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QUANTITATIVE ANALYSIS FOR INSTALLATION ACCESS PLANNING AT NAVAL BASE SAN DIEGO

by

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September 2012

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This thesis explores how the number of operating access control points (ACPs) and their configuration of lanes and staffing affect vehicular flow into Naval Base San Diego (NBSD). We examine this flow during normal and non-normal operations, such as heightened force protection conditions. Our research focuses on factors that affect throughput as well as managing the costs associated with different staffing configurations. These factors include the force protection condition, vehicle type, number of passengers in the vehicle, and the type of credentials used. We study the importance of these factors using statistical techniques to analyze the data collected during site visits to NBSD. We also formulate and analyze queuing models of the ACPs to capture the impact of staffing configurations at the ACPs. Our analysis provides insight into how best to increase, or maintain, the throughput with current configurations and requirements. The data collected and analyzed in this thesis provide a solid foundation for future research and can easily be adapted to other Department of Defense installations where similar congestion is prevalent.

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QUANTITATIVE ANALYSIS FOR INSTALLATION ACCESS PLANNING AT NAVAL BASE SAN DIEGO

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ABSTRACT

This thesis explores how the number of operating access control points (ACPs) and their configuration of lanes and staffing affect vehicular flow into Naval Base San Diego (NBSD). We examine this flow during normal and non-normal operations, such as heightened force protection conditions. Our research focuses on factors that affect throughput as well as managing the costs associated with different staffing configurations. These factors include the force protection condition, vehicle type, number of passengers in the vehicle, and the type of credentials used. We study the importance of these factors using statistical techniques to analyze the data collected during site visits to NBSD. We also formulate and analyze queuing models of the ACPs to capture the impact of staffing configurations at the ACPs. Our analysis provides insight into how best to increase, or maintain, the throughput with current configurations and requirements. The data collected and analyzed in this thesis provide a solid foundation for future research and can easily be adapted to other Department of Defense installations where similar congestion is prevalent.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACP	Access Control Point
AOR	Area of Responsibility
CAC	Common Access Card
CDF	Cumulative Distribution Function
CNIC	Commander Naval Installation Command
CNRSW	Commander Naval Region Southwest
DoD	Department of Defense
FPCON	Force Protection Condition
ICO	Installation Commanding Officer
IID	Independent and Identically Distributed
IQR	Inter-Quartile Range
MEP	Mission Essential Personnel
MSDDCTEA	Military Surface Deployment and Distribution Command – Transportation Engineering Agency
NBSD	Naval Base San Diego
NPS	Naval Postgraduate School
OPORD	Operation Order
SECO	Security Officer
SCCS	Solid Curtain/Citadel Shield Exercise
PLANORD	Planning Order
PMF	Probability Mass Function
UFC	Unified Facilities Criteria
USFF	United States Fleet Forces
USNORTHCOM	United States Northern Command
VPHPL	Vehicles per Hour per Lane

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EXECUTIVE SUMMARY

This thesis examines the process of efficiently bringing large quantities of vehicles onto a secure military installation during the morning commute hours. During this peak commute time, there can be significant congestion that spills onto surrounding roadways. Congestion creates an opportunity for terrorists as many potential targets sit vulnerable in traffic. Congestion also generates economic costs both directly for the military and indirectly for the surrounding communities. Personnel stuck in congestion cannot perform their duties and if the congestion impacts the surrounding roadways then local businesses may suffer. Even small increases in the throughput rate of vehicles onto an instillation can lead to a significant reduction of congestion so this thesis examines an important topic. While this problem applies to many military installations around the world, we specifically focus on installation access at Naval Base San Diego (NBSD).

This thesis provides initial analysis to Commander Navy Region Southwest (CNRSW) as it examines traffic patterns in and around NBSD's installation access points to determine what measures most effectively decrease congestion during peak commuting hours without compromising the integrity of the base. In the first step of our analysis, we toured operational access control points (ACPs) at NBSD and spoke with the current Security Officer (SECO) to gain a better understanding of the current operations and the key factors driving throughput. These factors include the number of lanes at each ACP and the number of sentries assigned to each ACP to process vehicles onto the base. The SECO often assigns multiple sentries stacked in tandem in the same lane during the morning commute to increase throughput. While many other factors impact the throughput, we only focus on the factors that the SECO can change on a daily basis: the number of ACPs and lanes to open and the sentry configurations in each lane. Following this initial visit we formulated a mathematical model to characterize the throughput of vehicles arriving at NBSD. The key component of this model is the time it takes sentries to vet and process vehicles, and thus on a subsequent visit to NBSD we focus our data collection effort on these processing times.

We performed various statistical analyses on the data we collected during our site visits to determine which factors influence the vehicle processing times. These include the type of vehicle, the type of credential presented, the number of individuals in a vehicle, and the force protection condition (FPCON). Most of the relationships confirm our intuition. For example, the more individuals in the vehicle, the longer the processing time. Similarly, it takes longer for sentries to process motorcycles than to process privately owned cars.

