

# Virginia Tech Parking Management Study

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## Executive Summary

Virginia Polytechnic Institute and State University (Virginia Tech), has evolved into a comprehensive university of national and international prominence with more than 25,000 full-time students. The mission of Virginia Tech, as a land-grant university, is to serve the Commonwealth of Virginia, the nation, and the world through the discovery and dissemination of new knowledge. Convenient parking, efficient traffic flow, and effective alternative transportation, particularly bus transit services, are crucial elements in meeting the University's mission as well as maintaining the continued growth of the institution. (Virginia Tech Transportation Master Plan)

The main campus of Virginia Tech has a current parking inventory of approximately 14,310 parking spaces in 88 surface lots.

The first phase (Phase I) of the Virginia Tech Parking Study conducted a detailed investigation of the various parking surveillance and enforcement systems that are commercially available. The second phase of this project expands on the Phase I study by conducting a field evaluation of the in-field technologies, characterizes the service rates associated with the various technologies, and conducts a modeling study of the queuing associated with each of the technologies on three prototype parking lots.

The first section of this report provides a brief background of the Virginia Tech parking facilities and describes the objectives and task of the study, followed by a description of the current Virginia Tech parking control equipment. The next section describes the data collection efforts and the concepts to define the operational characteristics of the parking lots. Subsequently a description of the findings for each parking lot is presented. The next section shows the historical data, its analysis and the validation results of the gathered field data. The following section presents a description of the different traffic simulation models, the input parameters and the simulation results. Finally, the conclusions of the study are presented together with recommendations for further research

For the Shultz parking lot the field data collection effort demonstrates that an average of 30 vehicles are present prior to the gate operation, more than 400 vehicles enter the parking lot by 4:00 p.m., and more than 200 vehicles remain in the parking lot after 4:00 p.m. The parking lot effective capacity is reached around 10:30 a.m. and the parking lot operates beyond the effective capacity for 4 hr during a typical weekday. For most of days, the arrivals peak around 9:00 a.m., with a maximum arrival rate of 30 veh/15 min. The average parking lot stay is 4 hr and 45 minutes. The percentage of each mode of entry are 56% to 60% of card users, 29% to 30% of code users, and 9% to 15% of AVI users. The percentage of cards that are read in the first try varies from 70% to 80%. The users that are required to swipe the card twice are around 15% and those required to try three or more times varies between 8% and 13%. The results demonstrated no statistical difference between Tuesdays and Wednesdays in terms of arrival rates and parking stay. The average service time is 16.7 s for the card users, 11 s for the code users, and 7.8 s for the vehicles that are equipped with AVI technology. When the cards users are analyzed in more detailed the service times are 12.7 for the users that only swipe the card one time, 17.5, and 27.6 s for the vehicles that swipe the card two and three times, respectively.

In the case of the Architectural Annex parking lot, the number of vehicles present in the parking lot prior to the gate operation is in the neighborhood of 30 vehicles. As expected, very few vehicles exit before noon. An average of 50 vehicles enters and exits the parking lot at 12:00 p.m. At 4:00 p.m. on average 120 vehicles remain in the parking lot. Tuesdays reach occupancy levels of 100% occupancy while Wednesdays have occupancies of 85% the parking lot capacity. The maximum occupancy is reached on both days around 11:00 a.m. The average parking duration is 3 hours and 45 minutes. The maximum arrival frequency for both days is around 9:00 a.m. and decreases noticeable after 2:00 p.m. Card readers are the most popular method with a percentage of 50%, followed by 30% of code users, and 17% to 19% of AVI readers. The percentage of cards that are read in the first try is around 70%. These values are very similar to the efficiency in Shultz parking lot. The users that are required to swipe the card twice are around 24% and those required to try three or more times are approximately 5% of the total card users. The average service time is 17.8 s for card users, 14.4 s for the code users, and 7.2 s for the vehicles that are equipped with AVI technology. The card users that are required to swipe one time have a service time of 14.5 s, while users that swipe two and three times have service times of 24.5 and 30.2 s, respectively. A statistical analysis of the vehicle arrivals demonstrated differences between Tuesdays and Wednesdays at a level of significance of 95%.

Approximately 1,200 vehicles enter the Perry Street parking lot during the data collection hours on both days (Tuesdays and Wednesdays). The number of vehicles present in the parking lot at 7:15 a.m. is approximately 30 for Tuesdays and 20 for Wednesdays. Until 8:30 a.m., very few vehicles exit the parking lot. Not only is effective capacity reached very quickly both days around 9:00 a.m. and maintained until 4:00 p.m., but values of total capacity of 100%

and larger are reached several times during the day. This situation indicates cars that enter the parking lot even when the parking lot is full in search of a parking space. The maximum arrival rate for Tuesday is 137 veh/15 min. at 8:00 a.m., and for Wednesday is 115 veh/15 min. at 9:00 a.m. More than 20% of vehicles stay less than 30 minutes in the parking lot.

When the queuing model is for an arrival rate of 100 veh/h, the average time spent in the system is 35 s if all the users are card users. Alternatively, if all users have AVI technology, the average time spent per vehicle is reduced to 10 s, and if all the users punch a code the average time spent is 25 s. An arrival rate of 100 veh/h equals a  $\rho$  of 0.5, 0.22, and 0.4 for cards, AVI, and codes, respectively. A 50% increase in arrival rates (150 veh/h) increases these values of traffic intensity to 0.75, 0.32 and 0.6, respectively. In this case the average vehicle delay increases to almost 70 s for card users, which is equivalent to a 100 % increase. For an arrival rate of 180 veh/h and all vehicles are card users the average delay per vehicle increases to 160 s and the average queue length of the queue is 0.5 vehicles (for an arrival rate of 100 veh/h), 2 vehicles (for an arrival rate of 150 veh/h) and 7 vehicles (for an arrival rate of 180 veh/h). For values approaching saturation rate for the card reader (200 veh/h) the average time spent in the system and the number of vehicles increases to more than 1400 s and 70 vehicles, respectively.

Simulation using INTEGRATION showed that for an arrival rate of 100 veh/h, the average delay per vehicle is 19, 6.3 and 15.5 for card reader, AVI, and key code technology, respectively. Alternatively, for an arrival rate of 200 veh/h (saturation flow rate for card readers) card reader vehicles incur an average delay of 20 s, a value much more realistic than what was obtained using queuing models.

The number of stops remains relatively constant for the AVI reader, they increase rapidly after the saturation rate for the card readers and the key code technologies is reached. For an arrival rates in excess of 200 veh/h the total delay increases dramatically for card readers and significantly for key code users. At an arrival rate of 400 veh/h the average delay per vehicle increases to 45 s for card users and 23 s for code users.

Taking into account the arrival rates of the Perry Street parking lot, installing card users or card readers will only result in a major disruption of the traffic facility. Even the use of AVI readers needs to be carefully considered, because at specific times they will also create significant delays.

# 1. Introduction

Virginia Polytechnic Institute and State University (Virginia Tech), has evolved into a comprehensive university of national and international prominence with more than 25,000 full-time students. The mission of Virginia Tech, as a land-grant university, is to serve the Commonwealth of Virginia, the nation, and the world through the discovery and dissemination of new knowledge. The institution's focus on teaching, learning, research, and outreach are enhanced by effective transportation and parking at its main campus in Blacksburg, Virginia. Convenient parking, efficient traffic flow, and effective alternative transportation, particularly bus transit services, are crucial elements in meeting the University's mission as well as maintaining the continued growth of the institution. (Virginia Tech Transportation Master Plan)

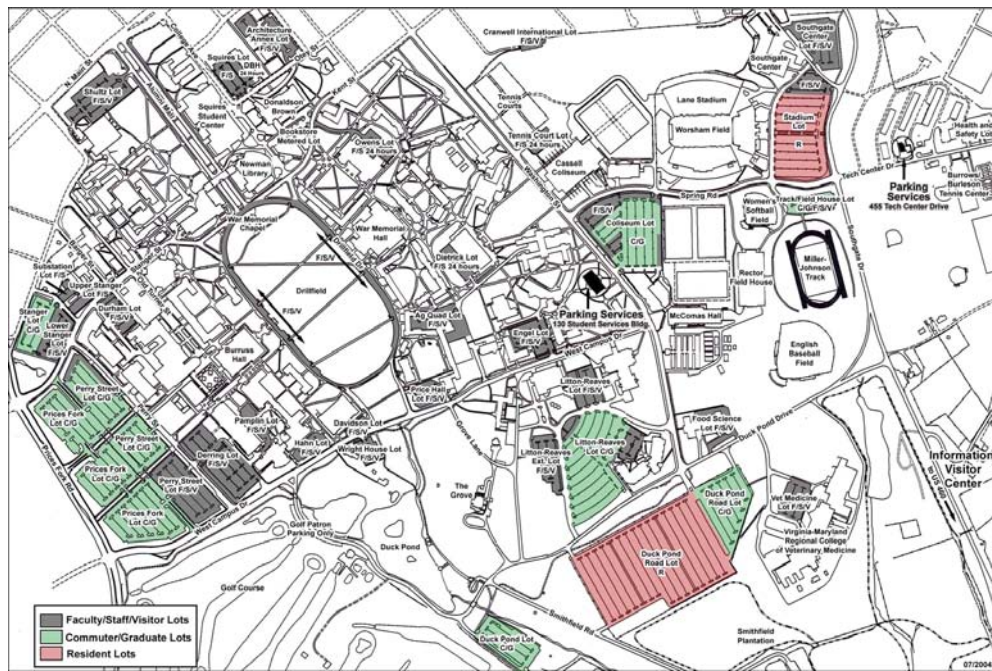
The main campus of Virginia Tech has a current parking inventory of approximately 14,310 parking spaces in 88 surface lots.

The first phase (Phase I) of the Virginia Tech Parking Study conducted a detailed investigation of the various parking surveillance and enforcement systems that are commercially available. The second phase of this project expands on the Phase I study by conducting a field evaluation of the in-field technologies, characterizes the service rates associated with the various technologies, and conducts a modeling study of the queuing associated with each of the technologies on three prototype parking lots.

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## 2. Background

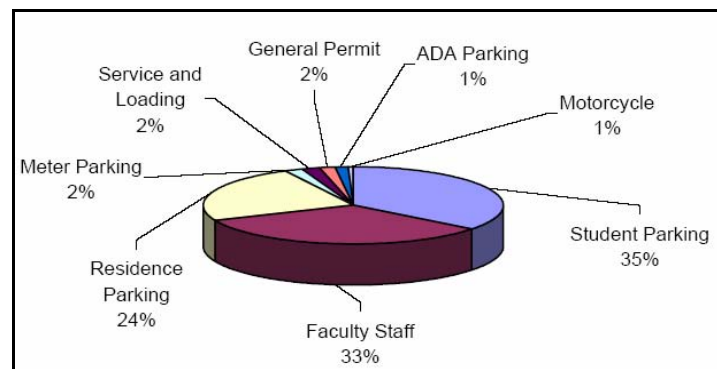
In 2002 the main campus of Virginia Tech had a parking inventory of approximately 13,020 parking spaces (including motorcycle spaces) in 77 surface lots as shown in Figure 1 and is also denoted in the Virginia Tech Parking and Transportation Master Plan.



**Figure 1: Virginia Tech Parking Lots**

These parking lots are classified into three categories (a) faculty, staff, and visitor; (b) commuter and graduate; and (c) resident. This classification is in effect for the five work-week days from 7:30 a.m. to 5:00 p.m. in most cases, with the exception of a few faculty/staff lots that retain their classification for 24 hours, seven days a week. For example, after 5:00 p.m. and on weekends, the parking lots for commuter/graduate are open to the general public. The parking permit required for each parking area is designated by signage. Any student, staff, or faculty affiliated with the university must purchase a parking permit to be able to park on campus. Virginia Tech does not restrict the number of parking permits sold to any user group. Vehicle registration is valid until the registrant is no longer affiliated with the university as a student, faculty, or staff member, or until the permit expires.

Of the 13,020 parking spaces, approximately 98% are designated for the use of Virginia Tech students, faculty, and staff members and follows a distribution, shown in Figure 2.

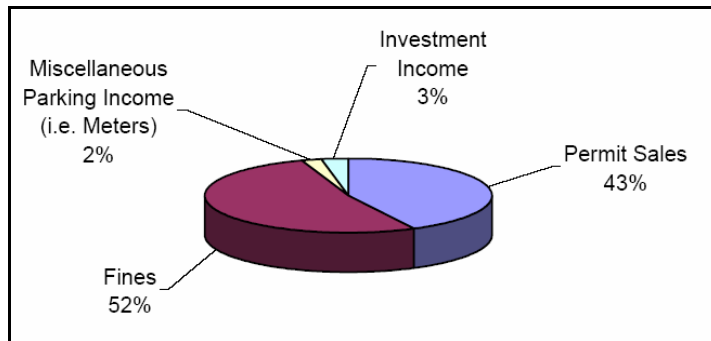


**Figure 2: User Parking Permit Assignment Distribution at Virginia Tech**

An individual may register more than one vehicle since the hangtag style permit can be moved from one vehicle to another. Individuals having two vehicles parked on campus at the same time must have each vehicle registered and

displaying a permit. However, a vehicle can be registered to only one person and only one permit type per vehicle is allowed. The permit must be displayed so that it is readable through the windshield by parking enforcement officers.

A 2002 survey showed an 85% occupancy rate for 55 parking lots, representing 95.3% of the total campus parking supply, with some parking lots exceeding their effective capacity of 90%. Most university parking lots have no type of access control. Virginia Tech Parking Services has parking control officers that issue tickets when a parked vehicle does not have the correct parking permit for the occupied lot. Despite a large parking patrol officer presence, Virginia Tech has a high violation rate, with 52% of the parking revenue coming from parking fines, as shown in Figure 3.



**Figure 3: 2001 Virginia Tech Parking Revenue Distributions**

Virginia Tech does not regularly collect data on:

- Overall parking occupancy.
- Occupancy by type of user.
- Stay duration for different user categories.
- Fill rate.
- Percentage of violators.

This information is critical in order to improve the quality of service, maximize the use of facilities, and determine parking trends that would further identify parking space deficits for specific users or near certain buildings.

## 3. Virginia Tech Parking Study Overview

### 3.1 Study Objectives

The objectives of the present study were:

- a. Characterize the operations of various surveillance technologies on the operations of parking facility gates.
- b. Characterize Virginia Tech parking facility traffic.
- c. Construct simulation models of Virginia Tech parking facilities to evaluate alternative what-if scenarios.

### 3.2 Study Tasks

The project tasks were:

1. Conduct a field study of the operations of the various parking surveillance technologies. The field study investigated the typical service times, typical number of card swipes (in the case of the card readers), and breakdown of the various technology users. The study also investigated the impact of weather and level of congestion on service times.
2. Conduct a field study to characterize the duration of time vehicles typically spend in the parking facilities. The characterization was conducted for each of the three technologies. The analysis involved 10 days of data for the fall and spring semesters for each parking facility.
3. Construct a simulation model of the three parking facilities that were analyzed in Tasks (a) and (b). This task involved constructing the simulation model and calibrating the model to local conditions. The intent of this task was to have a tool to evaluate alternative what-if scenarios.

### 3.3 Virginia Tech Parking Control Equipment

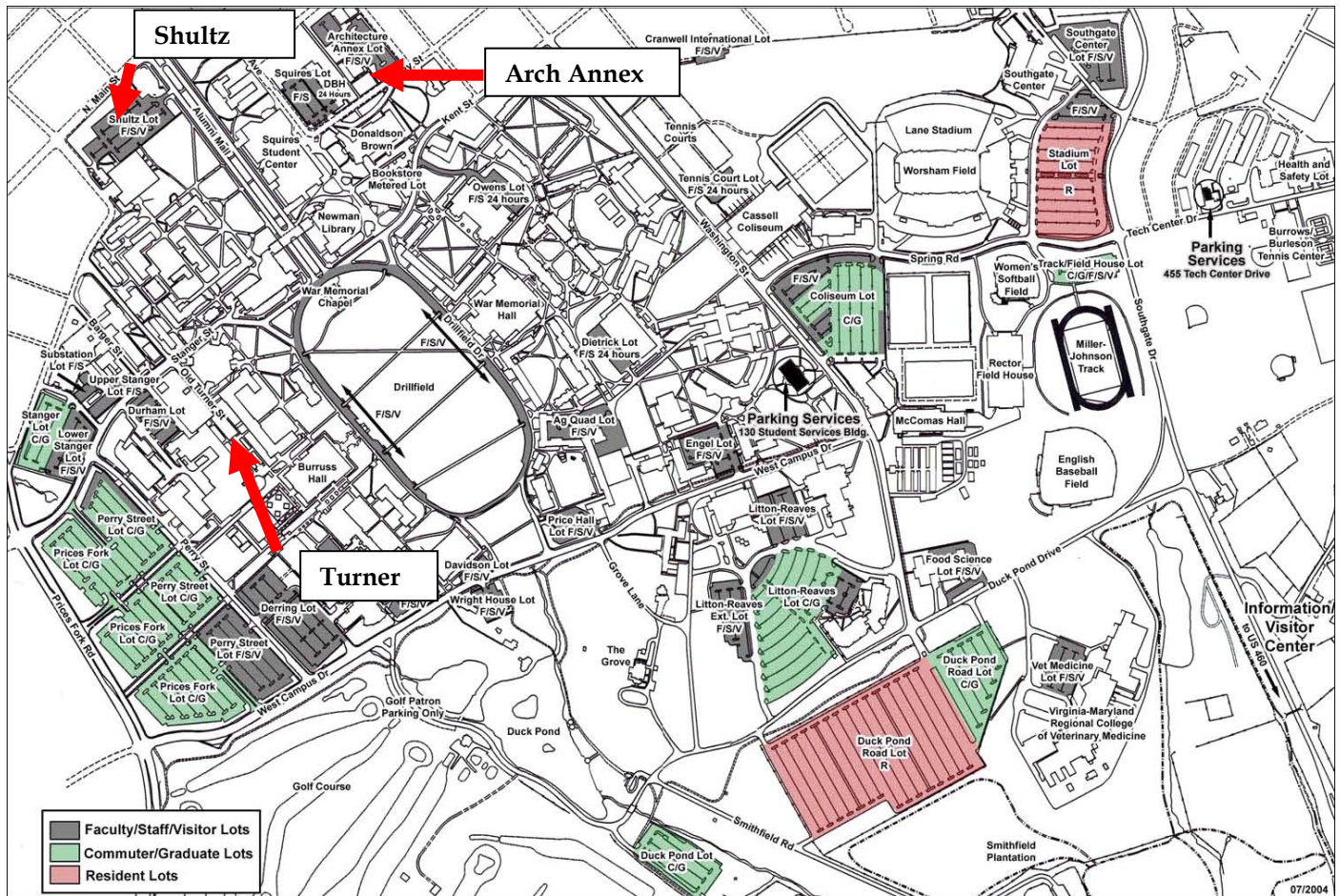
There are two major components in a University Parking System: parking control equipment and a parking control system. Parking control equipment refers to the equipment selected to control and supervise the entries and exits of the parking facility. This parking control can range from a single configuration, such as control spikes to direct traffic, to more sophisticated technical applications, such as license plate recognition equipment. A parking control system refers to the combination of different type of equipment to better satisfy the need of the user for a specific parking lot or combinations of parking. This system varies from independent parking lots, with onsite equipment, to a centralized system that provides information to users regarding space availabilities at different locations. The selection of the parking control equipment and system depends on physical variables, types of users, data to be collected, and available funds.

Available automatic parking control equipment includes:

- Barrier gates.
- Vehicle loop detectors.
- Card readers.
- Digital keypads.
- Proximity readers.
- Radio controllers.
- Automatic vehicle identifiers (AVI).
- License plate readers (LPR).

The first two types of equipment barrier gates and vehicle loop detectors are usually a system component for the other six types of equipment; however, they represent the less sophisticated type of automatic parking control access. The last two types of equipment, AVI and LPR, are usually categorized as “hands- free equipment” because no direct action is required by the driver. The specific parking facility and the application of different types of equipment will determine what equipment combinations yield the best results. Equipment like the card reader, keypads, radio controllers, and proximity readers all require driver input. Hands-free equipment automatically identifies the car as it enters the parking facility so it can be authorized and permitted to enter and exit. Different technologies give way to

vehicle identification, allowing the parking system to authorize entry and open the gate without the driver ever having to stop or open the window. This not only improves traffic flow in peak periods, but also provides the customer with a safe and convenient way to access parking. Virginia Tech has installed automated parking equipment in three parking lots: Shultz, Architectural Annex, and Turner shown in Figure 4.



