from this section of the research were in direct support of the Airport Cooperative Research Program (ACRP).

To explore the mode choice made by airport passengers, two logistic regression models were developed to serve as predictors for horizontal and vertical transition. Our findings through logistic models are that the number of rollers has an impact on a passenger's mode choice in both horizontal and vertical transitions. More rollers will decrease the probability of using moving walkways. Airport passengers tend to use escalators as compared to stairs and elevators over escalators when they have more rollers with them. Escalators are a highly preferable mode for both employees and passengers as compared to stairs or elevators in airports. Also, when the transit direction is up, passengers are more likely to prefer escalators over stairs and elevators.

The concourse operation simulation models were built by using the general purpose simulation software package ARENA. The simulation model was applied to indentify influential factors on corridor congestion, and the result shows that factors such as number of gates, aircraft size, percentage of people who take connection flight and passenger walking speed have significance in determining the corridor occupancy. Additionally, we include more factors such as gate configuration, flight frequency and passenger de-board time to investigate percentage of time during the day when LOS B or better is attained in the footprint area for each factor combination. A service level design standard matrix was established to assist in airport design and development.

In addition to the footprint area, the corridor occupancy in each section (zone) within the concourse was tracked in Chapters 6 and 7. The model was extended to include dwell points inside the concourse and departure lounges for each gate. Finally, data analysis, mode choice modeling and simulation were combined to address congestion in the airport terminal. Two scenarios (concourse with moving walkway, and concourse with escalator, elevator and stairs) were simulated to estimate passenger occupancy and the resulting LOS. In this section, moving walkways have been observed to reduce corridor congestion and move passengers more quickly. A concourse with sufficient corridor width and departure lounge capacity could further benefit from installing moving walkways.

The proposed models could be used as an effective decision-making reference for managing concourse operations under any desired LOS. The simulation models developed in this dissertation also provide a fundamental platform where many different applications can be extended. The models are flexible enough to accommodate different settings such as the total number of gates, allocation for conveyance facilities, aircraft schedule, etc. This flexibility in how to use the database, mode choice models and simulation tools provides airport planners and researchers with important information to make more informed decisions when considering corridor congestion and passenger conveyance systems.

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