Our empirical analysis confirms the experience of the SECO: having multiple sentries in tandem has diminishing returns. That is, putting two sentries in tandem in the same lane does not double the throughput in that lane. In fact, we observe that the actual throughputs are significantly lower than the published standards. The implication of this is that if these standards are used to determine staffing levels, then NBSD is certain to experience significant congestion during peak commuting hours.

We uncovered one additional surprising result in our empirical analysis: the average processing time decreased during periods of heightened FPCON. One possible explanation for this is that both drivers and sentries are more alert and efficient during periods of heightened FPCON.

Based on the number of available sentries, we recommend the number and staffing configuration of ACPs to maximize throughput. In the case where opening an additional ACP requires a fixed overhead of sentries to provide additional security, the SECO should maximize throughput by stacking sentries in tandem rather than opening additional ACPs.

Our analysis considers congestion solely from the perspective of service times and under the assumption that there is consistent demand for service at each ACP such that sentries are never idle. As a result, our estimates of throughput capability are apt to be overestimates, meaning that congestion could be even worse than projected. In order to get a more complete understanding of the way in which fluctuations in vehicle arrivals affect congestion, future work should focus on collecting data associated with vehicle commuting and arrival patterns.

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First and foremost, it is only through God's grace that I am able to do anything.

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I. INTRODUCTION

Solid Curtain-Citadel Shield is an annual exercise conducted by the United States Navy "designed to enhance the training and readiness of Navy Security Forces to respond to threats to installations and units" (Naval Base San Diego, 2012). Following the February 21–25, 2011 exercise, the United States Fleet Forces Command along with Commander Naval Installation Command (USFF/CNIC) issued a joint Mission Essential Personnel (MEP) Planning Order (PLANORD) to all installations in the United States Northern Command (USNORTHCOM) area of responsibility (AOR). In November of 2011, Admiral John Harvey Jr., then the Commander of USFF, sent an e-mail to his subordinates highlighting the purpose of the MEP PLANORD. He highlighted the importance of alleviating the "extreme traffic congestion, long-lines of vehicles at our installation gates (creating a significant target at exactly the time we're trying to minimize targets), and a marked negative impact on our local communities." USFF and CNIC directed each Installation Commanding Officer (ICO) to develop an installation access plan based on the inputs from all tenant commands. In response to this directive, Commander Navy Region Southwest (CNRSW) and Naval Base San Diego (NBSD) also began to look at traffic patterns in and around their installation gates in order to decrease gate congestion during peak commuting hours without compromising the integrity of the base. Specifically, CNRSW security personnel need to understand the key factors driving congestion and how to reduce it most effectively without compromising security protocols. This thesis proceeds in support of this objective.

A. BASE ACCESS OPERATIONS

In order to analyze congestion, we need to understand the process by which vehicles physically enter a secure military installation. In this section, we describe the different components of this process.

1. Access Control Point Design

Installation access control points (ACPs) at military installations are the designated areas where personnel enter installations via foot or by vehicle. ACPs are

comprised of three basic areas; the approach zone, the access control zone, and the response zone. A Department of Defense (DoD) report entitled "Unified Facilities Criteria (UFC) Security Engineering: Entry Control Facilities/Access Control Points" defines the vocabulary used to describe ACPs (UFC 4-022-01, 2005). The *approach zone* is where vehicles leave city streets, decrease their speed, and sort themselves prior to entering onto DoD-controlled land. The approach zone includes lanes going into and lanes coming out of the installation. These lanes may contain vehicle barriers to control the speed and the flow of incoming traffic. The size of the approach zone and the number of available lanes into the installation determine the number of vehicles that can wait to enter the installation before a backlog of vehicles begins to spill onto city streets. The *access control zone* is where security personnel known as *sentries* conduct identification procedures and restrict entrance to individuals who are authorized to enter. The *response zone* is the last area where sentries can respond to a crisis. In the event that a sentry inside the access control zone is unable to handle a threat, the response zone allows additional security forces the time and space to respond. Responses range in scope from turning vehicles away, to the use of kinetic force to stop vehicles intent on entering without permission. Figure 1 illustrates a generic overhead view of each of the zones that together comprise an ACP.
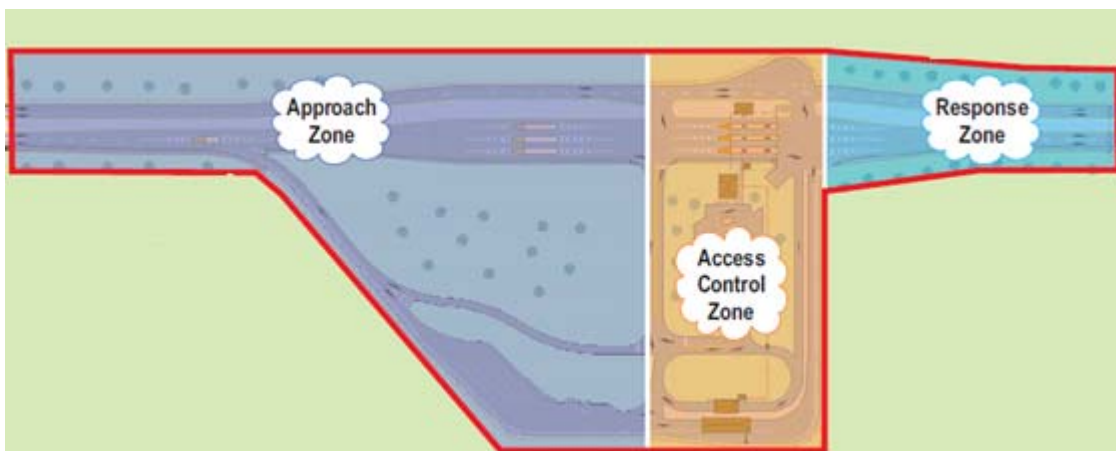
Figure 1.   Illustration of a Common Access Control Point, after MSDDCTEA 2009