**Figure 4: Location of the three equipped Virginia Tech Parking Lots**

In each parking lot the entrance is equipped with a barrier that is controlled by loop detectors, a card reader, a digital keypad, and an automatic vehicle tag reader. To better serve the needs of the user, different equipment types were combined to achieve the best system configuration. There were multiple reasons for using equipment combinations, including:

- To update a system that is already in place, but continuing to serve users that have a different form of identification.
- Consider special types of customers, like special events.
- Maximize the use of already in place identification cards (student identification cards).
- Serve users that also use the lot on a regular basis, along with other parking services (i.e., people that use public or town parking facilities but also are affiliated with the University).

Figures 5 and 6 show the equipment used in the three parking lots mentioned above, while Figure 7 shows a schematic representation of the parking lot entrances.



Figure 5: Digital Key Code and Card Keys Mounted on the Same Pedestal



Figure 6: Automatic Vehicle Identification Reader

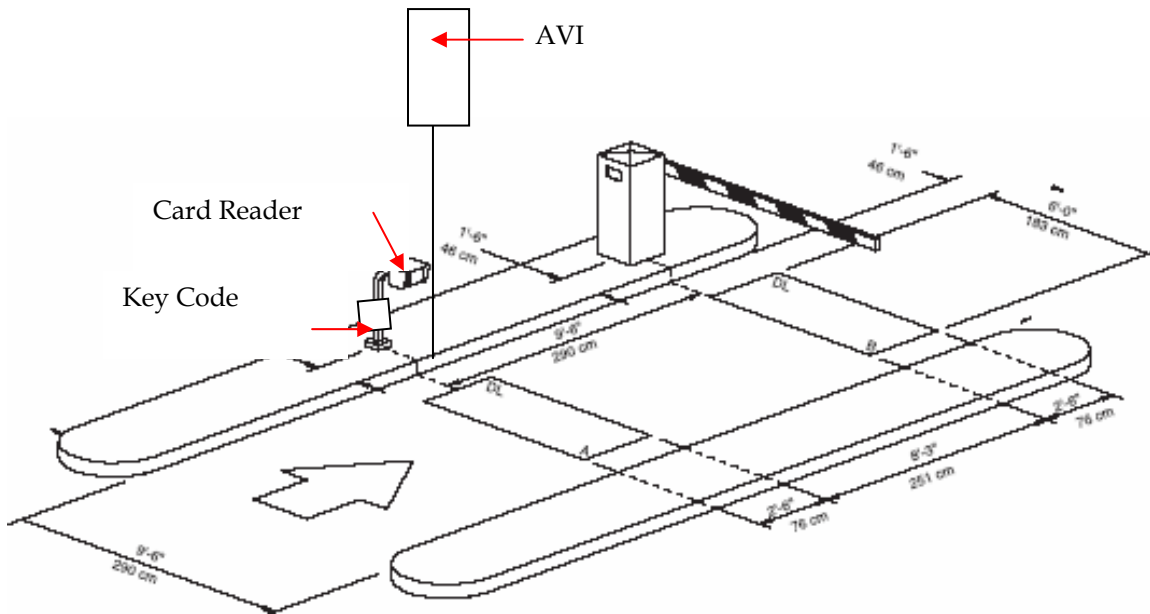


Figure 7: Card in diagram by Federal APD/ Federal Signal Corporation

### 3.3.1 Magnetic Card Reader System

Virginia Tech parking lots are equipped with the Mc-Gann Magnetic Card readers. The users are able to activate the reader using a Hokie Passport card. Card reader technologies include regular readers, proximity, magnetic striped, wiegand, bar, code and photo identification badges. The card reader provides a signal to an activation mechanism when a valid access card is presented, allowing the movement of a barrier and patron access to the facility. Card access control systems require the driver to swipe a card through a special card reader. The system for a card reader includes: (a) barrier gate; (b) reader; (c) loop detector before the gate (to assure that the gate is only open when a vehicle is present); (d) loop detector after the gate (to close the gate); (e) gooseneck stand; and (f) cards for the users.

The major benefits of card access control systems include:

- Security, where only authorized vehicles can enter the facility.
- Relatively cheap cost of the cards.
- Easily updatable database when a card is stolen or lost, allowing for no one to use the lost card.
- Low card replacement costs.
- Convenience to issue "one time card": for visitors or special events.
- Capability to have facility history usage.

As a major drawback, it takes time for the driver to find the card, stop near the reader, and pass the card through the reader. This situation can create considerable traffic problems, especially during peak hours. Consequently, one of the objectives of this study is to characterize the capacity of different technologies.

### 3.3.2 Digital key Code Reader

The parking lots use the International Electronics Inc.'s Door- Gard Technology- (Ruggedized Keypad (212R, 232R,SS-KP500R). The advantages and disadvantages are also similar to card readers; however, digital keypads have no need for cards. This advantage minimizes costs, where a central office would only issue a pin number for each customer. However, the same key code can be used by an authorized user. As a disadvantage, some customers prefer to have a card because they may not remember a key code or pin number. This type of system is not recommended for large facilities however, it can be a possibility for small restricted user, 24 hours, seven days a week parking facilities.

### 3.3.3 AVI System

The three parking lots are equipped with Sirit's Identity Zip Remote Antenna. The antenna is an all-weather dual aperture (transmit and receive) antenna. Connected to the Identity Zip reader, the antenna can be remotely located up to 75 ft from the reader location with the appropriate cabling.

AVI benefits include:

- Improve traffic flow.
- Provide a reliable technology with no moving parts.
- Offer lower operating costs.
- Offer superior level of customer service.
- Do not require site licenses.
- Reduces parking enforcement needs.
- Can be used indefinitely for perpetual parking access, thus the need for an annual permit renewal sales will be significantly reduced.

Key user advantages include:

- Fast entry, no waiting in line.
- Security, with no need to unroll the car window.
- Easy to use.
- Can be easily deactivated if lost or stolen, limiting the fees to the cost of the AVI device only, rather than the prorated permit.

## 4. Parking Data Collection

Field data were gathered at the entrance of the three parking lots. In order to characterize traffic patterns for typical weekdays, the data were gathered on Tuesdays and Wednesdays as shown in Table 1. The reason for selecting Tuesdays and Wednesdays is that the typical class schedules are either Tuesday/Thursday or Monday/Wednesday and thus these days would be reflective of both class schedules.

**Table 1: Parking Data Collection Schedule**

<b>Architectural Annex (Media)</b>	<b>Shultz</b>	<b>Perry Street</b>
3/15 Tuesday	3/22 Tuesday	4/12 Tuesday
4/06 Wednesday	3/29 Tuesday	4/13 Wednesday
	3/30 Wednesday	
	4/20 Wednesday	
	4/27 Wednesday	

The data were collected from the time the gate became operative around 7:30 a.m. until the parking lot was open to the public around 5:00 p.m. In addition to the above information, the entrance and exits were videotaped. The video taping allowed the researchers to validate the data and compute the time spent in a parking lot for each method of entrance. Initially, the researchers were planning to videotape the parking lot and analyze the data off-line. However, because the videotaping was conducted in a mobile laboratory it was possible to gather the data manually while video taping, as summarized in Table 2. This decision proved to be very valuable because it simplified the analysis of the data.

**Table 2: Manual Data Collected**

<b>Entry</b>	<b>Exit</b>
License plate	License plate
Time	Time
Method (card, code or AVI)	
Number of swipes if a card was used	

Because, in many instances, vehicles were present in the parking lot prior to the data gathering effort, the license plate numbers of existing vehicles were recorded.

The data that was gathered manually was input to a spread sheet and complemented with the video data. By matching the entering and exiting license plates the time spent in a parking lot was computed. The matching was done over a number of iterations. Specifically, the first match was made using the raw manual data. However, because of human error the vehicle license plates that were not matched were analyzed in further detail to identify errors in the data. Examples of errors were a missing letter or digit in the license plate, a 5 that was substituted by an S or vice versa. Efforts were also made to identify vehicles that enter and exit the parking lot more than one time, so each entrance and exit is recorded as an independent individual event.

The video tape information was also used to determine the average service time of each type of equipment as will be described later in the report.

For each parking lot the following characteristics were studied

- Entering and exiting time.
- Arrival frequency.
- Occupancy.

- Duration of stay.
- Method of entry.
- Number of swipes for card users.
- Efficiency of each method of entry.

## **Entering and exiting time**

The cumulative number of vehicles entering and exiting the parking lot was computed. The vehicles that were already in the parking lot at 7:30 a.m. were assigned an arrival time of 7:15 a.m. for analysis purposes.

### **Arrival frequency**

The frequency of arrivals was computed to see if the vehicles arriving at the parking lot followed a specific distribution and to compare patterns among different days of the week.

### **Occupancy rate**

Occupancy rate is defined as the number of the vehicles in the parking lot, divided by the lot capacity. When analyzing the occupancy data, it is important to take into account the “effective supply” factor. This factor essentially is a cushion of spaces in excess of the calculated demand to reduce the search time for the last available parking stalls, and to account for the temporary loss of spaces due to improperly parked vehicles. Typically, for permit parking areas, the effective supply factor recommended is 90%. This factor is reduced to 85% in the case of visitor parking areas, because it assumes that visitors are less familiar with the area.

### **Duration of stay**

The duration of stay is defined as the time spent in the parking lot by a specific vehicle. Due to the nature of University business, some vehicles enter and exit the parking lot more than one time, in this particular case each time the vehicle enters and exits the parking lot it is considered as a different vehicle recording. To compute the duration of stay, the exiting license plate numbers are matched with the entering license plate numbers.

### **Method of entry**

The method of entry is defined as the type of equipment that is activated by the user. The percentage of vehicles using each method of entry: code, card, or AVI is computed as part of the analysis.

### **Number of swipes required for cards users**

Since card users represented the majority of users, the efficiency of this type of equipment was of particular interest. The number of swipes is defined as the number of times the user has to make in order to pass the card through the reader until the card is successfully read and access is granted. The number of tries required to gain parking lot access is directly related to the service time, as is shown later in this report.

### **Efficiency of each method of entry**

One of the objectives of this study is to compare the efficiency of the different technologies. The efficiency is defined as the time required by the user to successfully enter the parking lot. This time is measured from the time the car is in front of the entrance gate until the time the entrance gate is closed after its entry.

## 5. Findings

### 5.1 Shultz Parking lot

The Shultz Parking location together with its entrance and exits is shown in Figure 8. The parking lot, which borders Main Street and the Virginia Tech Mall, serves faculty/staff (F/S) and handicapped parking needs. It has 279 parking spaces for F/S and 5 parking spaces for handicapped users. The parking lot has one entrance and two exits, with one of them located adjacent to the parking lot entrance. Figure 9 shows a view of the Shultz parking lot entrance/exit.

For the purpose of this study, the second exit was closed during the time the data were collected. This action does not in any way affect the normal use of the parking lot and represents a minimum nuisance to the users given that most drivers exit from the first exit. The data collection effort included two Tuesdays (March 22, and 29, 2005) and two Wednesdays (April 20, and 27, 2005) (the data were also gathered on Wednesday March 30, but because the gate was malfunctioning and was not operative for most of the day the information is not included in the analysis). The results are tabulated and the major findings are described in the following sections

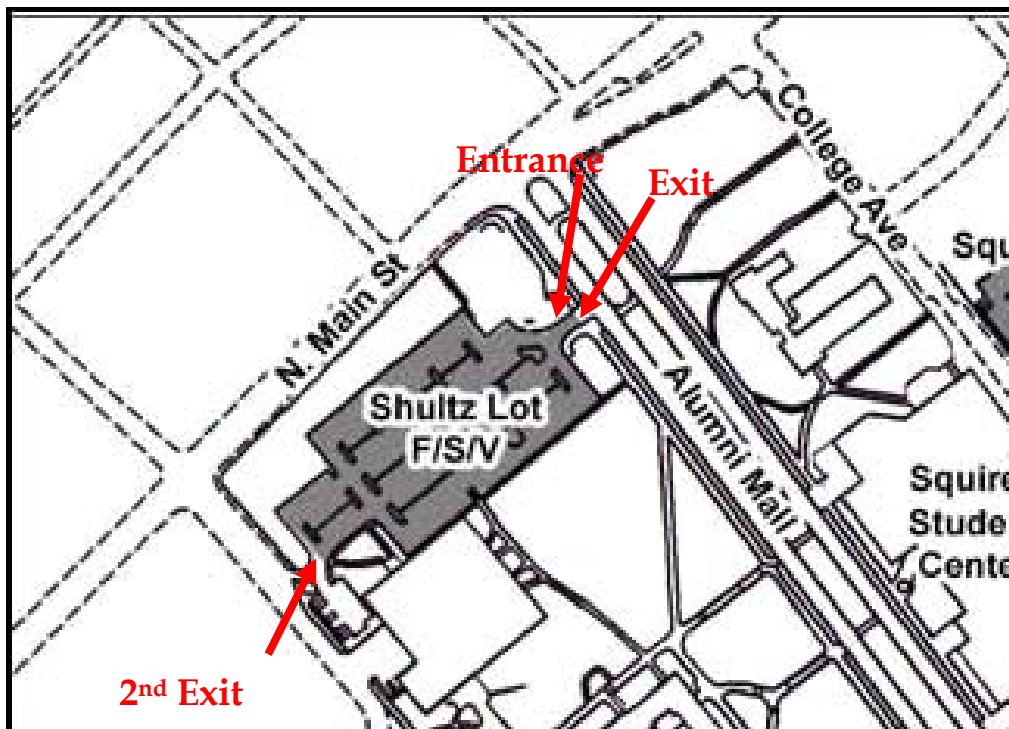


Figure 8: Shultz Parking Lot Location, Entrance and Exits



**Figure 9: Shultz Parking Lot Entrance and Exit**

### **5.1.1 Entering and Exiting Demand**

The number of vehicles entering and exiting the parking lot is shown in Figure 10. On average 30 vehicles are typically present in the parking lot prior to 7:30 a.m. For both Tuesdays and Wednesdays, more than 400 vehicles typically enter the parking by the conclusion of the day (4:00 p.m.). As is expected, very few vehicles exit before noon with a significant increase from noon until the end of the day. On average 50 vehicles enter and exit the parking lot at noon. At 4:00 p.m., an average of 200 vehicles still remain in the parking lot and 200 vehicles exit.

A comparison of the Tuesday and Wednesday trends seems to be very similar. This could be attributed to the fact that the parking lot is an F/S parking lot and thus is not typically impacted by the class schedule given that faculty and staff tend to be engaged in other non teaching activities on campus (e.g. research, etc.).

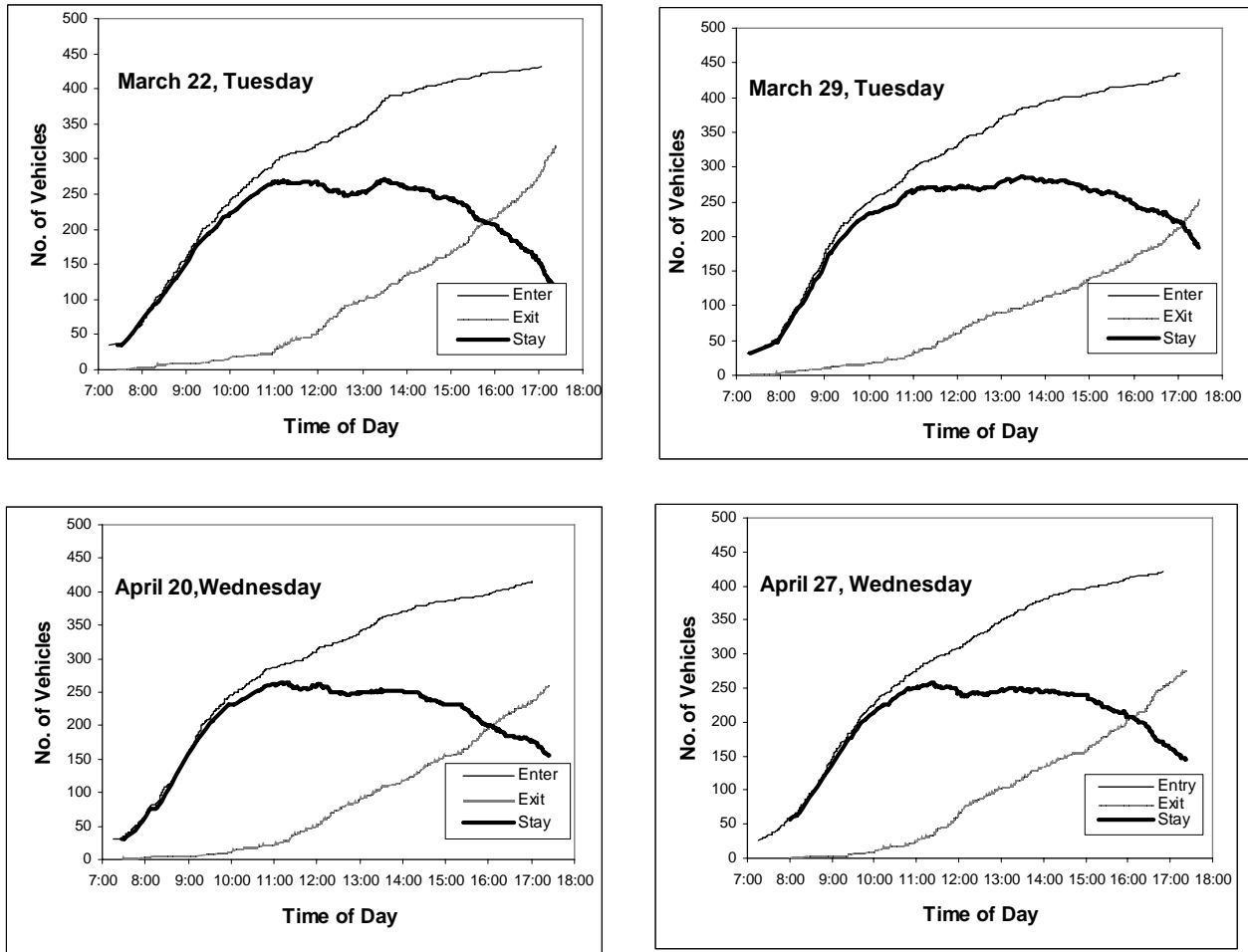
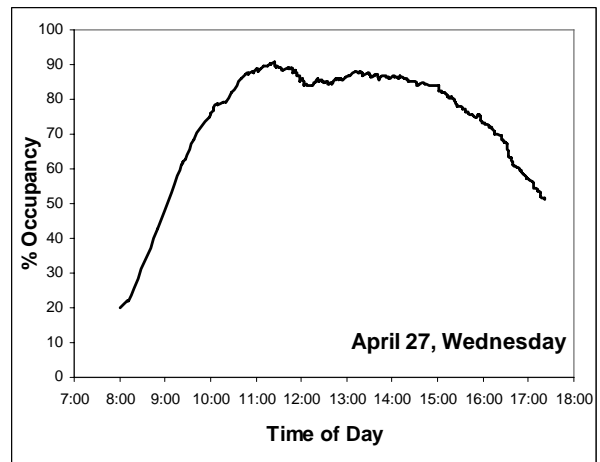
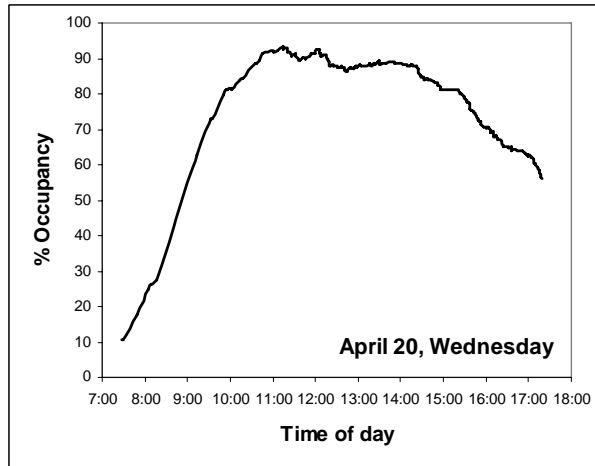
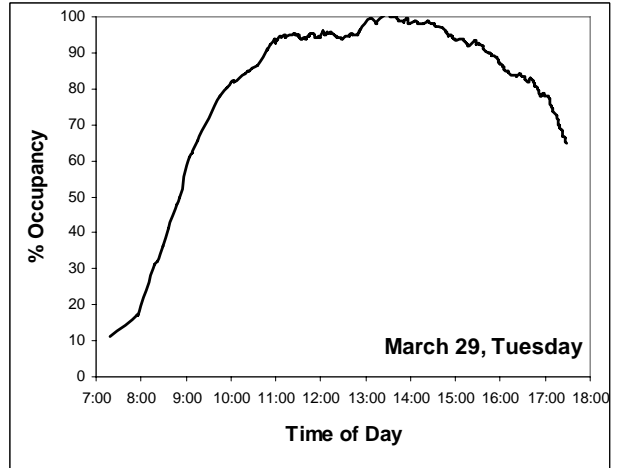
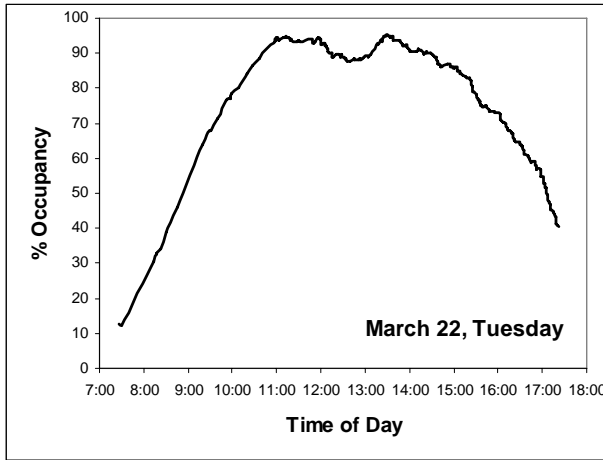


Figure 10: Total Number of Vehicles Entering, Exiting, and Remaining in the Parking Lot

### 5.1.2 Occupancy

The effective capacity of the parking lot is typically reached around 10:30 a.m., but the peak capacity is reached around 10:45 a.m. This peak is maintained until 2:30 or 3:00 p.m., with some fluctuations around noon. Tuesdays in particular show higher occupancy rates with values approaching 100%, and in some instances more than 100%, which represents vehicles entering the parking lot even when no space is available. Figure 11 shows that the Shultz parking lot is working beyond capacity on average for 4 hours during the day especially on Tuesdays.



**Figure 11: Daily Occupancy as a Percentage of Parking Lot Capacity**

### 5.1.3 Arrival Frequency

The 15-minute parking lot arrival rate demonstrates that for most days, the arrival rate peaks around 9:00 a.m., with an arrival rate of 30 vehicles per 15 minutes, as illustrated in Figure 12. There is a noticeable decrease in the arrival rate around 11:45 a.m. and a second peak appears for some days around 1:45 p.m. Generally, the frequency of arrivals on Tuesday, March 22 is slightly lower and different than the other days. These differences are accounted for in the statistical analysis presented later in this report.

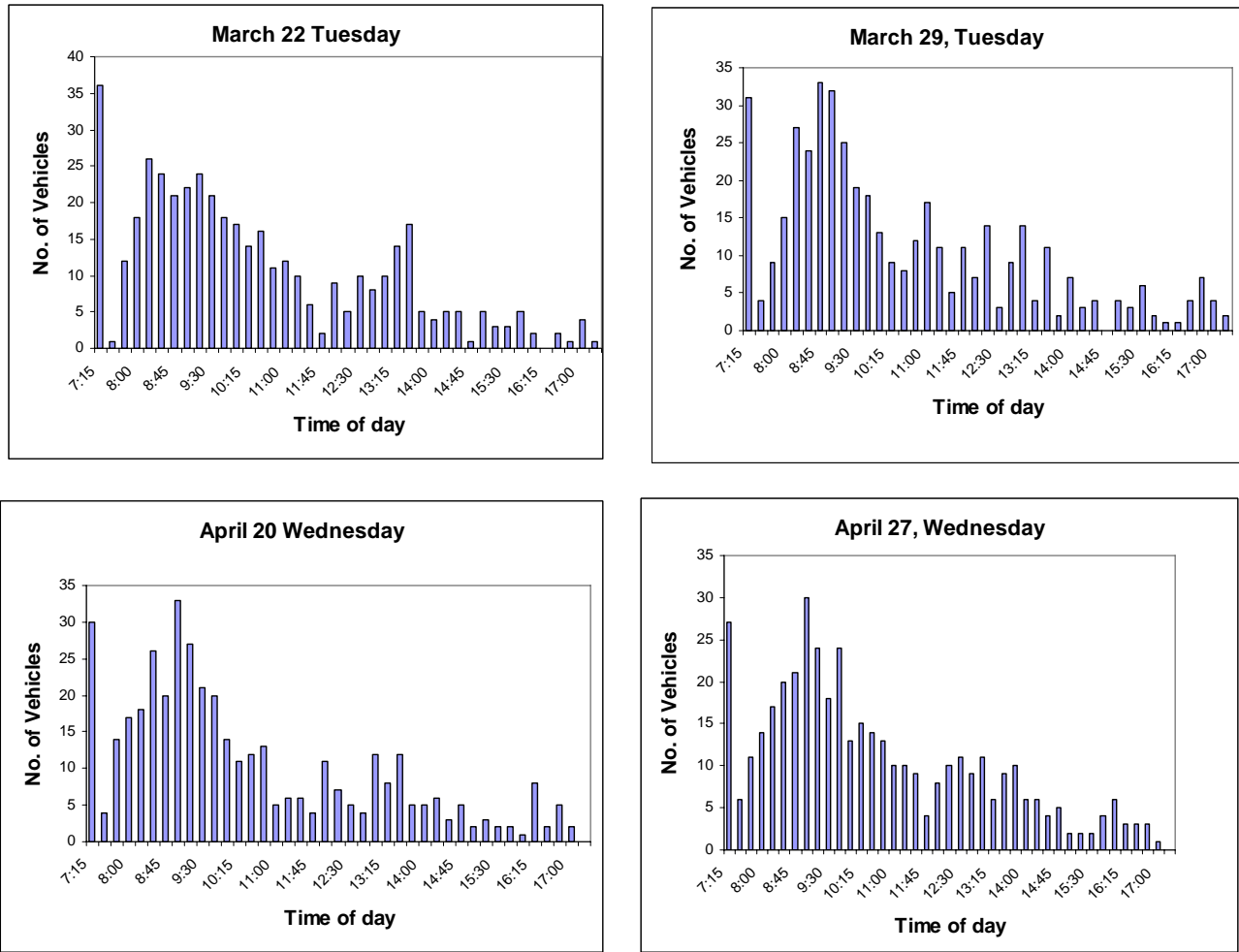


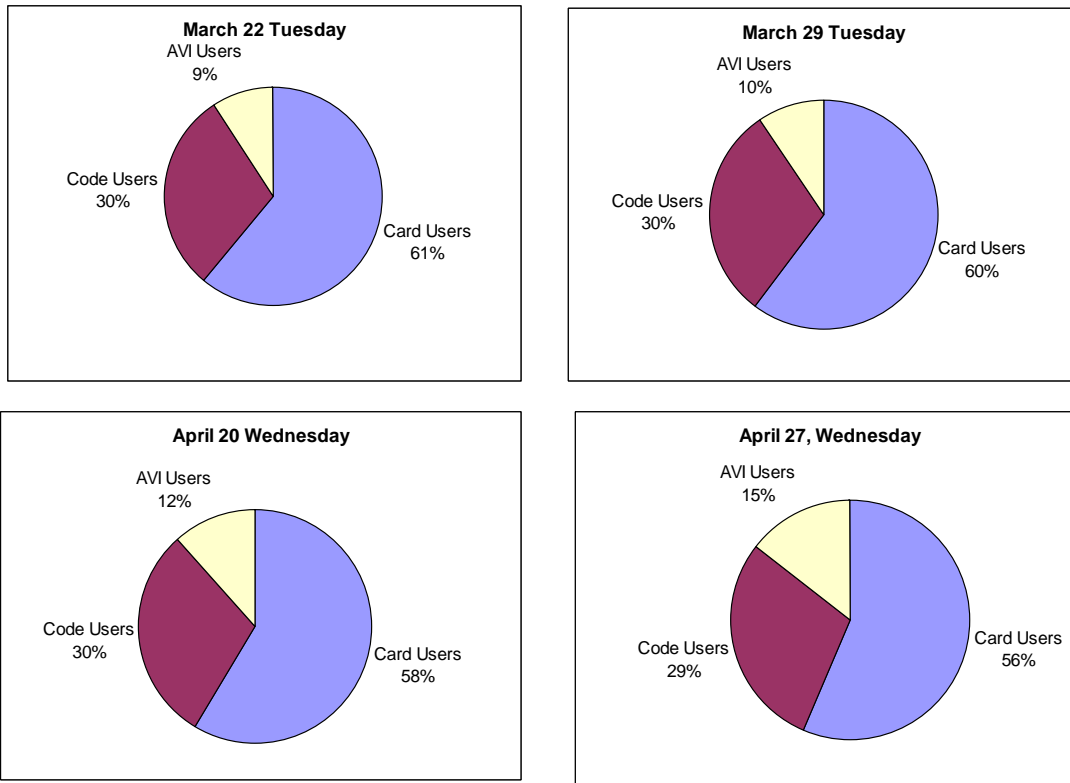
Figure 12: Arrival Frequency Every 15 Minutes

### 5.1.4 Mode of entry

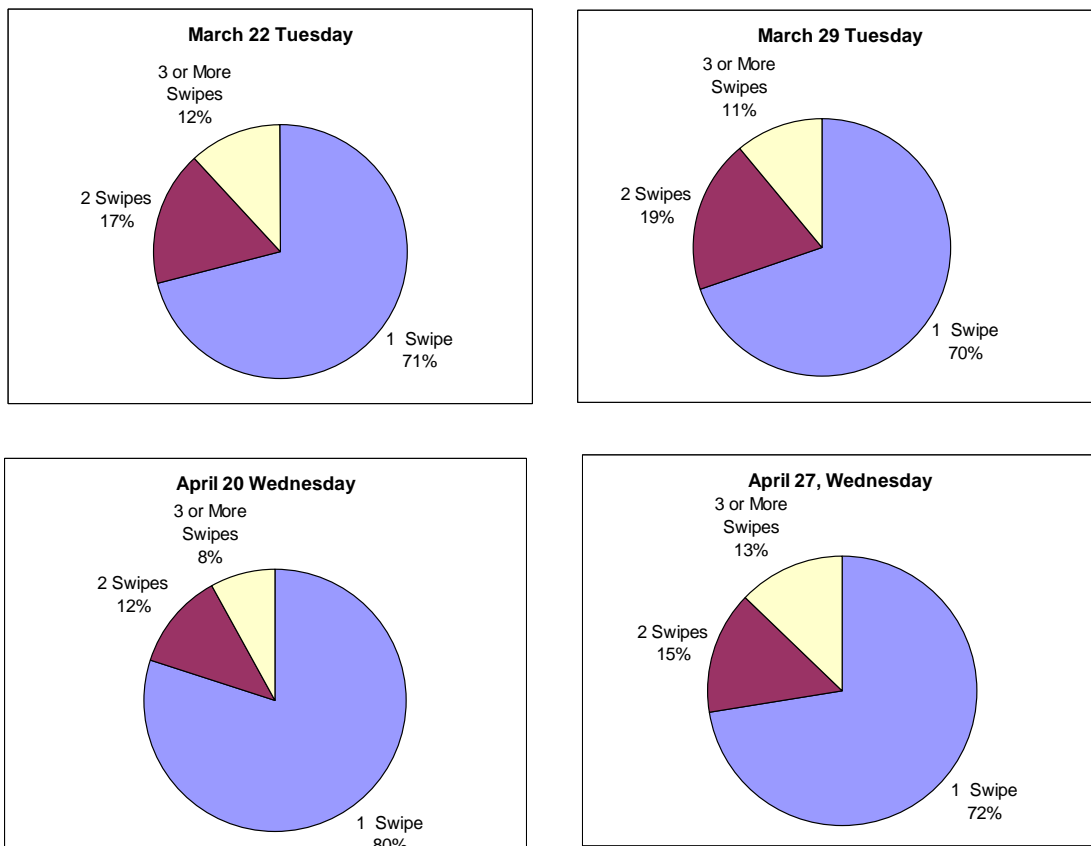
The mode of entry is specifically significant because it is directly related with the service time of the facility as a whole. The percentage of each mode of entry remains relatively constant for the different days with a 56 to 60 % breakdown of card users, 29 to 30% breakdown of code users, and 9 to 15% breakdown of AVI users. The different modes of entry for the different days are shown in Figure 13. The results demonstrate a slightly AVI usage rate on Wednesdays when compared to Tuesdays. However, the differences are minor in the 5% range.

Card readers are the most popular method of entry used. Because complaints have been received by the Virginia Tech Traffic Office about the number of times it was necessary to swipe the card in order to access to the parking lot, the number of card swipes or tries until the card was successfully read was also recorded manually and complemented with the video data. The number of swipes required as a percentage of the total number of cards users is shown in Figure 14. The percentage of cards that are read in the first try varies from 70 to 80%, with most days showing values in the lower range. The users that are required to swipe the card twice are around 15% and those required to swipe three or more times varies between 8 and 13%.

The results demonstrate that typically the number of users that are only required to make a single swipe are in the range of 70%. This value is much higher on April 20, however, it is not clear why the rate is higher on this day.



**Figure 13: Percentage of Users for each type of Equipment**



**Figure 14: Number of Swipes Required to Access**

### 5.1.5 Duration of Stay

The frequency distribution of the duration of stay, which is illustrated in Figure 15, appears to demonstrate a uniform distribution with ranges from 30 minutes up to over 8 hours. The average duration of stay is 4 hrs and 45 minutes. Alternatively, the duration of stay is expressed as a percentage of the total license plates matched in Figure 16. Again the distribution is uniform with an average of 6% across the different duration of stay values.

The vehicle stay is also presented as a wall graphic in Figure 17. For each horizontal line the most left point represents the time at which the vehicle enter the parking lot and the right most point represents the time at which the vehicle exits the parking lot. The figure clearly demonstrates that the early vehicle arrivals tend to stay longer in the parking lot and that the later arrivals typically incur shorter stays.

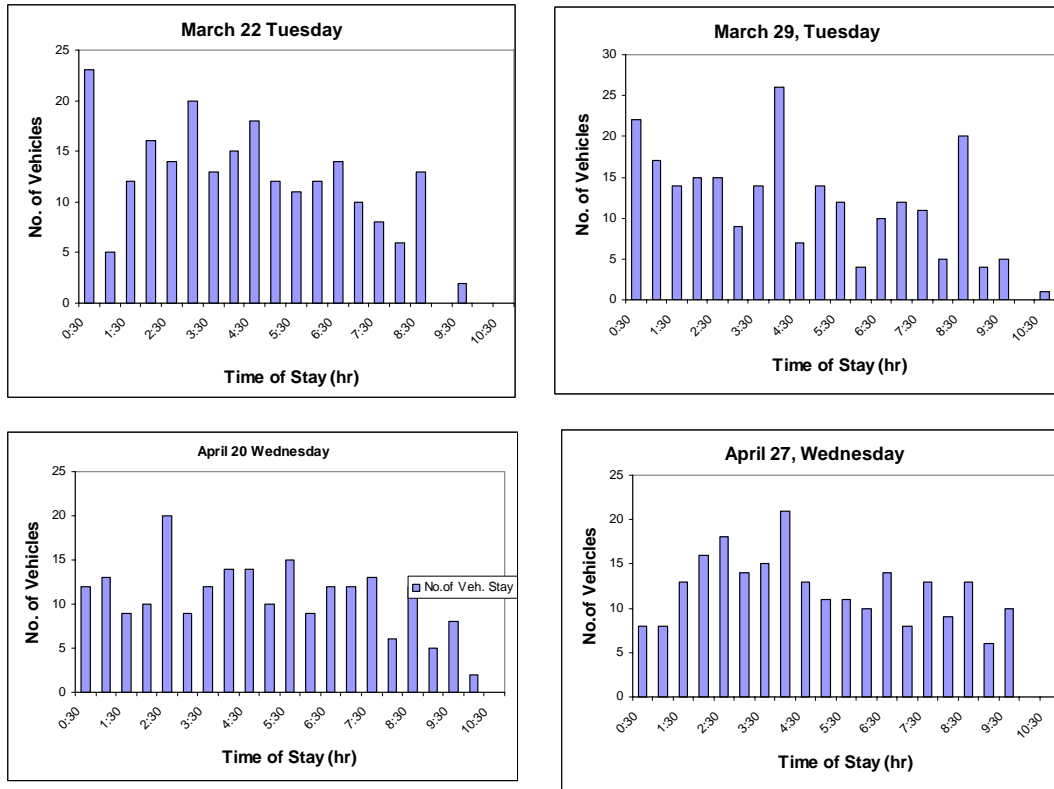


Figure 15: Frequency of "Duration of Stay" in the Shultz Parking Lot

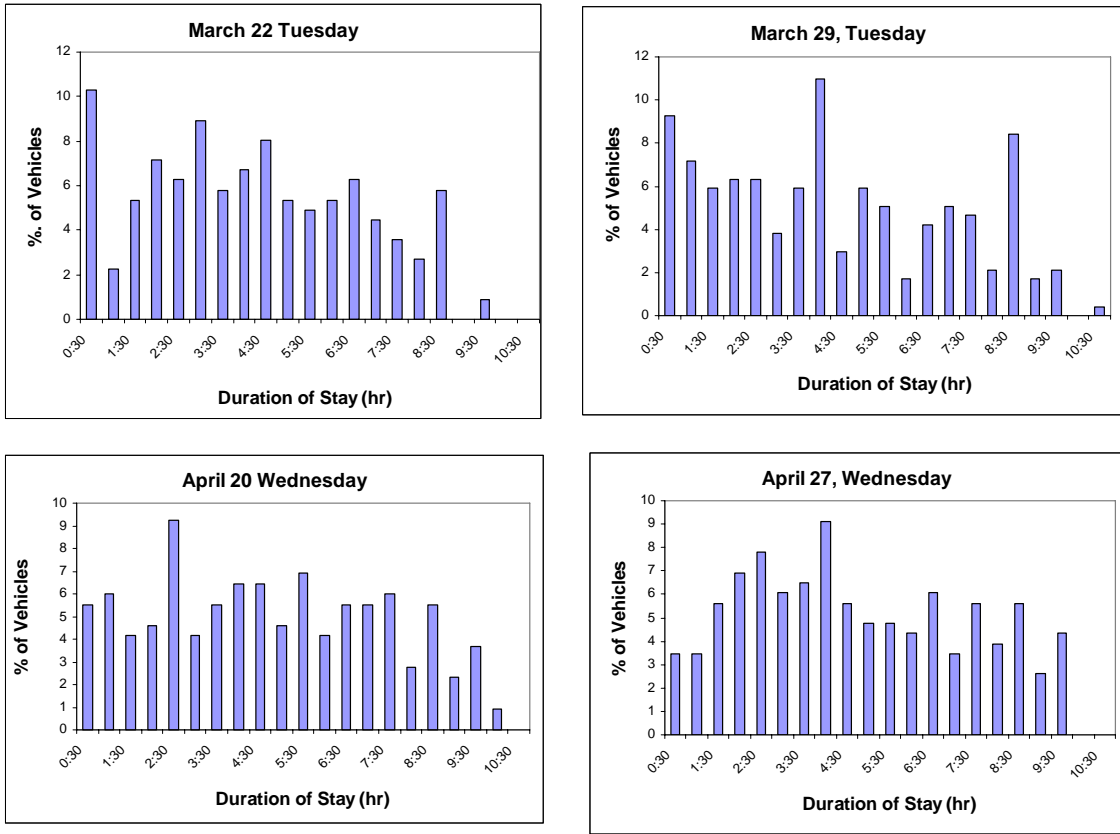


Figure 16: Frequency of "Time of Stay" (Percentage)

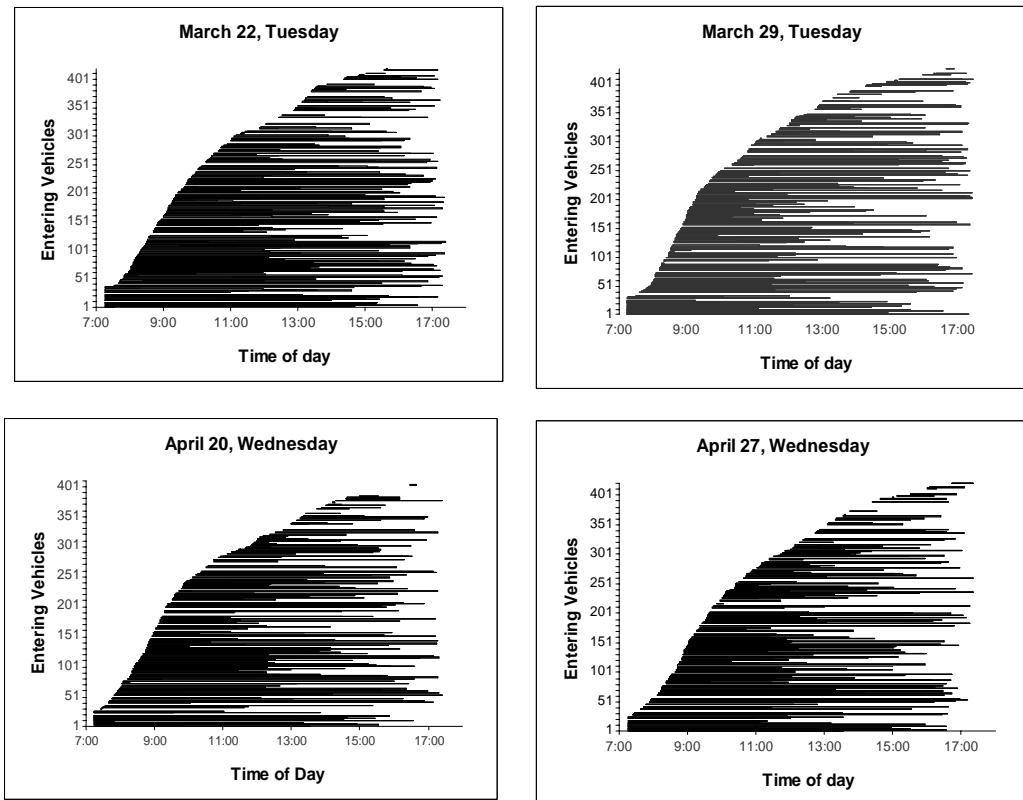


Figure 17: Time Spent by Each Vehicle in the Parking Lot

### 5.1.6 Statistical Analysis

A statistical analysis of the data was performed with the objective to determine if there were significant statistical differences within and between the two days of the week (Tuesday and Wednesday).