2. Sentries

Sentries at ACPs check whether each vehicle attempting to access the installation is authorized to enter. Staffing of ACPs is primarily a responsibility of the installation's Force Protection Department. This department's primary mission is to "provide physical security for all property and material within the jurisdiction of the Commanding Officer" (Naval Base San Diego, 2012). The department accomplishes a portion of its mission by providing physical security at the ACPs. The Force Protection Department typically does not have enough personnel to staff all gates at all hours. Instead, they typically close some ACPs during off-peak hours and also rely on augmented personnel supplied by tenant commands within the installation. Augmented personnel are loaned from their commands to the Force Protection Department on a rotating schedule for a few hours, usually during the morning rush hours, to perform the duties of a sentry. Augmented personnel allow more ACPs to open during peak hours, but at a cost of pulling personnel from their primary jobs. In this thesis, we do not distinguish between sentries from the Force Protection Department and those augmented personnel from other commands.

As written in the Unified Facilities Criteria (UFC) 4-022-01, sentries must conduct identification procedures for everyone attempting to access the installation. The standard duties of sentries within the access control zone of an ACP include verification of vehicle decals and personnel credentials, general surveillance of the vehicle and its contents, and random inspections of vehicles and their occupants. During heightened force protection conditions (FPCON), sentries may have additional responsibilities and conduct more strenuous verifications procedures. Force protection conditions are set in response to current threats towards military facilities and personnel. The time to clear, or *process,* a vehicle is critical in determining congestion. In general, this time depends on several factors such as verification requirements, the current FPCON, and the individual sentry and vehicle.

The type of credentials that a person must provide to a sentry depends upon the status of the individual. Military and DoD civilian personnel are each issued a Common Access Card (CAC). CACs are the most common type of credential. Contractors and personnel who do some of their work on the installation may obtain a RAPIDGate

credential (Naval Base San Diego, 2012). These special credentials streamline the access procedures for contractors and sentries. When a contractor arrives at a gate with a RAPIDGate credential, a sentry inspects the card with a handheld scanner in order to process the contractor. This is faster than having to validate a contractor's unique ID with paperwork from the Pass and Decal office, but in general it still takes more time to process a RAPIDGate credential than a CAC credential. Individuals in rental cars or newly purchased cars without license plates also have to provide additional paperwork to the sentry.

3. Processing Lanes

Each access control zone consists of one or more parallel processing *lanes* where the sentries and vehicles interact. The number of processing lanes within the access control zone is not necessarily equal to the number of input lanes in the approach zone. It is possible that one input lane in the approach zone can split into multiple processing lanes in the access control zone. It is much less common for there to be fewer processing lanes than input lanes due to the merging of input lanes. As each vehicle approaches, its driver must stop and present his credentials to the sentry. Once a vehicle has been cleared or processed by the sentry, it may proceed onto the installation. In addition to providing credentials, the operator of a vehicle must maintain the vehicle's registration, pass all safety inspections, and follow all safety laws. In the event a sentry observes any violations, he can deny entrance to the installation.

A lane can have more than one sentry assigned to it. When the number of vehicles attempting to access an installation is low, a single sentry will often suffice to process incoming vehicles in a timely manner. When demand for installation access increases, a second sentry may process vehicles in the same lane, to increase the processing rate. This addition of a second, or in some cases third, sentry is called *tandem processin*g. The ability to employ tandem processing depends not only on having the available sentries, but also on the physical layout to support having more than one vehicle inside the access control zone. If the FPCON increases, the staffing of lanes can be restricted. The restrictions specify the number of sentries required at an ACP, at a lane,

and the equipment they must carry. Additional equipment requirements, such as specific weapons or personal protective equipment, can reduce the number of sentries and lanes available due to training and qualification requirements, and availability of equipment. Operation Order (OPORD) 3300-11 delineates these requirements.

4.   Measuring ACP Performance

We use the *throughput* of vehicles per hour to measure the efficiency of an ACP its and lane operations. We measure throughput in terms of the average number of vehicles that can be processed and gain access to the base during some time period. We use one hour as our standard time period. The throughput of a lane depends on the *demand*, or the number of vehicles attempting to gain access to the installation, and the staffing configuration of sentries, which will depend upon the current FPCON. The Army Military Surface Deployment and Distribution Command Transportation Engineering Agency's (MSDDCTEA) 2009 study provides baseline throughput numbers under different FPCON levels. Table 1 shows that two sentries in tandem do not necessarily double the throughput over a single sentry processing lane. According to this table, tandem processing will increase throughput from 300–450 vehicles per hour per lane (VPHPL) with one sentry to 400–600 VPHPL with tandem (two sentries per lane) processing. Taking the midpoint of both the single and tandem processing numbers, this suggests an expected 33% increase in vehicular flow with tandem processing. In this thesis, we examine the efficiency of tandem sentries and provide mathematical reasoning for the apparent diminishing rate of throughput.