When the frequency of arrivals was analyzed, the results concluded that for a level of significance of 5%, there was no significant statistical evidence to conclude that the frequencies of arrival for the two Wednesdays were different, as summarized in Table 3. When the frequencies of arrival on Tuesdays were analyzed, it was concluded that for a level of significance of 5% the Tuesday frequency of arrivals were statistically different. If the average Tuesday is compared with the average Wednesday, the results show that there is no statistical significant difference between the two days ( $16.5 < 28.87 - X^2 < X^2_{0.5\%}$ ).

**Table 3: Chi Calculation for Vehicle Arrival for the Shultz Parking Lot**

	<b>Tuesdays</b>	<b>Wednesdays</b>	<b>Tuesday/Wed</b>
<b>Calculated Chi-square</b>	<b>40.88</b>	<b>18.14</b>	<b>16.52</b>
<b>Degrees of freedom</b>	<b>18</b>	<b>18</b>	<b>18</b>
<b>Tabulated Chi-square</b>	<b>28.87</b>	<b>28.97</b>	<b>28.97</b>
	Calculated $X^2 > X^2_{5\%}$ , Therefore <b>significant difference exist</b> between two Tuesdays.	Calculated $X^2 < X^2_{5\%}$ , Therefore <b>NO significant difference</b> between Wednesday Vehicle Stay Times.	Calculated $X^2 < X^2_{5\%}$ , Therefore <b>NO significant difference</b> between Tuesdays and Wednesdays

When the “duration of stay” was analyzed, it was found that for a level of significance of 5%, the differences between the studied Wednesdays is not statistically significant, but the difference between Tuesdays is significant. If the average Tuesday is compared with the average Wednesday, the results show that there is no statistical significant difference between the two days ( $22 < 27.58 - X^2 < X^2_{0.5\%}$ ), as summarized in Table 4.

**Table 4: Chi Calculation for Time Spent in the Parking lot per Vehicle for the Shultz Parking Lot**

	<b>Tuesdays</b>	<b>Wednesdays</b>	<b>Tuesday/Wed</b>
<b>Calculated Chi-square</b>	<b>33.3</b>	<b>9.55</b>	<b>22</b>
<b>Degrees of freedom</b>	<b>17</b>	<b>17</b>	<b>17</b>
<b>Tabulated Chi-square</b>	<b>27.587</b>	<b>27.587</b>	<b>27.587</b>
	Calculated $X^2 > X^2_{5\%}$ , Therefore <b>significant difference exist</b> between two Tuesdays.	Calculated $X^2 < X^2_{5\%}$ , Therefore <b>NO significant difference</b> between the two Wednesdays	Calculated $X^2 < X^2_{5\%}$ , Therefore <b>NO significant difference</b> between Tuesdays and Wednesdays

### 5.2 Architectural Annex

This section presents the results of the Architectural Annex parking lot that is illustrated in Figure 18. Again, as was the case with the Shultz parking lot this lot is a F/S and handicapped parking lot with access through Otey Street. It has 152 parking spaces for F/S, 2 parking spaces for handicapped users, and 6 service vehicles and 1 motorcycle space, for a total of 161 parking spaces. The parking lot has one entrance and one exit adjacent to one another, as shown in Figure 19. The parking data were gathered on Tuesday, March 15 and Wednesday, April 6.

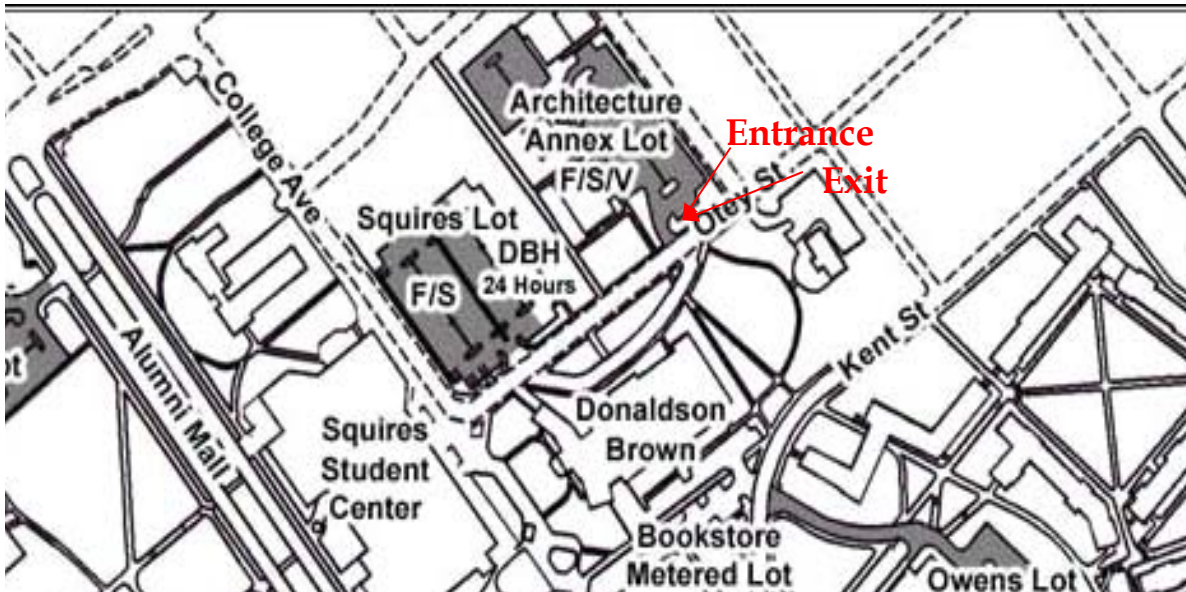


Figure 18: Architectural Annex Parking Lot: Location, Entrance and Exit



Figure 19: View of the Architectural Annex Parking Lot and its equipment

### 5.2.1 Entering and Exiting the Parking Lot

The number of vehicles entering and exiting the parking lot is shown in Figure 20. The number of vehicles present in the parking lot prior to the gate operation was 25 on Tuesday and 32 on Wednesday. On Tuesday at 5:00 p.m., 270 vehicles entered the parking lot compared with 243 vehicles on Wednesday. As was expected, very few vehicles exited before 12:00 noon. On average 50 vehicles entered and exited the parking lot at 12:00 noon. At 4:00 p.m., 100 vehicles remained in the parking lot on Wednesday and 130 vehicles remained on Tuesday. The temporal trend for Tuesdays and Wednesdays seems very similar, as illustrated in Figure 20.

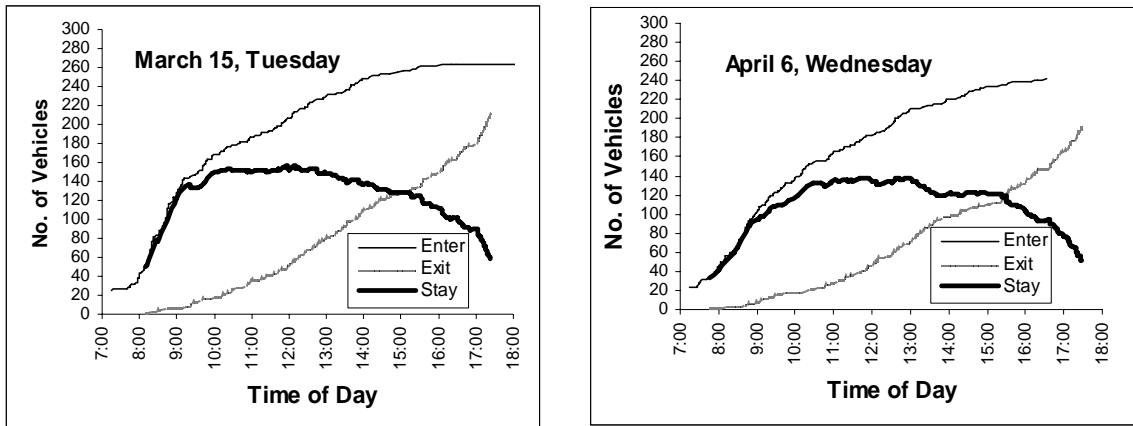


Figure 20: Total Number of Vehicles Entering, Exiting and Staying in the Parking Lot

### 5.2.2 Occupancy

The occupancy rate for both days is shown in Figure 21. Tuesdays reach values near 100% occupancy and Wednesday have values of 85 % capacity. The maximum occupancy is reached in both days around 11 a.m.

This peak is maintained until 2:30 or 3:00 p.m., with some fluctuations around noon. Figure 21 shows that the parking lot is working beyond capacity for 4 hrs on Tuesday, but does not reach capacity on Wednesday.

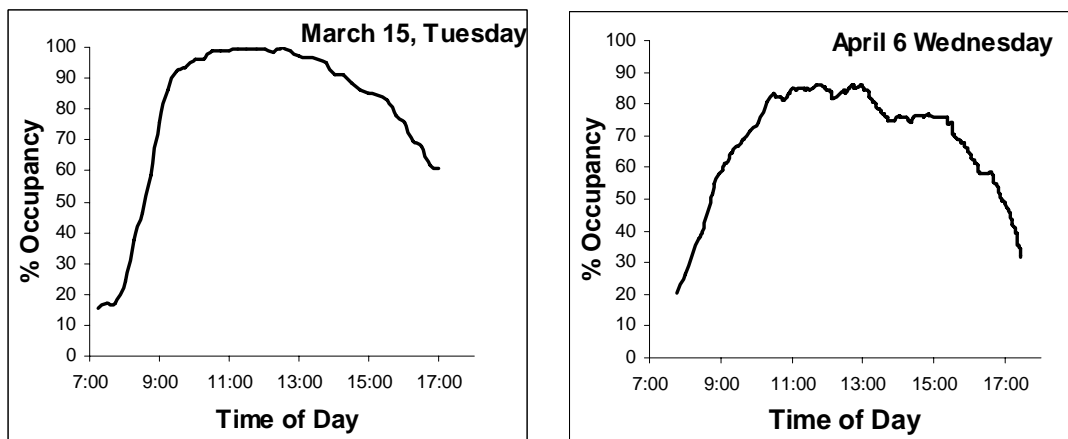
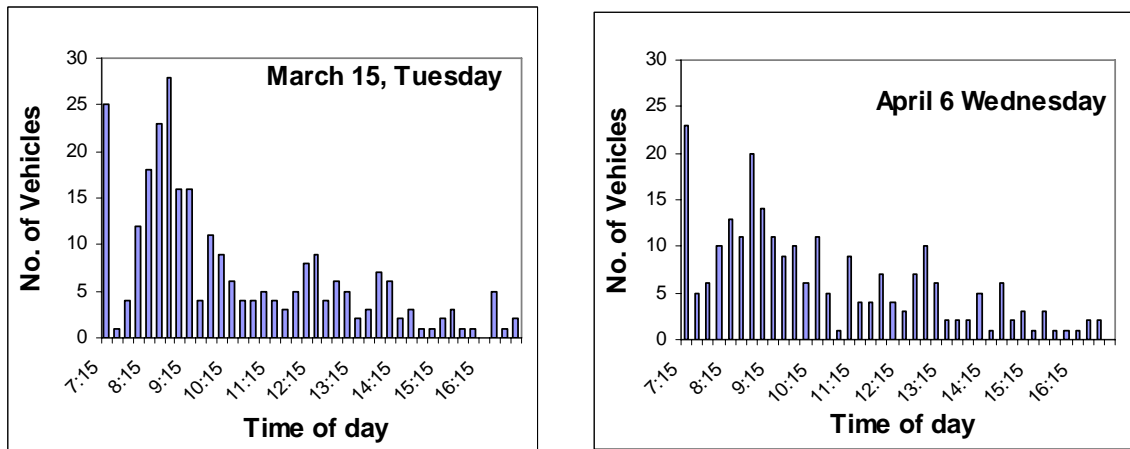


Figure 21: Daily Occupancy as a Percentage of Parking Lot Capacity

### 5.2.3 Arrival Frequency

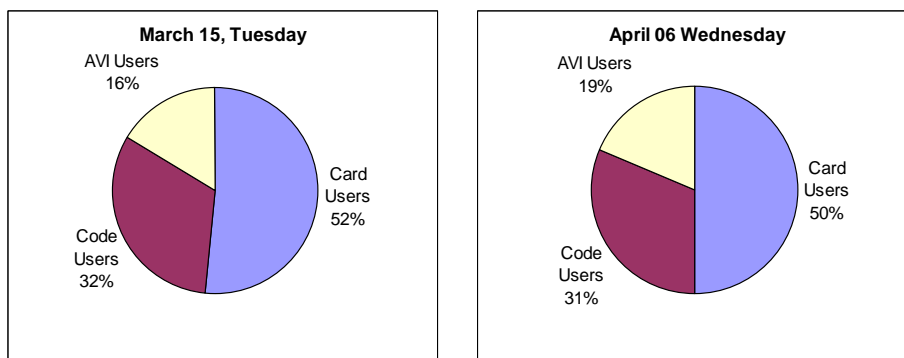
The arrival frequency of vehicles entering the parking lot every 15 minutes is shown in Figure 22. The arrival frequency for both days is relatively similar with a peak arrival exhibited around 9:00 a.m. and a significant decrease after 2:00 p.m.



**Figure 22: Arrival Frequency every 15 minutes**

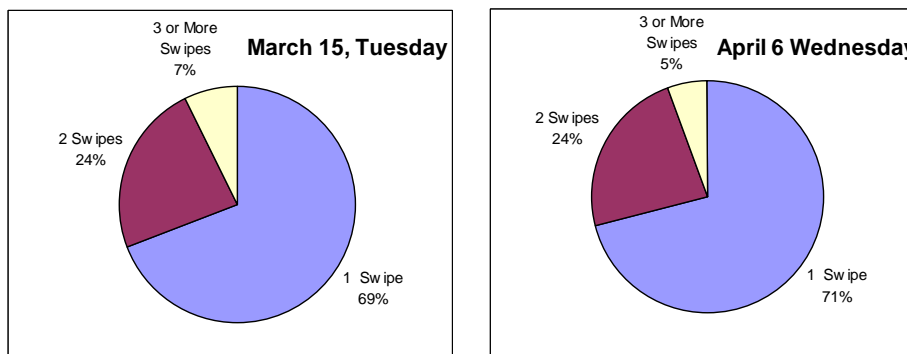
### 5.2.4 Mode of Entry

The percentage of mode users (card, code, and AVI) remains fairly constant over the two days, as illustrated in Figure 23. Card readers are the most popular method with 50% usage, followed by code users (30%), and AVI readers 17 to 19%. In general, it appears that the Annex lot has more AVI reader users when compared to the Shultz lot.



**Figure 23: Percentage of Users for each type of Equipment**

The percentage of cards that are read in the first try is around 70%. These values are very similar to the findings in the Shultz parking lot. The users that are required to swipe the card twice are around 24% and those required to try three or more times varies between 5% and 7%, as shown in Figure 24. The system in this parking lot seems to be relatively more efficient compared with the Shultz parking lot, because, even though the percentage of users required to swipe two times is higher, the percentage of users required to swipe three times is lower.



**Figure 24: Number of Swipes Required to Access**

### 5.2.5 Duration of Stay

The average stay time in the Annex lot was 3 hrs and 45 minutes, as illustrated in Figure 25. The duration of stay is also presented as a percentage of the total license plates matched. Twelve percent of vehicles did not stay more than 30 minutes and 13% stayed more than 9 hrs. It is important to note that stay duration was computed once a vehicle exited the parking lot. If the same vehicle entered the parking lot again, it was counted as a different vehicle for the second round. Vehicles remaining in the parking lot after the gates were opened were not included in these calculations and figures.

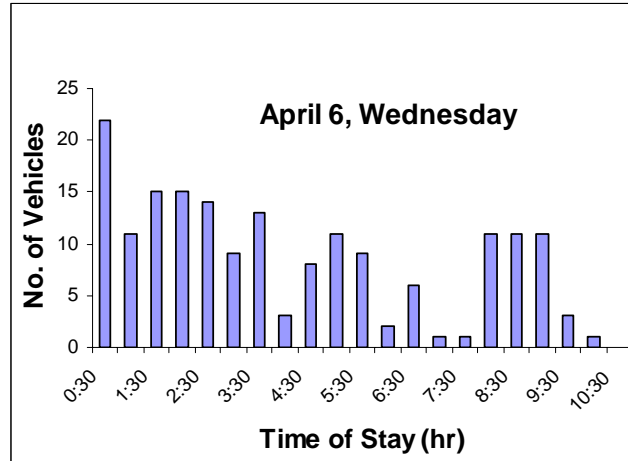


Figure 25: Frequency of "Time of Stay" in the Parking Lot

The duration of stay is shown also in Figure 26. For each horizontal line, the most left point represents the time at which the vehicle entered the parking lot and the right most point represents the time at which the vehicle exited the parking lot.

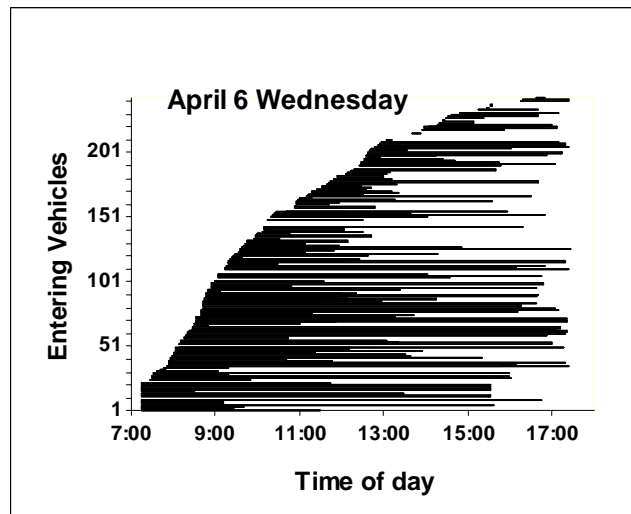


Figure 26: Time Spent by Each Vehicle in the Parking Lot

### 5.2.6 Statistical Analysis

A statistical analysis of the data collected was performed in order to determine if there were significant statistical differences between Tuesdays and Wednesdays. When the frequency of arrivals was analyzed, the results concluded that for a level of significance of 95%, there was statistically significant evidence to conclude that the arrival rates for Tuesday and Wednesday were different, as shown in Table 5. For the first day data was gathered, March 15, videotape data was available for the whole day, but manual data was not available for the first 4 hours, making the computation of stay more complicated and less accurate for that day. For this reason a statistical analysis of duration of stay is not presented here.

Table 5: Chi Calculation for Vehicle Arrival for the Architectural Annex Parking Lot

	<b>Tuesday/Wed</b>
<b>Calculated Chi-square</b>	<b>75.5</b>
<b>Degrees of freedom</b>	<b>15</b>
<b>Tabulated Chi-square</b>	<b>24.996</b>
Calculated $X^2 > X^2_{.05}$ , Therefore <b>significant difference</b> between Tuesday and Wednesday exist	

### 5.3 Perry Street Parking Lot

The Perry Street parking lot, which is shown in Figure 27, unlike the previous lots, serves not only Faculty and staff F/S but also graduate and commuter students. Three separate parking lots form the Perry Street Lot. This study was performed in parking lot number 2, situated in the middle of the figure. Figure 28 shows a view of the Perry Street Parking Lot, which has 328 parking spots, 13 of them metered, and with no overall access control. The data were gathered on Tuesday, April 12 and Wednesday, April 13 from 7:30 a.m. to 5:30 p.m. Due to its location on campus near major departments and teaching facilities, the parking lot is used close to 100% of the total capacity for most of the time with vehicles entering and exiting the parking lot continuously.

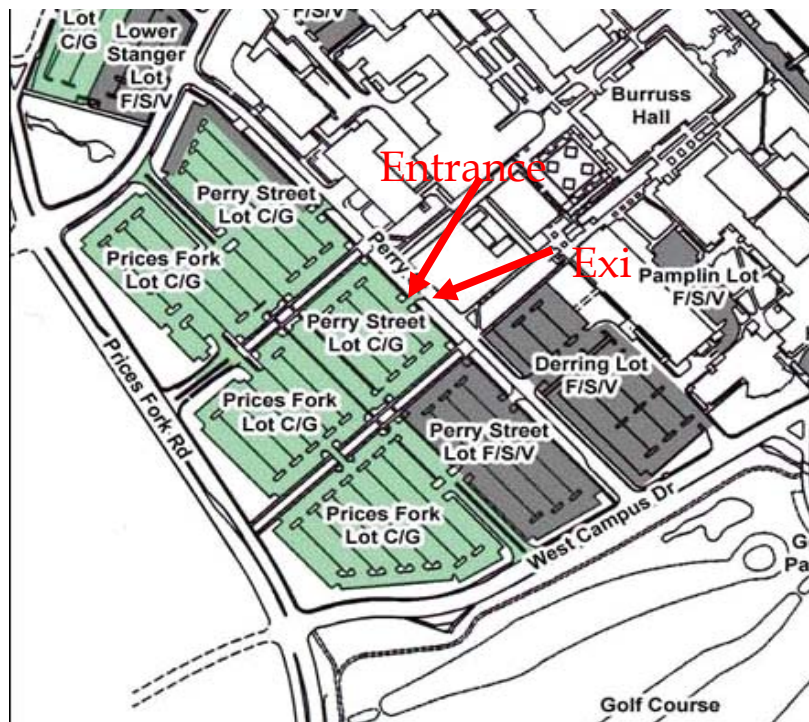


Figure 27: Perry Street Parking Lot: Location, Entrance, and Exit



Figure 28: View of the Perry Street Parking Lot

### 5.3.1 Entering and exiting the parking lot

The number of vehicles entering and exiting the parking lot is shown in Figure 29. While data were gathered manually, due to the excessive number of vehicles entering the parking lot, the data needed to be complemented by the video data. Approximately 1,200 vehicles entered the parking lot on both days, with 1,258 on Tuesday and 1,178 on Wednesday. The number of vehicles present in the parking lot before the data collection began was 30 for Tuesday and 20 for Wednesday. Prior to 8:30 a.m., very few vehicles exited the parking lot. However, as seen in Figure 29 after 9:00 a.m., the cumulative entry and exit curves remain parallel, demonstrating equal entering and exiting volumes. At 5:30 p.m. when the data collection was concluded, approximately 150 vehicles remained in the parking lot.

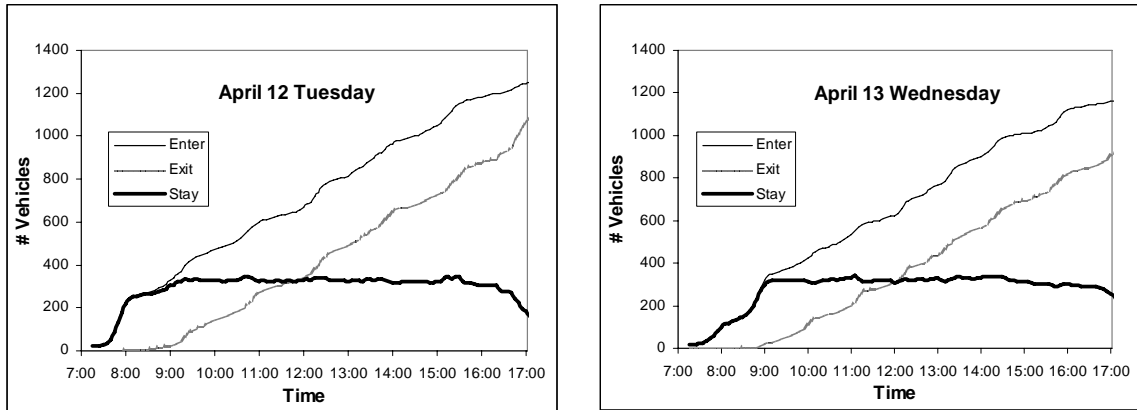


Figure 29: Total Number of Vehicles Entering, Exiting and Staying in the Parking Lot

### 5.3.2 Occupancy

The occupancy rate for both dates demonstrates that not only is the effective capacity reached very quickly, but operates at full capacity from 9:00 a.m. until 4:00 p.m., as illustrated in Figure 30. In some instances the occupancy increases beyond the capacity when cars entering the parking lot to find a parking spot unaware that the parking lot is completely full.

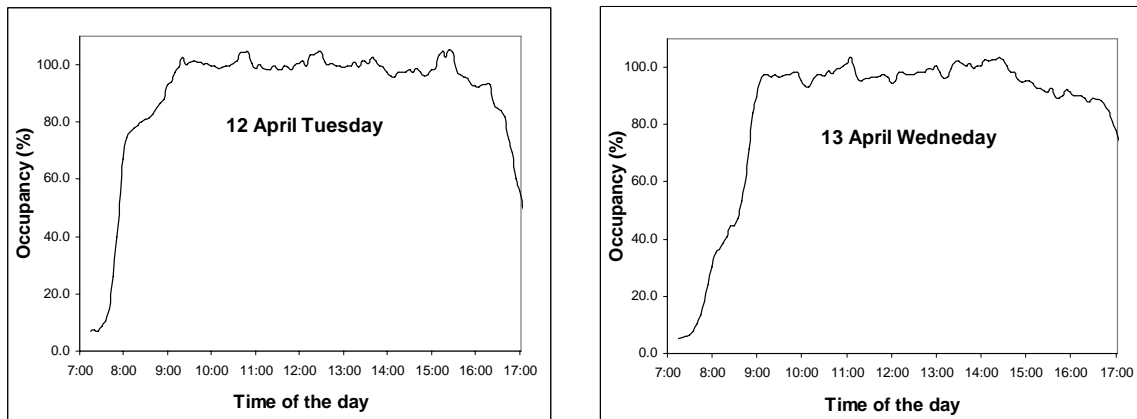


Figure 30: Daily Occupancy as a Percentage of Parking Lot Capacity

### 5.3.3 Arrival Frequency

The arrival frequency of vehicles entering the parking lot every 15 minutes is shown in Figure 31. The maximum arrival rate for Tuesday is 137 vehicles per 15 minutes at 8:00 a.m., and for Wednesday is 115 vehicles per 15 minutes at 9:00 a.m.

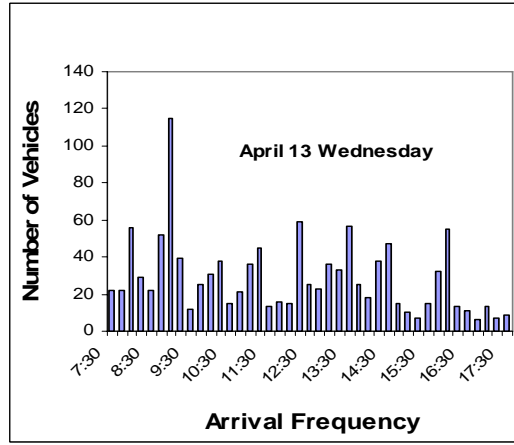
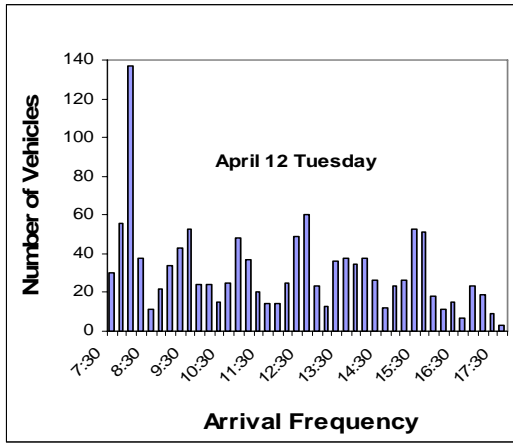


Figure 31: Arrival Frequency for Tuesday and Wednesday for the Perry Street parking Lot

### 5.3.4 Duration of Stay

The duration of stay, which is illustrated in Figure 32, demonstrates that more than 20% of the vehicles typically stayed less than 30 minutes. The duration of stay is shown also in Figure 33. While Figure 32 considers all the vehicles together, Figure 33 plots each vehicle individually. For each horizontal line, the most left point represents the time at which the vehicle enters the parking lot and the right most point represents the time at which the vehicle exits the parking lot. Figure 33 demonstrates that the early arrivals tend to stay longer in the parking lot when compared to the later arrivals.

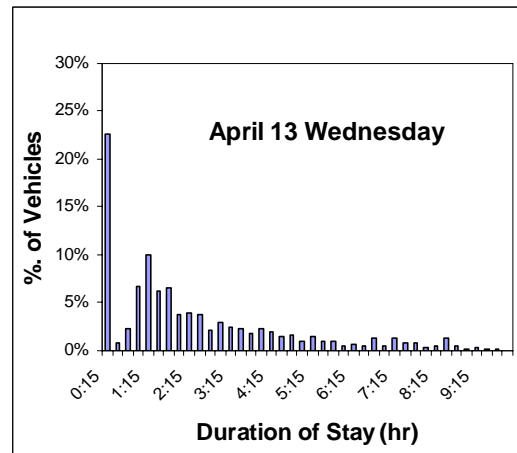
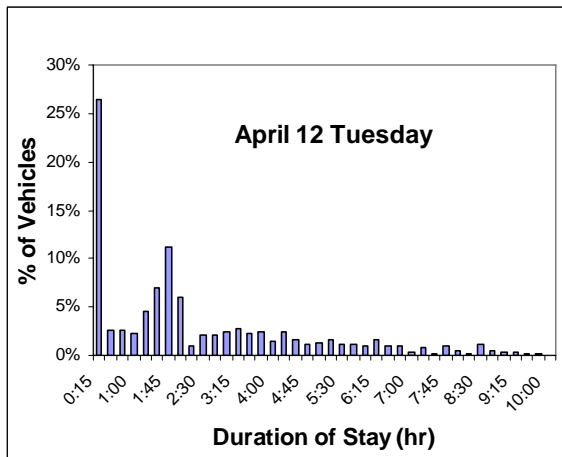


Figure 32: "Duration of Stay" Frequency at the Perry Street Parking Lot

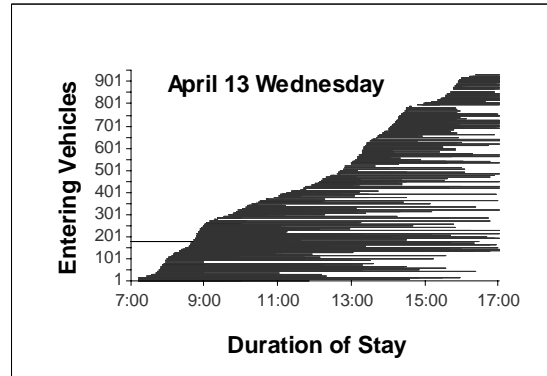
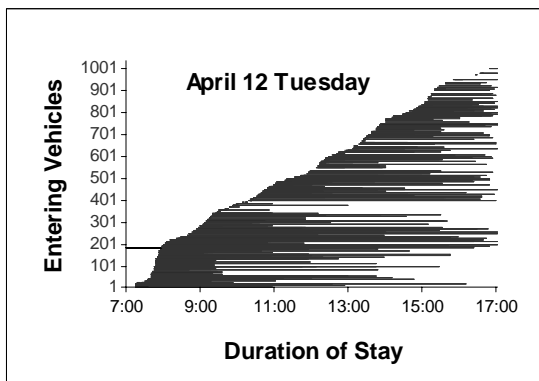


Figure 33: Time Spent by Each Vehicle in the Parking Lot

A statistical analysis of the data was performed in order to determine if there were significant statistical differences between Tuesdays and Wednesdays. When the frequency of arrivals was analyzed, the results concluded that for a level of significance of 95%, there was statistically significant evidence to conclude that the arrivals rates for Tuesday and Wednesday were different, as shown in Table 6.

**Table 6: Chi Calculation for Vehicle Arrival for the Perry Street Parking Lot**

	<b>Tuesday/Wed</b>
<b>Calculated Chi-square</b>	<b>674</b>
<b>Degrees of freedom</b>	<b>39</b>
<b>Tabulated Chi-square</b>	<b>54.5</b>
Calculated $X^2 > X^2_{5\%}$ , Therefore <b>significant difference</b> between Tuesday and Wednesday exist	

When the “Duration of Stay” was analyzed, it was found that for a level of significance of 95% that the frequency of duration of stays for Tuesdays and Wednesdays were statistically different. Consequently, it can be concluded that the parking lot demand on Tuesdays is higher than that on Wednesdays.

**Table 7: Chi Calculation for Time Spent per Vehicle for the Perry Street Parking Lot**

	<b>Tuesday/Wed</b>
<b>Calculated Chi-square</b>	<b>78.79</b>
<b>Degrees of freedom</b>	<b>19</b>
<b>Tabulated Chi-square</b>	<b>30.14</b>
Calculated $X^2 > X^2_{5\%}$ , Therefore <b>significant difference</b> between Tuesday and Wednesday exist	

## 5.4 Service Time

The efficiency of each type of equipment can be determined by the service time. The service time is defined for the purpose of this report as the time from when the vehicle reaches the entrance gate until the time the gate is closed after serving the vehicle. The service time includes: a) the time it takes to swipe the card, enter the key code or the time it takes the AVI to read the tag; b) the time it takes for the gate to be activated and opened; and c) the time it takes for the gate to close. These times were manually recorded using the video data. One entire day was studied using the Architectural Annex parking lot and 4 hrs of video were reviewed for the Shultz parking lot. The results of the analysis for the different three techniques are shown in Table 8. The results clearly demonstrate that the card readers involve the longest service time and the AVI technology provides a service time that is approximately half the card reader service time. These results clearly demonstrate that the use of AVI technology has the potential of doubling the capacity of the entrance gate. The maximum capacity for the AVI technology is approximately 500 veh/h/lane (3600/7.16).

The card reader service times were further analyzed as a function the number of swipes required to access the parking lot as shown in Table 9. As would be expected, the service time increases as the number of swipes increases. The results of Table 8 and 9 demonstrate that the use of card readers only provides an entrance capacity of approximately 200 veh/h/lane.

**Table 8: Service Time for the Different Type of Technologies for the Tow Parking Lots**

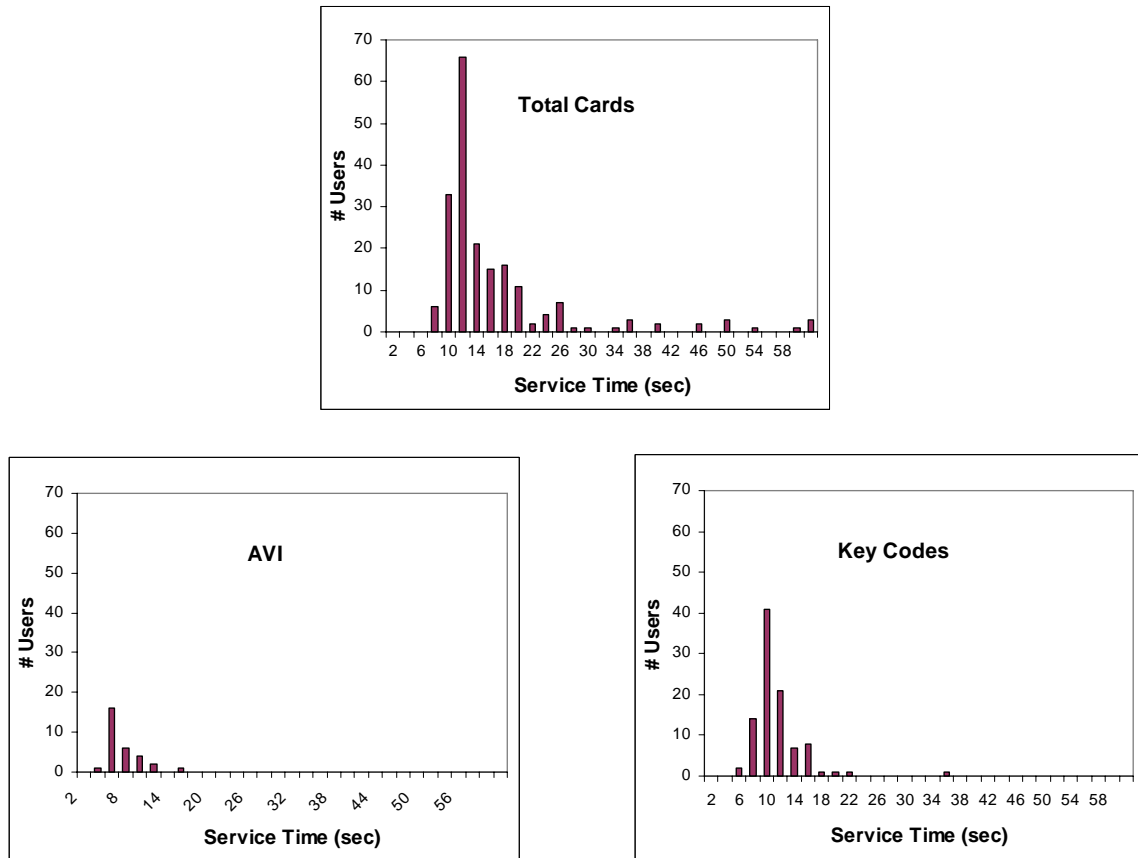
<b>Technology</b>	<b>Service time(s)</b>	
	<b>Shultz</b>	<b>Architectural Annex</b>
Card Reader	16.73	17.78
Digital Key Code	11.06	14.4
Automatic Vehicle Identification	7.82	7.16

**Table 9: Service Time for the Card Reader by Number of Swipes**

Card Reader Technology	Service time(s)	
	Shultz	Architectural Annex
Average	16.73	17.78
1 Swipe Required	12.73	14.53
2 Swipes Required	17.47	24.5
3 Swipes Required	27.62	30.25
More than 3 Swipes required	49.3	40.5

The results show that the card reader technology is almost as effective as the digital key code when only 1 swipe is required. An analysis of the video data demonstrated that the access of the card reader was not an easy task for some users, requiring some drivers to exit their vehicle in order to swipe the card. Frustration was also shown in the face of the users when the card needed to be swiped multiple times. It was also noticed in the video data that a limited number of users initially used a wrong card and thus needed to switch the card after recognizing the problem. This effort demonstrates that the efficiency of a system is not only dependent on the efficiency of the hardware, but also depends on the capabilities of the users.