FPCON	Manual Checks	
	Single Lane Checks	Tandem Lane Checks
Alpha	800 to 1,400 VPHPL	No Data Available
Bravo, Bravo+, and Charlie	300 to 450 VPHPL	400 to 600 VPHPL
Delta	20 to 120 VPHPL	Not Allowed

Table 1.   Vehicle Throughput per Hour per Lane at Standard ACPs, after MSDDCTEA 2009

5.   Configuration and Operation of ACPs

The ultimate responsibility for the operations of ACPs belongs to the installation Security Officer (SECO). As the head of the Force Protection Department, the SECO authorizes opening and closing of ACPs, and determines staffing configurations at the ACPs. The USFF Anti-Terrorism Operation Order (OPORD) 3300-11 stipulates the minimum requirements. The SECO has the ability to increase staffing level and open extra ACPs to help alleviate congestion at his or her own discretion, but cannot authorize any relaxation of the requirements.

In this thesis, we primarily focus on the decisions available to the SECO each day. These include the number of open ACPs and the staffing configuration of sentries at each ACP. The SECO has much less control over other factors that impact congestion and throughput. Examples include the FPCON levels, extreme weather, where people decide to live, and preexisting infrastructure. In the long term, NBSD could build new ACPs, expand existing ACPs, or reroute traffic outside the installation (probably in conjunction with the city of San Diego). These measures would incur large overhead costs of time and money and we do not consider them in our analysis.

B.   NAVAL BASE SAN DIEGO

Naval Base San Diego consists of over 2,000 land acres and 326 acres of water. It houses approximately 180 shore-based commands and more than 60 Afloat Commands.

The base is populated by roughly 40,000 personnel, including military service members, DoD civilians, and contractors that work within the gates on any given day. Of that 40,000, approximately 4,000 reside on the installation. On weekdays, between 0500 and 0800, peak demands for bringing personnel onto the installation typically exceed the capacity to do so. During these peak arrival times (i.e., typical morning commute times), ACPs quickly fill to capacity and create backups on city streets. On average, 30,000 vehicles transit through NBSD's ACPs each day (Naval Base San Diego, 2012).

The base is divided into two distinct areas, a "wet" side and "dry" side, by Harbor Drive. Personnel can access the waterfront side, or "wet" side, of NBSD via one of six ACPs. The personnel at NBSD refer to these ACPs as "gates" and designate each with a number. Each ACP has different physical characteristics both in the number of lanes and in the layout of the approach zones. Table 2 lists the number of in and out lanes in the approach zone of each ACP and the number of parallel processing lanes in the access control zone. Each of the ACPs at NBSD has a traffic signal at the intersection of the approach zone and the city street to control the flow into the approach zone. The installation does not own these signals; therefore NBSD personnel cannot manipulate these signals in real time to control arrivals into the approach zone. The approach zones for ACPs can buffer anywhere from two to more than ten vehicles before traffic backs up onto city streets. Figure 2 is an overhead representation of NBSD.

Access Control Point	Gate 2	Gate 6	Gate 6A*	Gate 7**	Gate 9	Gate 13
Lanes In	1	2	1	2	3	2
Lanes Out	1	2	-	2	3	2
Processing Lanes	1	3	1	Not Available	3 or 4***	2

* For Commercial Deliveries Only
** Under Construction during research
*** Can use contraflow

Table 2.   Number of Lanes Available for Each ACP at NBSD
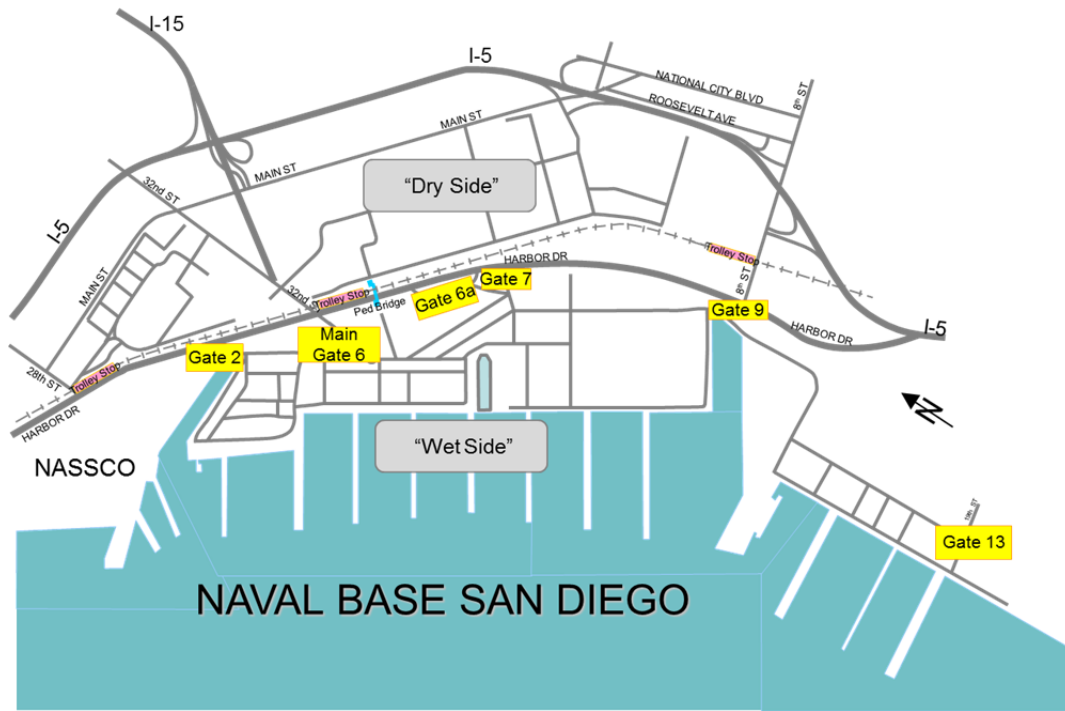
Figure 2.   Overhead of Naval Base San Diego, after NBSD Website 2012

NBSD regularly collects data on installation access at different times throughout the year. During a given collection period, they collect, in hourly increments, the number of vehicles that enter the installation at each ACP over the course of one designated week. In some instances, they also record the number of ships in port during their data collection periods. NBSD provided eight weeks of throughput data ranging from April of 2010 to September of 2011. The average throughput between Monday and Friday for the six o'clock hour at ACP 6 was 1,265 vehicles with a standard deviation of 381 vehicles. The maximum number of vehicles that entered through ACP 6 in a single hour was 2,296 vehicles, while the minimum number through was 97 vehicles. As a more specific example, Table 3 presents data from ACP 6 during the week of 23 through 29 January 2011 during peak commute times. The table shows that NBSD's recorded throughput between the hours of 0600 and 0700 from Monday through Friday ranged from 1116 to 1740 vehicles with an average throughput of 1348 vehicles.

DATE	23-Jan-11	24-Jan-11	25-Jan-11	26-Jan-11	27-Jan-11	28-Jan-11	29-Jan-11
ACP 6 (24/7)	Sun	Mon	Tue	Wed	Thur	Fri	Sat
Total Ships In	38	38	38	38	42	42	42
Flat Decks	4	4	4	4	4	4	4
Visiting Ships	0	0	0	0	0	0	0
0500-0559	240	1366	1411	820	1170	1376	108
0600-0659	912	1116	1132	1740	1266	1486	433
0700-0759	503	879	851	2038	704	893	289
0800-0859	209	423	241	687	365	584	137

Table 3.   Example of Data Collected by NBSD from January 2011. Flat Decks
are considered large amphibious ships in this data

C.   RELATED WORK

Before concluding this chapter, we discuss other work related to this research and how our work fits into this larger body of literature. Traffic congestion impacts many facets of life all over the world (Downs, 2004, Ch. I). Congestion results in large economic and environmental costs. Downs (2004, Ch. VI) describes measures taken to alleviate congestion and evaluates how well they succeeded. Nelson (1981) applies mathematical and statistical models of traffic to examine congestion similar to that at NBSD. These references are very relevant to the congestion faced at NBSD, but they apply at a more macroscopic level than what we focus on in the thesis. Measures that NBSD could implement that relate to this line of research include adding or modifying public transportation options, modifying the roads leading to NBSD, changing traffic light timing, and altering work schedules to avoid peak commute times. Future research may incorporate these aspects; however, in this thesis, we focus only on the measures the SECO can alter on a daily basis to reduce congestion and increase throughput.

Other systems with traffic considerations similar to those at NBSD include national parks (White, 2007), sporting events (Bale, 2000), and concerts (Chase and Healey, 1995). These all involve many vehicles arriving to a location and then interacting with a sentry-like individual (e.g., paying a parking attendant). Most of these articles also take a macroscopic view of the problem, examining what can be done farther

away from the venue to reduce this congestion. White (2007) examines a suggestion to eliminate personally owned vehicles in Yosemite and to use buses instead. Chase and Healey (1995) and Bale (2000) examine how congestion associated with concerts and sporting events impacts the surrounding communities, and they attempt to associate costs with the congestion. Most of the measures discussed in these articles are serious traffic engineering remedies also seen in Potts *et al.* (2010) (e.g., adding lanes, widening shoulders) that are outside the scope of this thesis. Nava and Okumura (2010) examine traffic commuting to a university, which has peak commute times similar to those at NBSD, and that article uses mathematical machinery similar to our approach. However, the university setting has no notion of a sentry and that article focuses on the decision calculus of a student driving a moped to arrive to class on time.

DoD is aware of the congestion issue and has studied it. DoD provides its official guidance on ACPs in the report "Unified Facilities Criteria Security Engineering: Entry Control Facilities/Access Control Points" (UFC 4-022-01, 2005). The Army has studied automating the processing of vehicles to increase the throughput rate (MSDDCTEA, 2009). Walker (2011) examined a similar automated process that would use biometric information to process vehicles and passengers. NBSD may someday implement one of these measures to increase throughput efficiency. However, we do not include these considerations in our analysis. The purpose of this thesis is to provide insight to the SECO that could have immediate impact.