To further analyze the system performance the distribution of service times was also analyzed, as illustrated in Figure 34. Figure 34 illustrates the distribution of service times for the different types of technologies at the Shultz parking lot entrance. The figure clearly demonstrates a large variation in service times in the case of the card readers (maximum service times exceed 60 sec in duration). The AVI technology is much more confined with a maximum service time of 20 sec.



**Figure 34 Distribution of Service Time of the Different Type of Technologies for Shultz Parking Lot**

In addition, card reader frequency plots were generated depending on the number of times required to swipe the card, as illustrated in Figure 35. The figure clearly demonstrates an increase in service time variability with an increase in the number of swipes. Similar results are observed for the Architectural Annex parking lot, as illustrated in Figures 36 and 37.

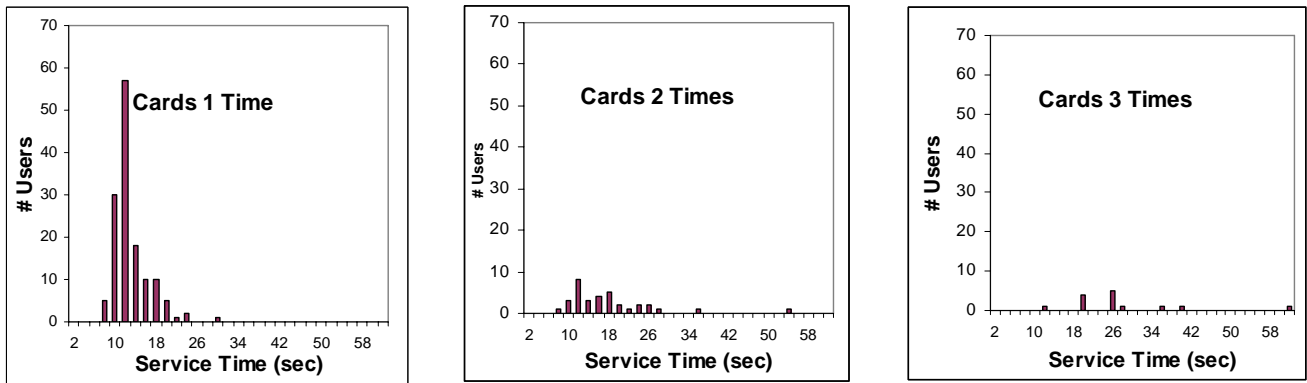


Figure 35: Service Time Distribution as a Function of the Number of Swipes for Shultz Parking Lot

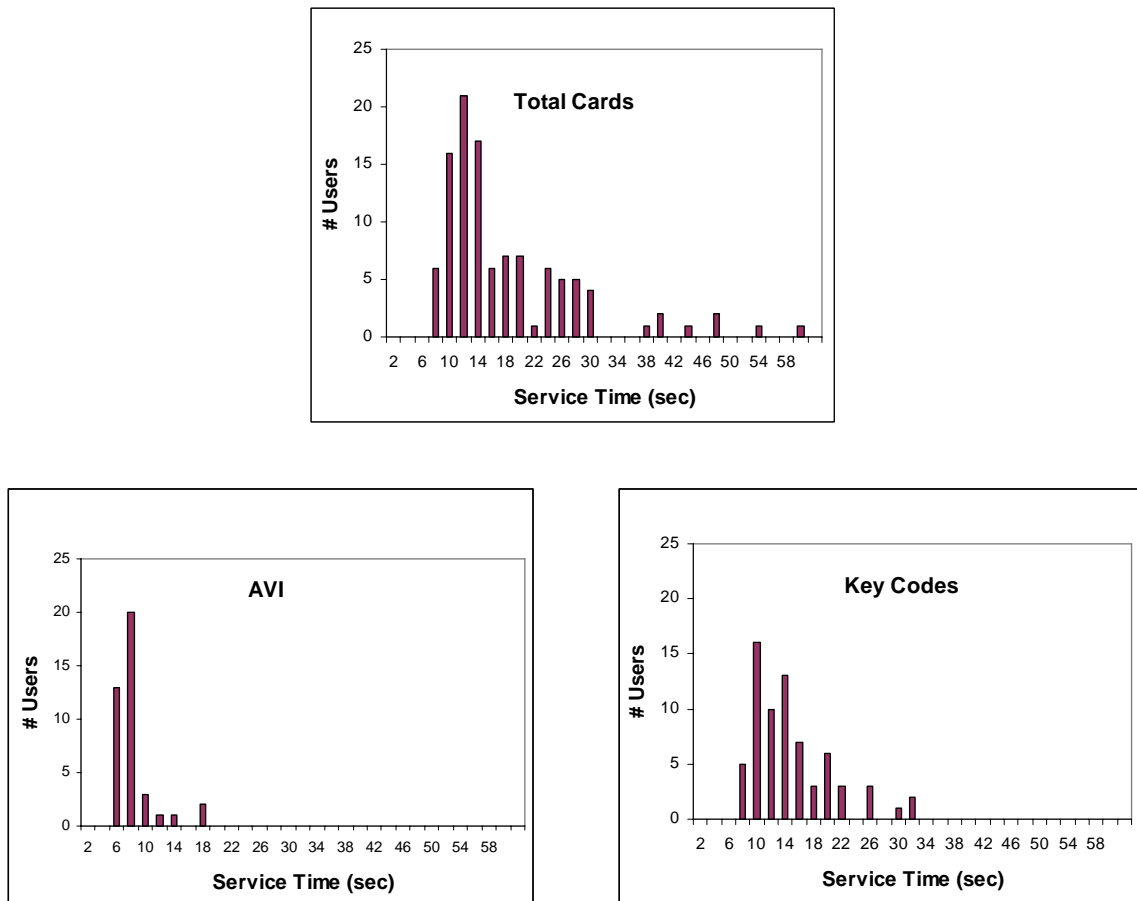


Figure 36: Service Time Distribution for Different Technologies at the Architectural Annex Parking Lot

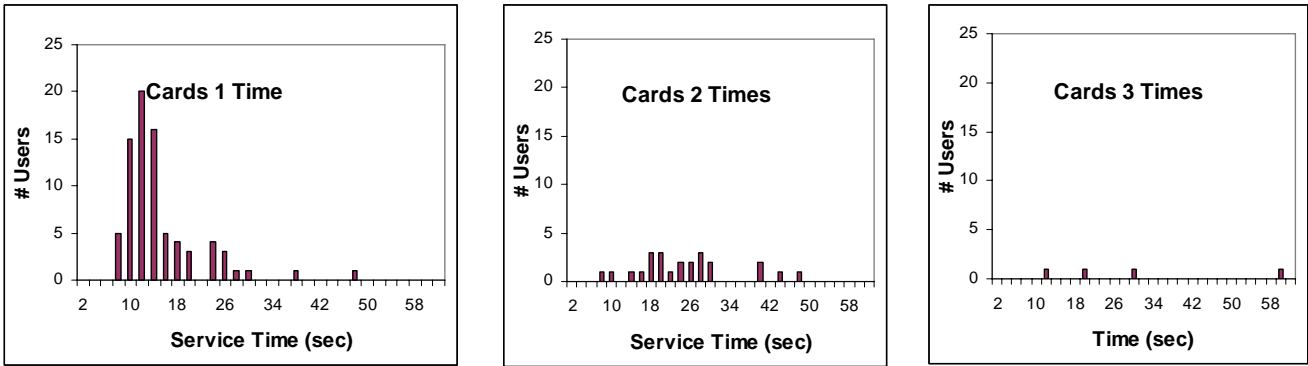


Figure 37: Service Time Distribution as a Function of the Number of Swipes for Architectural Annex Parking Lot

## 5.5 Historical Data Analysis

The Virginia Tech parking management system gathers parking data and stores the data in a central database. The data are used to grant or deny access to the parking lot to vehicles using a card reader or the AVI technology. Key code vehicles are granted or denied entrance independently. This central system gathers data 24 hours a day, seven days a week. The collected information is shown in Table 10.

Table 10: Data Collected by the University on a Daily Basis

Variable	Description
Contract_access.card_num	Identifies the encoded Hokie passport ID or mapped Transporter ID
Contract_access.reader	Identifies which parking lot and what reader Contract_access.card_num was read from: <ol style="list-style-type: none"> <li>1. Media Hokie Card</li> <li>2. Media Transporter</li> <li>3. Shultz Hokie Card</li> <li>4. Shultz Transporter</li> <li>5. Turner Hokie Card</li> <li>6. Turner Transporter</li> </ol>
Contract_access.allow	Indicated if the access was granted or denied <ol style="list-style-type: none"> <li>1. -1 Access granted</li> <li>2. 0 Access denied</li> </ol>
Contract_access.when	Time stamp when the contract_access.card.num was red

It is important to note that no information is gathered regarding the key code users. Three parking lots are equipped with this triple technology (card readers, tag readers, and code readers): the Media Building (also known as Architectural Annex), Shultz, and Turner parking lots. Although the Turner parking lot was not part of the field data collection effort because it was recently equipped with the parking control system, the historical data analysis is included as part of this report.

Daily data from January 1 through March 16 was analyzed. The objective was two fold; first, determine the use of the parking lot and second to study if there were statistical differences among the different days of the week. The data were missing days because of equipment malfunction. The Shultz parking lot seemed to have more significant data problems compared to the other lots.

The data were processed for each day of the week (DOW) for each parking lot. The system registered the exact time the reader (card or AVI) was recorded. The data were aggregated into 15 min intervals and the average 15min flow for each DOW was computed. Engineering judgment was used to ignore days where the equipment was not functioning for the entire day or for parts of the day. The differences in the number of vehicles, if any, are mostly observed from

8:30 a.m. to 10:00 a.m. After this time, the graphics remain almost parallel. Figures 38, 39 and 40 show the historical data for each DOW for the Architectural Annex, Shultz, and Turner parking lots.

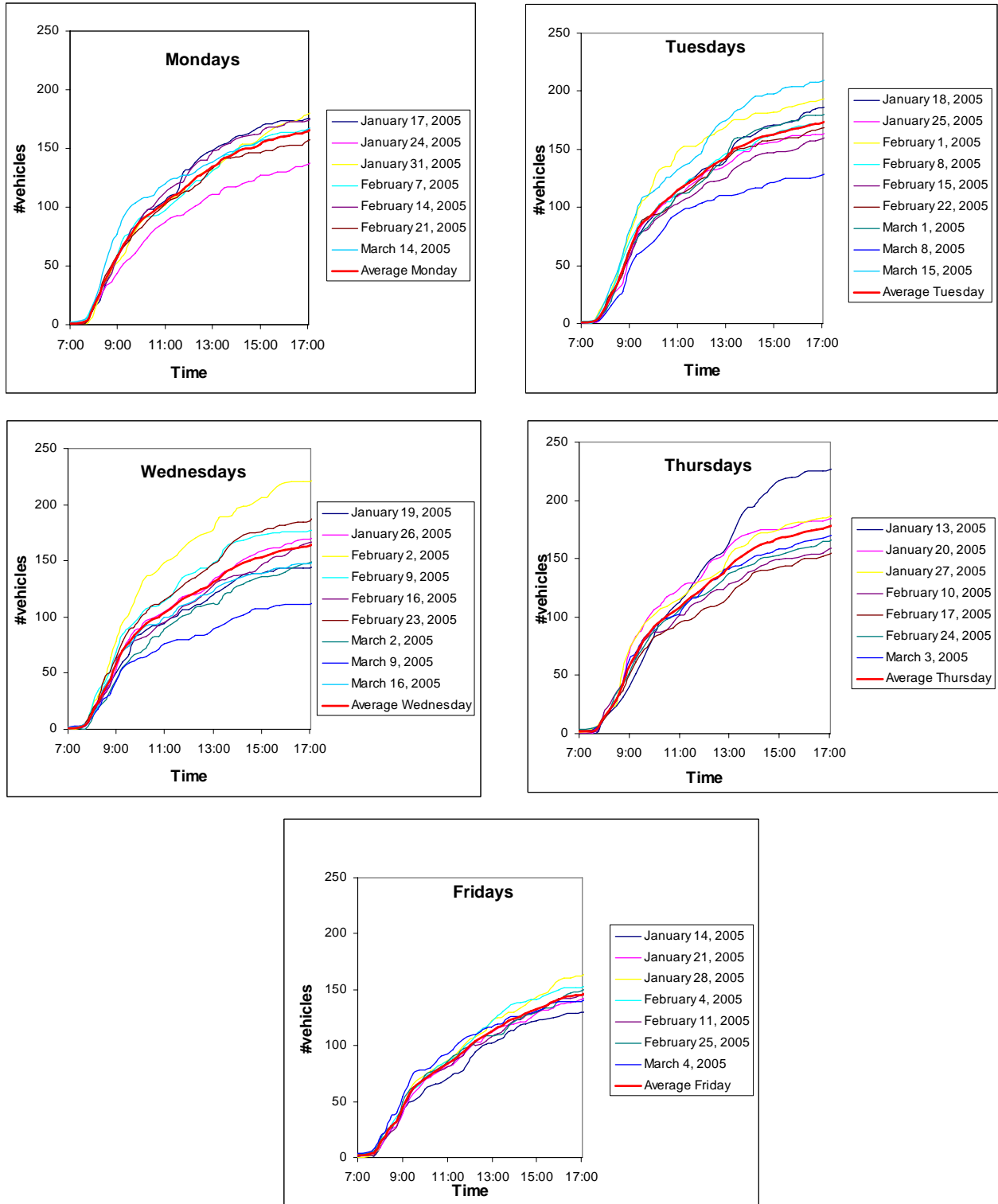


Figure 38 Historical Parking Data for the Architectural Annex Parking Lot

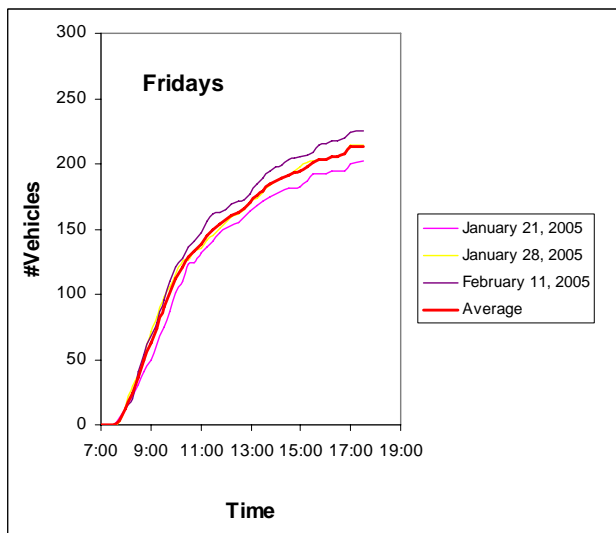
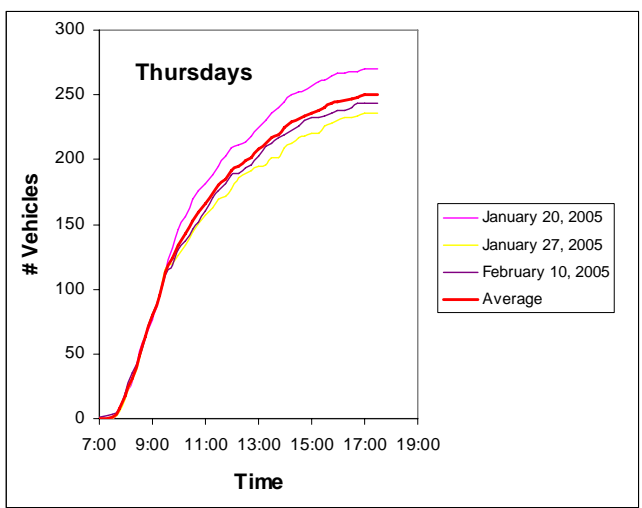
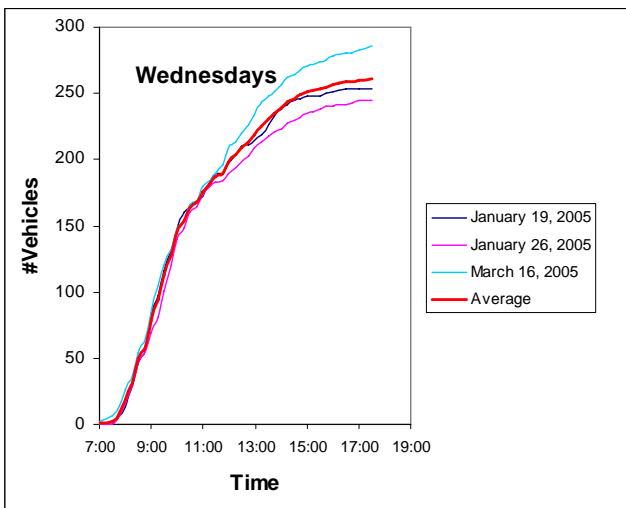
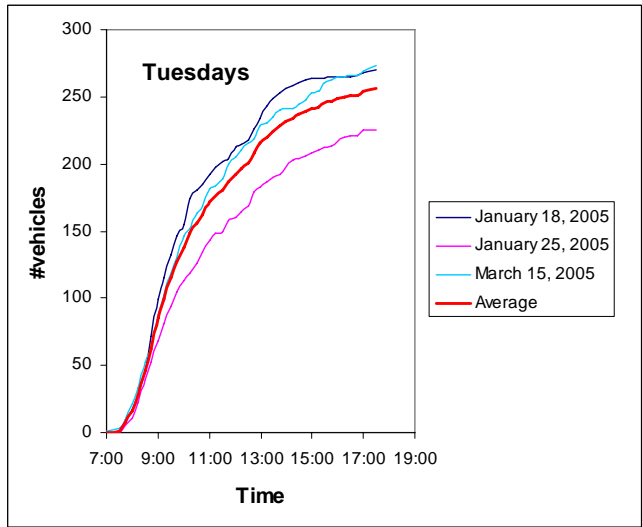
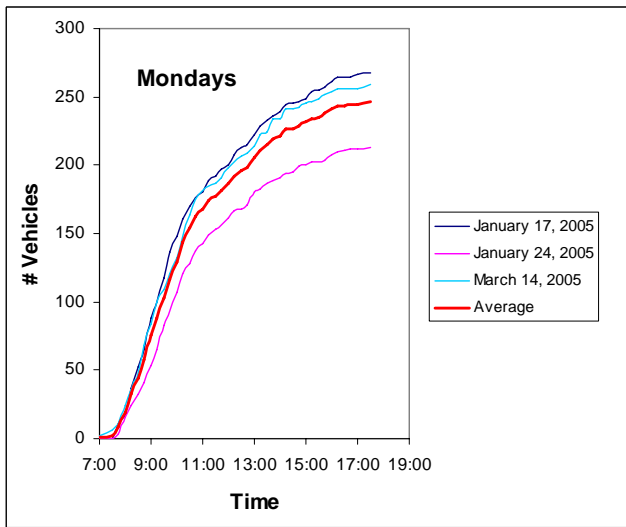


Figure 39 Historical Parking Data for the Shultz Parking Lot

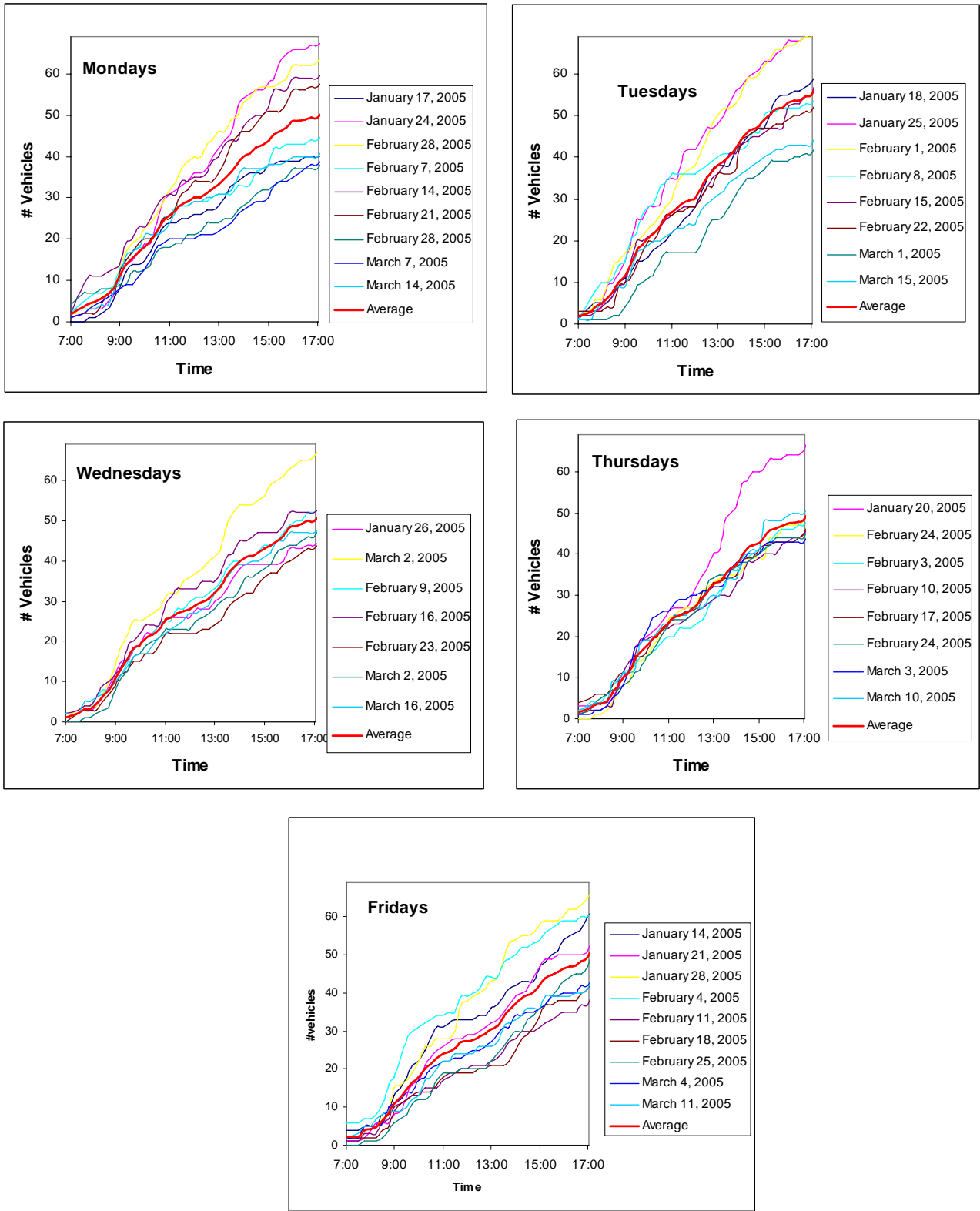


Figure 40 Historical Parking Data for the Turner Parking Lot

A statistical t-test was done to check if there were significant differences between the various DOWs and the average day. The results for each parking lot are shown in Tables 11, 12, and 13. The results show that in general Mondays, Tuesdays, Wednesdays, and Thursdays are not statistically different, and that there is statistically significant

difference between Fridays and typical days. These findings seem to demonstrate that the days selected to conduct the study (Tuesdays and Wednesdays) are a good representation of what happens during the rest of the week.

In the case of the Media parking lot, Fridays are statistically different with Tuesdays. For the Shultz parking lot, the Friday value is statistically different from Wednesdays, and for the Turner parking lot Fridays are not statistically different from other days of the week. For the three parking lots, the number of vehicles entering the parking lot for each day does not show any statistical difference with respect to the average day.

**Table 11: T-test for Historical Data Shultz Parking Lot**

	Monday	Tuesday	Wednesday	Thursday	Friday	Average
Monday	1	0.726796	0.541752721	0.87658658	0.110777	0.9440753
Tuesday		1	0.792264292	0.8451812	0.0539741	0.6750946
Wednesday			1	0.64693217	0.0305668	0.4970467
Thursday				1	0.080377	0.821573
Friday					1	0.1269699
Average						1

**Table 12: T-test for Historical Data Media Parking Lot**

	Monday	Tuesday	Wednesday	Thursday	Friday	Average
Monday	1	0.524449	0.95788374	0.583469	0.113543	0.948735
Tuesday		1	0.491213781	0.943255	0.02949	0.4871
Wednesday			1	0.549264	0.125836	0.990498
Thursday				1	0.040628	0.544521
Friday					1	0.132171
Average						1

**Table 13: T-test for Historical Data Turner Parking Lot**

	Monday	Tuesday	Wednesday	Thursday	Friday	Average
Monday	1	0.438426	0.880332277	0.675465	0.668014	0.973306
Tuesday		1	0.361502506	0.243578	0.236705	0.424062
Wednesday			1	0.790081	0.78368	0.907841
Thursday				1	0.995884	0.703157
Friday					1	0.696034
Average						1

### 5.5.1 Field Data Validation

The field data were validated by comparing to the historical data available for March 15 at the Architectural Annex parking lot. The University does not collect information regarding key code users, so only card and AVI users were validated. The results are shown in Figure 41 and 42, respectively. Slight differences are expected due to the fact that the entry time for the automated equipment is recorded when access is granted before the gate is open, while in the manual data the time is recorded when the vehicle passes the gate rounded to the nearest minute. The results clearly illustrate the validity of the field data collection effort.

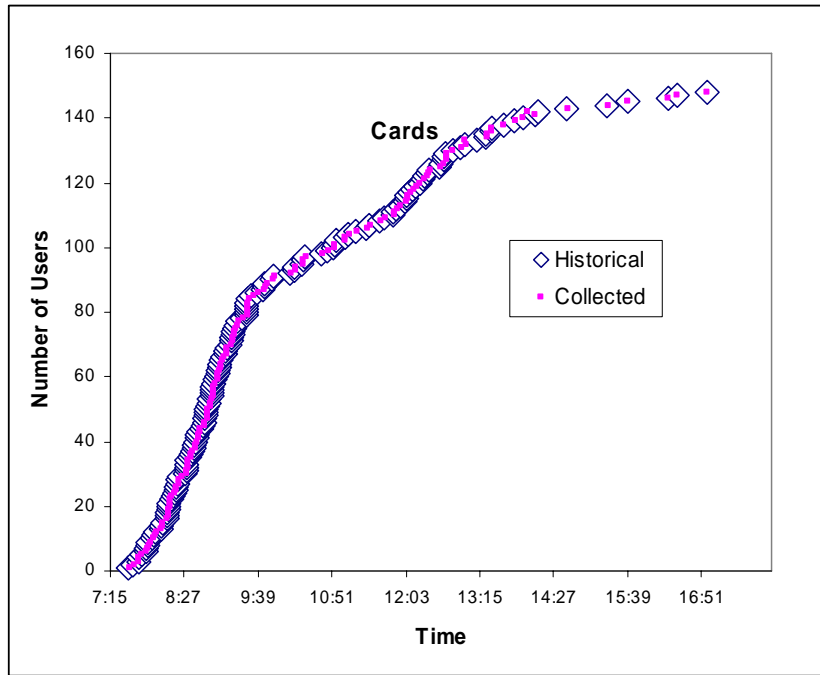


Figure 41: Comparison of Card User Historical and Collected data for March 15

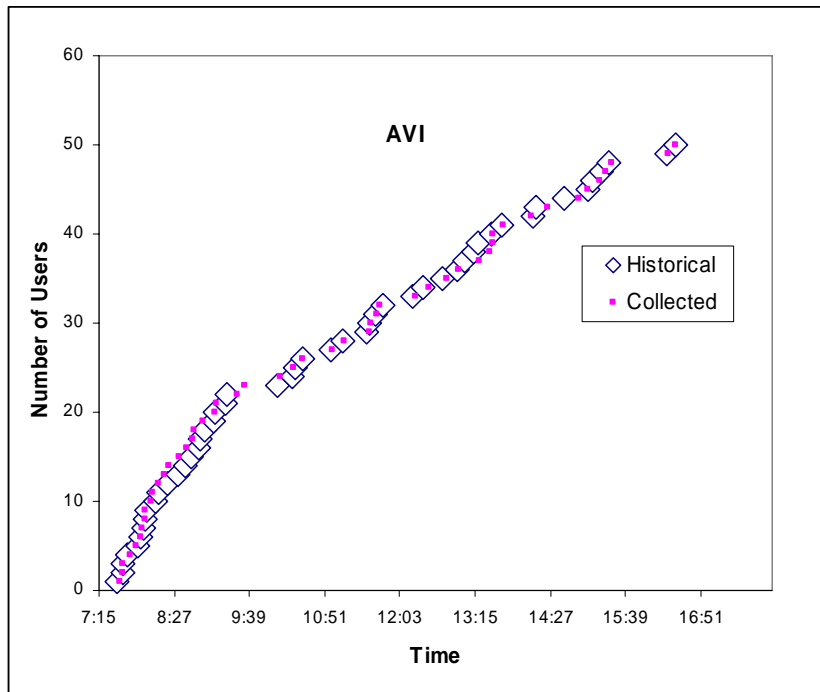


Figure 42: Comparison of AVI User Historical and Collected data for March 15

## 6. Modeling Results

Task 3 of this project was to construct a simulation model of the parking facilities that were analyzed. Traffic queuing models and the INTEGRATION traffic simulation model were applied and simulated for the local conditions

### 6.1 Queuing Model Analysis

Traffic queuing models are used to estimate vehicle delay and traffic queue lengths. Queuing models are derived from underlying assumptions such as arrival patterns, departure characteristics, and queue disciplines. Traffic arrival patterns, given an average vehicle arrival rate ( $\lambda$ ), can include: equal time intervals (derived from the assumption of uniform, deterministic arrivals) or exponentially distributed intervals (derived from the assumption of Poisson-distributed arrivals). Similar to the average arrival rate, given an average vehicle departure rate ( $\mu$  in vehicles per unit time), the assumption of a deterministic or exponential distribution of departure time is appropriate. The final necessary assumption is the queue discipline. Two options have been popularized in the development of queuing models: first-in first-out (FIFO), and last-in, first-out (LIFO) models. For most traffic oriented queues, the FIFO queuing discipline, indicating that the first vehicle to arrive is the first vehicle to depart, is the more appropriate of the two. Queuing models are often identified by three alphanumeric values. The first value gives the arrival rate assumption, the second value indicates the departure rate assumption, and the third value indicates the number of departure channels.

In order to model the parking lot entrance operations the M/M/1 Queuing Model was selected. This is a model that assumes exponentially distributed arrival times, exponentially distributed departure times; and a single departure channel (only one entry lane).

Under standard M/M/1 assumptions, it can be shown that the following queuing performance equations apply:

$$\bar{Q} = \frac{\rho^2}{1 - \rho} \quad (1)$$

$$\bar{w} = \frac{\lambda}{\mu(\mu - \lambda)} \quad (2)$$

$$\bar{t} = \frac{1}{\mu - \lambda} \quad (3)$$

Where  $\lambda$  is the average arrival rate in vehicles per unit time,  $\mu$  is the average departure rate in vehicles per unit time,  $\rho$  is the traffic intensity (computed as  $\lambda/\mu$ ),  $Q$  is the average length of queue in vehicles,  $w$  is the average waiting time in the queue, in unit time per vehicle,  $t$  is the average time spent in the system, in unit time per vehicle, and  $\mu$  is the saturation flow rate.

It should be noted that when the traffic intensity tends to be 1 (that is arrival rates approach the saturation flow rate), the expected number of vehicle in the system tends to infinite, because the queuing model assumes that the conditions exist indefinitely. In general the queue is not significant when the traffic intensity is less than 0.5. When the traffic intensity is more than 0.75, the average queue lengths tend to increase rapidly as shown in Figure 43.

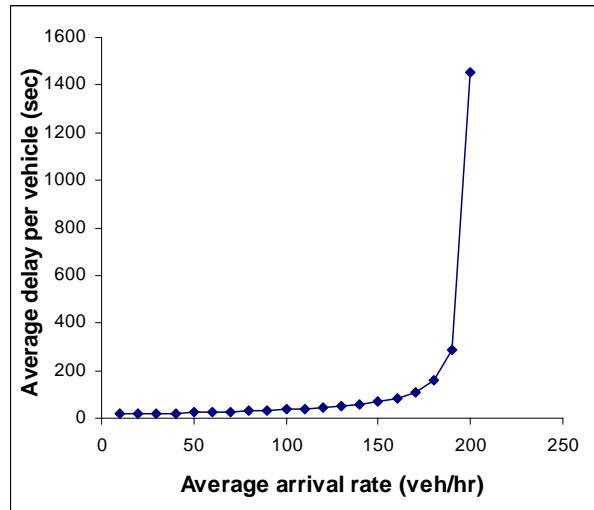


Figure 43: Average Delay per vehicle M/M/1 model

The service times that were observed in the field were utilized to compute the saturation flow rate for each technology ( $\mu$ ), as summarized in Table 14.

Table 14: Service Time and computed departure rates per Technology and Type of Equipment

Parking Lot	Cards		AVI		Code	
	Service Time (s)	$\mu$ (veh/h)	Service Time (s)	$\mu$ (veh/h)	Service Time (s)	$\mu$ (veh/h)
Arch. Annex	17.78	202	7.82	460	14.4	249
Shultz	16.73	215	7.16	502	11.06	325

Because the validity of the model depends of the traffic intensity model, Table 15 shows for each parking lot the maximum arrival rate. This maximum arrival rate was computed as the maximum arrival rate per 15 min, multiplied by 4.

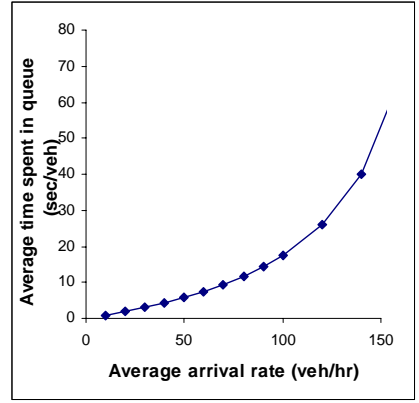
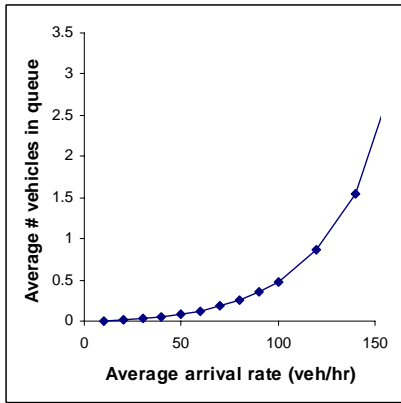
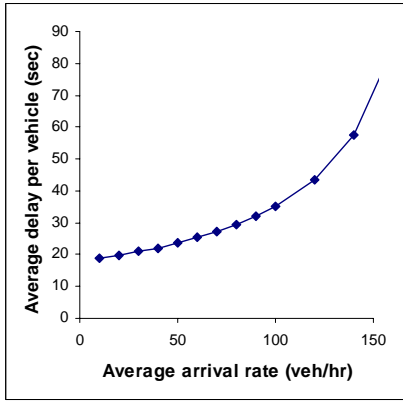
Table 15: Maximum Arrival Rate for Different Parking Lots

Architectural Annex		Shultz		Perry Street	
Day	$\lambda$ (veh/h)	Day	$\lambda$ (veh/h)	Day	$\lambda$ (veh/h)
3/15 Tuesday	108	3/22 Tuesday	104	4/12 Tuesday	460
4/06 Wednesday	80	3/29 Tuesday	132	4/13 Wednesday	548
		4/20 Wednesday	132		
		4/27 Wednesday	120		

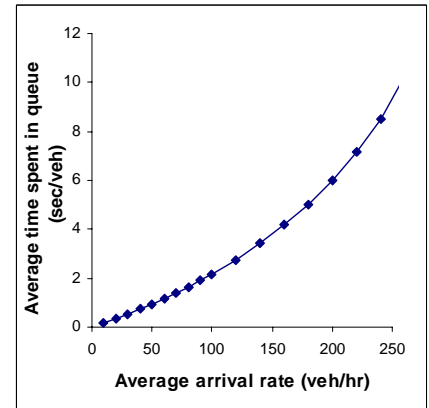
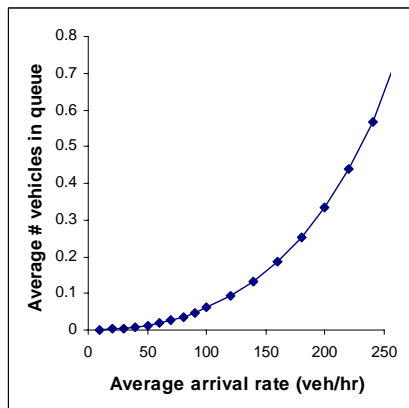
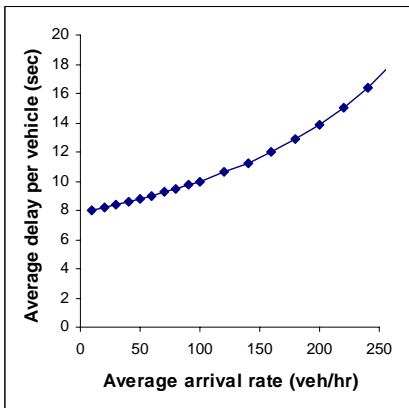
Figures 44 and 45 illustrate the variation in the average delay, number of vehicles in queue, and time spent in the system as a function of the average arrival rate. Figure 42 illustrates that for an arrival rate of 100 veh/h, the average time spent in the system is 35 s if all the users are card users. Alternatively, if all users have AVI technology, the average time spent per vehicle is reduced to 10 s, and if all the users punch a code the average time spent is 25 s. An arrival rate of 100 veh/h equals a  $\rho$  of 0.5, 0.22, and 0.4 for cards, AVI, and codes, respectively. A 50% increase in arrival rates (150 veh/h) increases these values of traffic intensity to 0.75, 0.32 and 0.6, respectively. In this case the average vehicle delay increases to almost 70 s for card users, which is equivalent to a 100 % increase. For an arrival rate of 180 veh/h and all vehicles are card users the average delay per vehicle increases to 160 s and the average queue length of the queue is 0.5 vehicles (for an arrival rate of 100 veh/h), 2 vehicles (for an arrival rate of 150 veh/h) and 7 vehicles (for an arrival rate of 180 veh/h). For values approaching saturation rate for the card reader (200 veh/h) the

average time spent in the system and the number of vehicles increases to more than 1400 s and 70 vehicles, respectively.