Finally, the vehicles in the approach zone wait "in line" for processing by a sentry. Queuing theory (Gross *et al.,* 2008) is a rich branch of mathematics that study these types of problems. We leverage queuing theory machinery to formulate our mathematical model of the NBSD system. We can view multiple sentries in tandem as processing a batch of vehicles at one time. Researchers have studied these batch models for a long time (Bailey, 1954; Deb and Serfozo, 1974). However, in the NBSD system, the batch processing time should increase as the number of sentries in tandem increases. We could not find any work that examines this specific variant of batch queuing models.

D.   OBJECTIVES AND SCOPE

This thesis explores how the number of open ACPs and their configuration of lanes and staffing affect vehicular flow into Naval Base San Diego. We examine this flow during normal and non-normal operations, such as heightened force protection conditions. Our research focuses on increasing throughput and decreasing wait times, as well as managing the costs associated with implementing improvements. We formulate mathematical models of the ACPs to determine which factors matter most.

In Chapter II, we describe the data we collected about NBSD ACPs and perform statistical analyses on this data. Chapter III presents the mathematical model of throughput at ACPs and tests the validity of the model with the data described in Chapter II. In Chapter IV, we determine the optimal number of ACPs to open along with the optimal lane and staffing configurations as a function of the number of available sentries. We present conclusions in Chapter V.

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II. DATA ANALYSIS

Following initial conversations with CRNSW N3 Staff, a team from the Naval Postgraduate School (NPS) visited NBSD on 14–15 December 2011. The objective was to understand the basic workings of their Force Protection Department and ACPs. We toured the ACPs and spoke with the NBSD SECO to gain a better understanding of the current operations, including staffing decisions as each of the ACPs. The SECO stressed during our initial visit that increasing the number of sentries per lane from one to two or three in tandem does not double or triple throughput. Following the visit, we formulated an initial mathematical model to characterize the processing of vehicles arriving to NBSD. We describe this model in Section A of this chapter.

We visited NBSD again during the 2012 Solid Curtain-Citadel Shield (SCCS) exercise between 22 and 26 March 2012. We observed ACP operations under heightened FPCONs and collected data on throughput values and the time required to process vehicles. Between 0500 and 0800 on Thursday, Friday, and Monday, we collected data at various ACPs. We visited two ACPs under heightened FPCON, as well as one ACP under normal operations. After describing the initial mathematical model in Section A, we discuss our data collection methodology in Section B. In Section C, we present summary statistics of the data before conducting a more in depth analysis in Sections D and E.

A. MATHEMATICAL FRAMEWORK

A vehicle driving onto an installation must first potentially wait behind several other vehicles before a sentry can process it. This system is not unlike the one in a grocery store, where a customer must wait in line behind other shoppers before a cashier checks him or her out. The branch of mathematics that studies the dynamics of waiting in line is called *queuing theory*. The ACPs and the interaction of vehicles and sentries is an example of a queuing system. A key component of queuing theory is that a customer waits in line to receive *service*. In a grocery store, the service is the cashier checking out groceries and for our NBSD example the service is a sentry processing a vehicle. The

entity providing service in a queuing system is denoted as the *server*. In a grocery store, a cashier is a server, and at NBSD a sentry is a server. The general flow of a customer in a queuing system proceeds as follows: the customer arrives to a designated place to receive service, waits for the service, receives the service, and then departs the area. Any queuing system has three main quantities of interest: total number of customers in the system (usually line length), total time in system, and utilization rate (i.e., how often the server is busy serving a customer). The two factors that determine these performance measures are the arrival process and the service process (Gross *et al.,* 2008, pg. 3-4). Specifically, and in accordance with Little's Law (Gross *et al.,* 2008, pg. 10), the performance depends upon the rate at which customers arrive to the system and the rate at which servers process customers. The lower the arrival rate of customers and the higher the processing rate of servers, the shorter the lines and the less total time a customer will spend in the system. While NBSD could attempt to influence arrival rates by staggering start times of certain commands, the SECO will have no control over arrivals on a short-term basis. Furthermore, as described by the SECO, the ACPs are fully saturated with vehicles during the morning commute. Thus, the throughput will directly depend upon the service rate at the ACPs, and so we focus on how the SECO can influence the service rate.

With one sentry per processing lane, the notion of service by a sentry is fairly straightforward: a sentry processes a vehicle by inspecting the driver's credentials. However, with multiple sentries in tandem, we must take care to precisely define service. We first define a *batch*. A batch consists of a group of one or more vehicles processed in the same lane at the same time by different sentries of a tandem team. We define the *service time* for a batch to be the entire time it takes to process *all* vehicles in the batch. Thus vehicles in a batch move together and share a collective service time. Service times include more than just the examination of credentials by sentries. The service times also include the time it takes a batch of vehicles to move into position next to the sentries and then depart the access control zone. During most of the morning rush the queue is saturated and thus the ending time of service for one batch coincides with the start time of

service for the next batch.   If no vehicles are waiting in the approach zone, sentries remain idle until additional vehicles arrive.