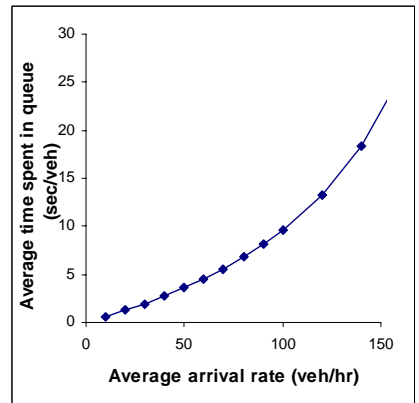
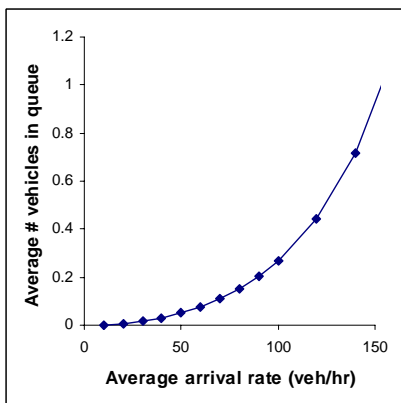
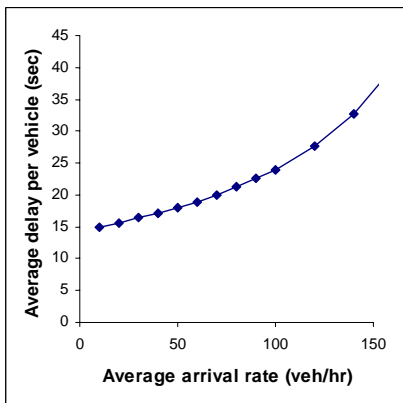
**a. Cards**



**b. AVI**

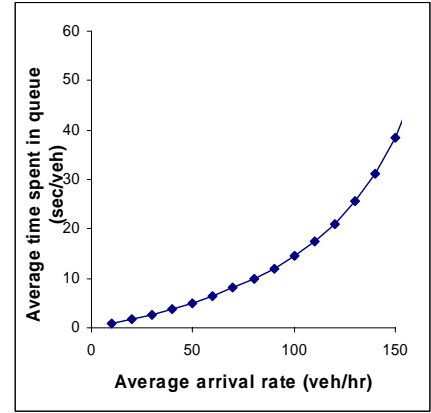
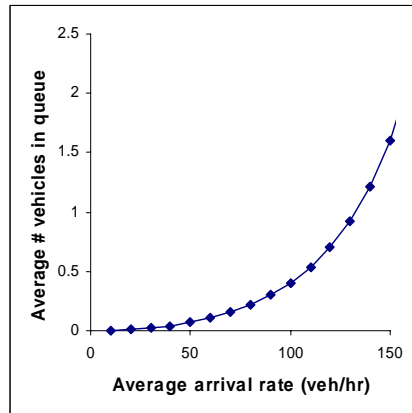
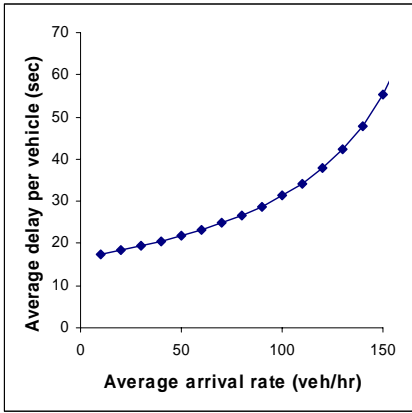


**c. Code**

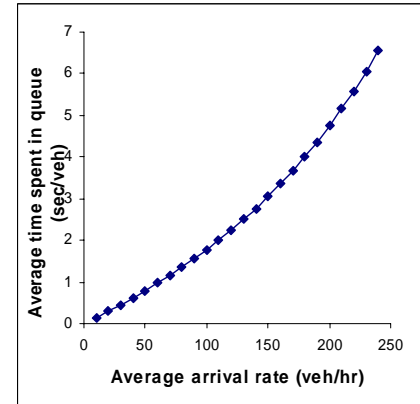
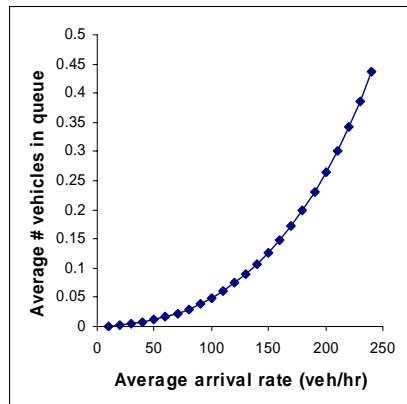
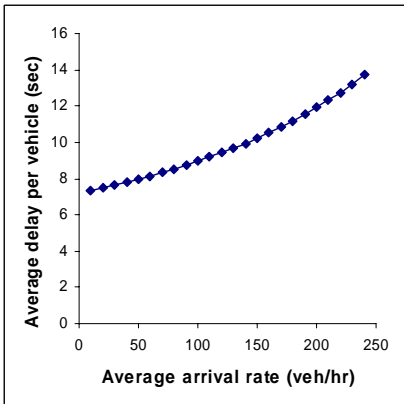


**Figure 44: MOE's for the different types of Technology for the Architectural Annex Parking Lot**

**a. Cards**



**b. AVI**



**c. Code**

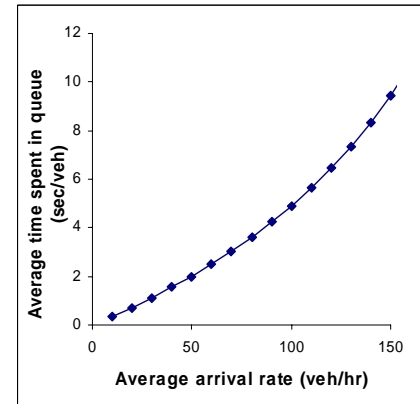
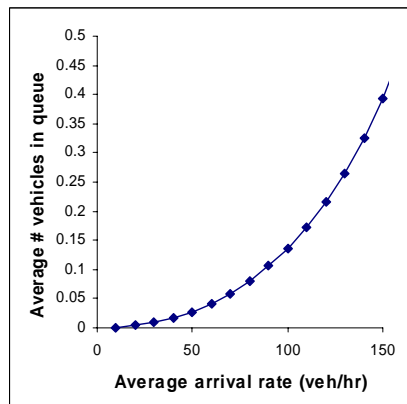
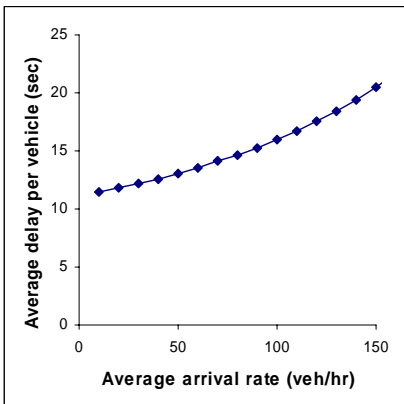


Figure 45: MOE's for Different Technologies at the Shultz Parking Lot

## 6.2 INTEGRATION Traffic Simulation Model

In order to model the different parking lot equipment technologies, the INTEGRATION microscopic traffic assignment and simulation model was selected for the study. The INTEGRATION model has been in continuous development over the past 20 years and has been the subject of numerous validations. It was conceived as an integrated simulation and traffic assignment model and performs traffic simulations by tracking the movement of individual vehicles every 1/10th of a second. This allows detailed analyses of lane-changing movements and shock wave propagations. It also permits considerable flexibility in representing spatial and temporal variations in traffic conditions. In addition to estimating stops and delays, the model can also estimate the fuel consumed by individual vehicles, as well as the emissions. The INTEGRATION model computes the speed of vehicles each deci-second.

The INTEGRATION model estimates vehicle delay every deci-second as the difference in travel time between travel at the vehicle's instantaneous speed and travel at free-flow speed. This model has been validated against analytical time-dependent queuing models, shockwave analysis, the Canadian Capacity Guide, Highway Capacity Manual, and the Australian Capacity Guide procedures,

Each time a vehicle decelerates, the drop in speed is recorded as a partial stop. The sum of these partial stops is also recorded. This sum, in turn, provides a very accurate explicit estimate of the total number of stops that are incurred by a vehicle.

It is noteworthy that INTEGRATION will often report that a vehicle has experienced more than one complete stop along a link. Multiple stops arise from the fact that a vehicle may have to stop several times before ultimately clearing the link stop line. This finding, while seldom recorded by or even permitted within macroscopic models, is a common observation within actual field data for links on which considerable over-saturation queues exist.

The purpose of this simulation was to determine the delay incurred by the vehicles with the different technologies at different arrival rates. The three technologies were modeled independently and simultaneously. The network was loaded for one hour with the different arrival rates, and the model was simulated for three hours to guarantee that all vehicles cleared the network.

Figure 46 shows the total delay for the different technologies as a function of the arrival rate. As expected the technology with the highest service time, in this case the card reader, incurs more delay, especially with rates above 200 veh/h. For an arrival rate of 100 veh/h, the average delay per vehicle is 19, 6.3 and 15.5 for card reader, AVI, and key code technology, respectively. Alternatively, for an arrival rate of 200 veh/h (saturation flow rate for card readers) card reader vehicles incur an average delay of 20 s, a value much more realistic than what was obtained using queuing models.

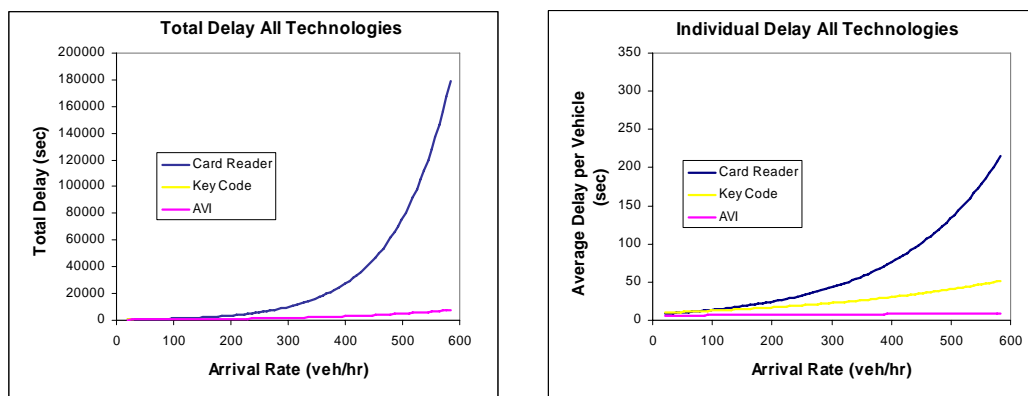


Figure 46: Delay for the Different Technologies

Figure 47 shows the total number of vehicle stops and the average number of stops for each vehicle for the different technologies. While the number of stops remains relatively constant for the AVI reader, they increase rapidly after the saturation rate for the card readers and the key code technologies is reached. Figure 48 shows the total, acceleration/deceleration delay, stopped delay, and average delay per vehicle for the different technologies.

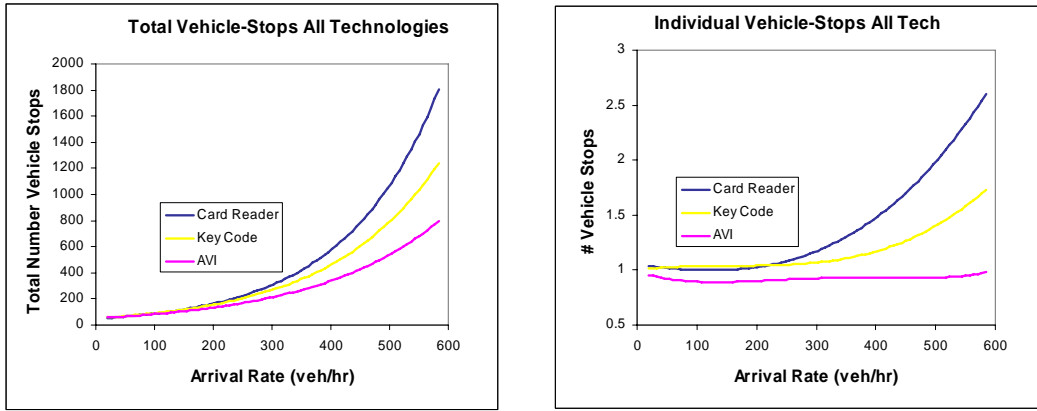


Figure 47: Number of Stops for the Different Technologies

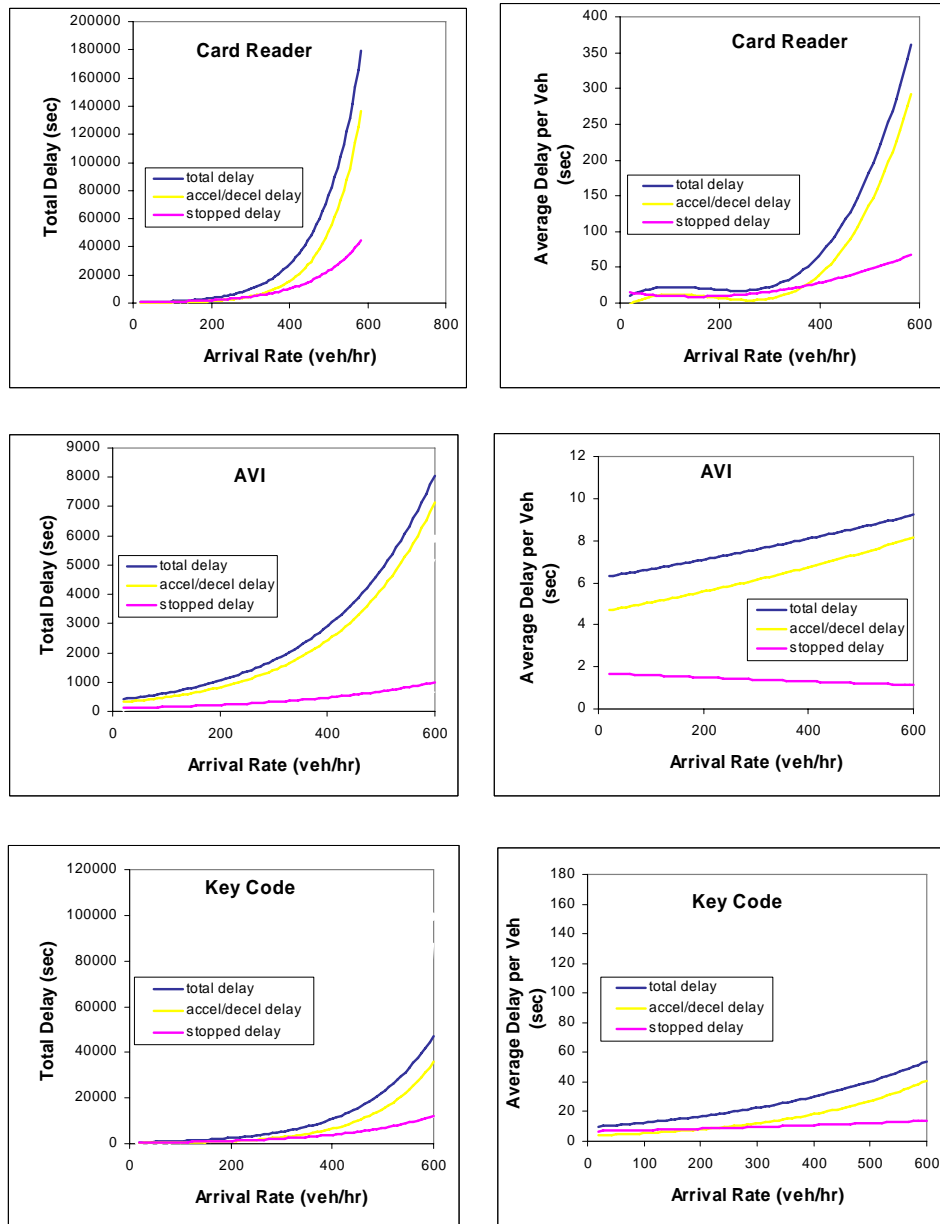


Figure 48: Total Delay and Average Delay per Vehicle for the different technologies

For an arrival rates in excess of 200 veh/h the total delay increases dramatically for card readers and significantly for key code users. At an arrival rate of 400 veh/h the average delay per vehicle increases to 45 s for card users and 23 s for code users. Taking into account the arrival rates of the Perry Street parking lot, installing card users or card readers will only result in a major disruption of the traffic facility. Even the use of AVI readers needs to be carefully considered, because at specific times they will also create significant delays.

## 7. Conclusions

The data collection combination of videotaping and manually collecting license plate data proved to be successful for this study.

For the Shultz parking lot the field data collection effort demonstrates that an average of 30 vehicles are present prior to the gate operation, more than 400 vehicles enter the parking lot by 4:00 p.m., and more than 200 vehicles remain in the parking lot after 4:00 p.m. The parking lot effective capacity is reached around 10:30 a.m. and the parking lot operates beyond the effective capacity for 4 hr during a typical weekday. For most of days, the arrivals peak around 9:00 a.m., with a maximum arrival rate of 30 veh/15 min. The average parking lot stay is 4 hr and 45 minutes. The percentage of each mode of entry are 56% to 60% of card users, 29% to 30% of code users, and 9% to 15% of AVI users. The percentage of cards that are read in the first try varies from 70% to 80%. The users that are required to swipe the card twice are around 15% and those required to try three or more times varies between 8% and 13%. The results demonstrated no statistical difference between Tuesdays and Wednesdays in terms of arrival rates and parking stay. The average service time is 16.7 s for the card users, 11 s for the code users, and 7.8 s for the vehicles that are equipped with AVI technology. When the cards users are analyzed in more detailed the service times are 12.7 for the users that only swipe the card one time, 17.5, and 27.6 s for the vehicles that swipe the card two and three times, respectively.

In the case of the Architectural Annex parking lot, the number of vehicles present in the parking lot prior to the gate operation is in the neighborhood of 30 vehicles. As expected, very few vehicles exit before noon. An average of 50 vehicles enters and exits the parking lot at 12:00 p.m. At 4:00 p.m. on average 120 vehicles remain in the parking lot. Tuesdays reach occupancy levels of 100% occupancy while Wednesdays have occupancies of 85% the parking lot capacity. The maximum occupancy is reached on both days around 11:00 a.m. The average parking duration is 3 hours and 45 minutes. The maximum arrival frequency for both days is around 9:00 a.m. and decreases noticeable after 2:00 p.m. Card readers are the most popular method with a percentage of 50%, followed by 30% of code users, and 17% to 19% of AVI readers. The percentage of cards that are read in the first try is around 70%. These values are very similar to the efficiency in Shultz parking lot. The users that are required to swipe the card twice are around 24% and those required to try three or more times are approximately 5% of the total card users. The average service time is 17.8 s for card users, 14.4 s for the code users, and 7.2 s for the vehicles that are equipped with AVI technology. The card users that are required to swipe one time have a service time of 14.5 s, while users that swipe two and three times have service times of 24.5 and 30.2 s, respectively. A statistical analysis of the vehicle arrivals demonstrated differences between Tuesdays and Wednesdays at a level of significance of 95%.

Approximately 1,200 vehicles enter the Perry Street parking lot during the data collection hours on both days (Tuesdays and Wednesdays). The number of vehicles present in the parking lot at 7:15 a.m. is approximately 30 for Tuesdays and 20 for Wednesdays. Until 8:30 a.m., very few vehicles exit the parking lot. Not only is effective capacity reached very quickly both days around 9:00 a.m. and maintained until 4:00 p.m., but values of total capacity of 100% and larger are reached several times during the day. This situation indicates cars that enter the parking lot even when the parking lot is full in search of a parking space. The maximum arrival rate for Tuesday is 137 veh/15 min. at 8:00 a.m., and for Wednesday is 115 veh/15 min. at 9:00 a.m. More than 20% of vehicles stay less than 30 minutes in the parking lot.

When the queuing model is for an arrival rate of 100 veh/h, the average time spent in the system is 35 s if all the users are card users. Alternatively, if all users have AVI technology, the average time spent per vehicle is reduced to 10 s, and if all the users punch a code the average time spent is 25 s. An arrival rate of 100 veh/h equals a  $\rho$  of 0.5, 0.22, and 0.4 for cards, AVI, and codes, respectively. A 50% increase in arrival rates (150 veh/h) increases these values of traffic intensity to 0.75, 0.32 and 0.6, respectively. In this case the average vehicle delay increases to almost 70 s for card users, which is equivalent to a 100 % increase. For an arrival rate of 180 veh/h and all vehicles are card users the average delay per vehicle increases to 160 s and the average queue length of the queue is 0.5 vehicles (for an arrival rate of 100 veh/h), 2 vehicles (for an arrival rate of 150 veh/h) and 7 vehicles (for an arrival rate of 180 veh/h). For values

approaching saturation rate for the card reader (200 veh/h) the average time spent in the system and the number of vehicles increases to more than 1400 s and 70 vehicles, respectively.

Simulation using INTEGRATION showed that for an arrival rate of 100 veh/h, the average delay per vehicle is 19, 6.3 and 15.5 for card reader, AVI, and key code technology, respectively. Alternatively, for an arrival rate of 200 veh/h (saturation flow rate for card readers) card reader vehicles incur an average delay of 20 s, a value much more realistic than what was obtained using queuing models.

The number of stops remains relatively constant for the AVI reader, they increase rapidly after the saturation rate for the card readers and the key code technologies is reached. For an arrival rates in excess of 200 veh/h the total delay increases dramatically for card readers and significantly for key code users. At an arrival rate of 400 veh/h the average delay per vehicle increases to 45 s for card users and 23 s for code users.

Taking into account the arrival rates of the Perry Street parking lot, installing card users or card readers will only result in a major disruption of the traffic facility. Even the use of AVI readers needs to be carefully considered, because at specific times they will also create significant delays.