B.   DATA COLLECTION AND METHODOLOGY

Because we view the NBSD ACPs as a queuing system, the service times will dictate congestion and throughput. Thus, our data collection plan focused on recording the individual service times, which we used to generate an empirical service time distribution and eventually reconstruct throughput values. We also collected other pieces of information that might impact service times. A small sample of the data collected appears in Table 4. Each row corresponds to the observation of one batch of vehicles. The first four columns of Table 4 describe the configuration of the ACP (labeled Gate) under observation, the number of sentries in tandem per lane, the FPCON, and the day the observations took place. The 5th column contains the main quantity of interest: the service time of each batch. The 6th column contains an "I," to signify sentry idleness, if no vehicle pulls into the access control zone immediately after the sentries finish processing the current batch. In cases where an abnormal event prolonged the service time, we record an "E" in column seven. Examples of abnormal events include drivers asking for directions and drivers being turned away from the installation. The data in columns six and seven are binary values.

We observe that the vehicle type could impact the service times. For example, when sentries required a driver to physically hand his credentials over for inspection, motorcycle operators tended to take more time as they usually had to remove safety gear to access their credentials. We denote specific vehicle types (motorcycle, buses, or commercial vehicles) in column eight. Any row without a specific entry in the "Type of Vehicle" column corresponds to a privately owned vehicle such as a car or truck. The number of individuals in each vehicle appears in column nine. For rows with multiple vehicles per batch, we report only the vehicle with the largest number of individuals. In column ten we record whether the vehicle had a RAPIDGate credential. Finally column eleven presents the number of cars that passed in one batch. The number of vehicles usually matches the number of sentries. In some cases, around idle periods, the sentries

processed fewer vehicles than the number of sentries. In other rare cases, a group of sentries could actually process more vehicles if a batch was held up by the lead vehicle in the batch.

Gate	Number of Sentries in Tandem	FPCON	Day of Observation	Service Time of Batch in Seconds	Idle Time	Abnormal Event Occurred	Type of Vehicle	Number of Individuals in Vehicle	Number of RAPIDGate Credentials	Number of Vehicles Passed
9	1	Bravo	Thursday	23	I		Motorcycle	1	0	1
9	1	Bravo	Thursday	9	I			1	0	1
9	1	Bravo	Thursday	22	I	E		1	0	1
6	1	Charlie	Friday	8				2	0	1
6	3	Bravo	Monday	29				1	1	3

Table 4.   Sample from Data Collected at NBSD during 22 – 26 March 2012

C.   DESCRIPTION OF OBSERVED DATA

We analyze our main quantity of interest, the service time, in the next section. In this section, we present summary statistics of many of the other variables we collected. We describe these variables in the previous section.

We collected data on 1,513 batches over the course of three days. Only 5% of the batches attempting to gain access to the installation had a vehicle that used RAPIDGate credentials. The remainder used CACs. We classify 3% of the batches as abnormal observations. Many of these abnormal observations correspond to extended service times. Nearly all of the vehicles (90%) contained a single individual. The remaining 10% of vehicles held between 2 and 11 individuals. Approximately 12% of the batches were followed by an idle period of time before the next batch moved into the access control zone. These idle times ranged from a few seconds of inactivity as vehicles made their way through the approach zone to the access control zone, to an occasional lapse of a minute where traffic signals had stopped the arrival process. Although idle times might seem inconsistent with our assumption that the system is fully saturated, we do not believe this significantly impacts our analysis. When the time between two batches was only a few seconds, it is debatable whether we should have recorded that as an idle period. Also when the traffic signals stopped traffic from entering into the approach zone, often some of the lanes would remain saturated, while other lanes would empty out.

A period of time would elapse before vehicles recognized this situation and moved from a saturated lane to an open lane. In 92% of the batches, the number of processed vehicles equaled the number of sentries in tandem. In most of the remaining 8% of observations, the number of sentries in tandem exceeded the number of vehicles processed. In only 6 observations was the batch size greater than the number of sentries. These few instances correspond to situations where the lead vehicle had an abnormally long service time and held up the rest of the batch. Sentries in the rear of the batch would then process vehicles in the approach zone until the lead vehicle cleared the access control zone. Privately owned cars and trucks made up the bulk (96%) of the vehicles. Motorcycles (3%) and commercial vehicles such as food trucks, delivery trucks, and buses accounted for the remaining vehicles.

Our working hypothesis was that the number of sentries in tandem and FPCON would create differences in service times. We observed 689 batches during FPCON Bravo and 824 batches in FPCON Charlie. These included 1113 single sentry interactions, 146 two-sentry cases, and 254 instances of three sentries in tandem. All FPCON Charlie batches correspond to one sentry. For the remainder of the thesis, when we refer to the number of sentries we actually mean the number of vehicles processed. For example, if a lane contains three sentries but these sentries only process two vehicles, then only two sentries actually take part in the vetting process and so we label this a two-sentry interaction. In Table 5, we present a summary of the variables described in this section broken down by FPCON and sentry combinations. For example, 12% of vehicles contained more than one individual during FPCON Bravo with one sentry. This table shows that in our case the fraction of vehicles with multiple passengers varied a non-trivial amount between batch sizes of one and three (note that in general we might expect the opposite, namely that larger batch sizes would yield a higher frequency of vehicles with multiple passengers. The idle period also varies considerably. As stated previously, there is a degree of subjectivity in defining these idle periods and we do not read too much into these differences.

Sentries in Tandem	FPCON	Total Sample Size (n)	Occurrence of an Abnormal Event	More than One Individual per Vehicle	Percent of RAPIDGate Credential	Percent Idle Time	Percentages of Motorcycles
1	Bravo	289	3%	12%	4%	38%	4%
2	Bravo	146	4%	5%	8%	29%	2%
3	Bravo	254	--	3%	10%	7%	1%
1	Charlie	824	3%	12%	4%	< 1%	4%
TOTAL Observed Percentage		1513	3%	10%	5%	12%	3%

Table 5.   Percentages of Throughput Based on Different Factors

D.   CHARACTERIZING SERVICE TIMES

We now focus on the analysis of the service times. The mean service time for all batches over the three days was 14.2 seconds with a median of 11 seconds and a standard deviation of 9.6 seconds. Figure 3 presents a histogram of recorded service times. Fifty-three observations recorded fell outside of two standard deviations from the mean.
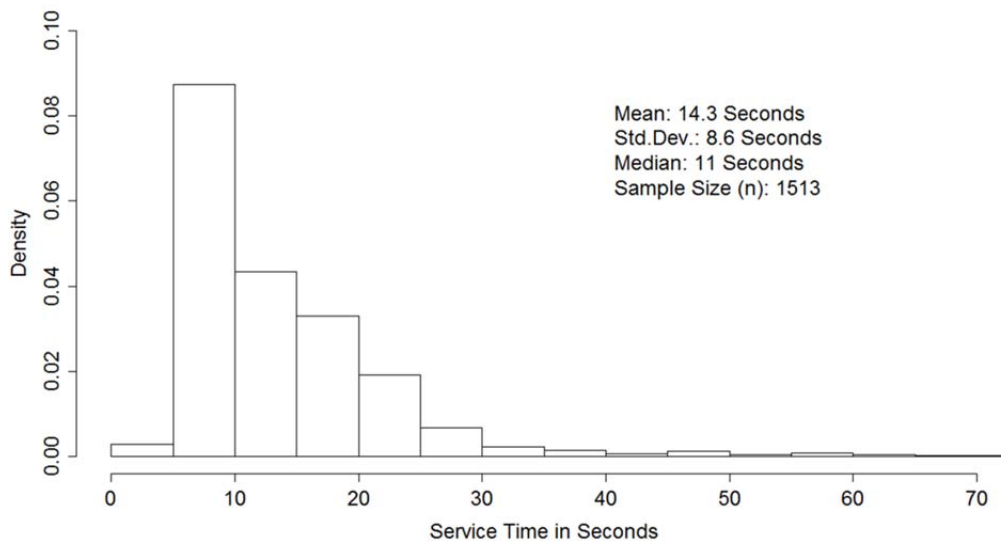

Mean: 14.3 Seconds
Std.Dev.: 8.6 Seconds
Median: 11 Seconds
Sample Size (n): 1513

Figure 3.   Histogram of Collected Service Times

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We analyze the data with comparative boxplots, which are side by side representations of the observations grouped by key factors (see Figure 4). These plots allow us to examine the impact that various factors had on the service time. We present each boxplot using the standard structure (Devore, 2009, pg. 35–39). The median of the data appears as the bold line in the middle of the individual boxes. The median is a measurement of central tendency, or a single value that attempts to describe the central point of the data, that is more robust and less sensitive to outliers than the average. Each box captures the middle 50% of the data: the upper boundary of the box is the 3rd quartile and lower boundary is the 1st quartile. Inter-Quartile Range (IQR) denotes the difference between the two quartiles. The "whiskers," represented by the dotted lines and light horizontal bars above and below the quartiles, provide a postulated upper and lower bound of the data. The upper whiskers correspond either to the largest data point, or to the 3rd quartile (upper boundary of box) plus 1.5 times the IQR. The circles above and below the whiskers correspond to observations that fall outside the whisker range. One often refers to the circles as *outliers*.

Figure 4 presents the observed batch service times broken into groups by both the number of sentries in tandem and the associated FPCON. The grouping of data to the far left shows that one sentry can process one vehicle on average in 13.1 seconds during FPCON Bravo. This corresponds to an average throughput of 275 vehicles per hour. The average throughput for two and three sentries in tandem is 402 and 486, respectively. These results illustrate the significant diminishing returns from tandem processing described by the SECO in our conversations. Three sentries working in three independent processing lanes would generate an average throughput of 825 vehicles per hour (275 × 3), whereas three sentries working in tandem in one processing lane can only process 59% of this value: 486 vehicles per hour. Table 6 summarizes the mean service times and throughput values. Column 4 of Table 6 presents the 95% confidence intervals for the population mean of sampled service times. We invert the endpoints of these intervals and multiply by the number of sentries to produce 95% confidence intervals for the hourly throughput rates. These appear in column 5.
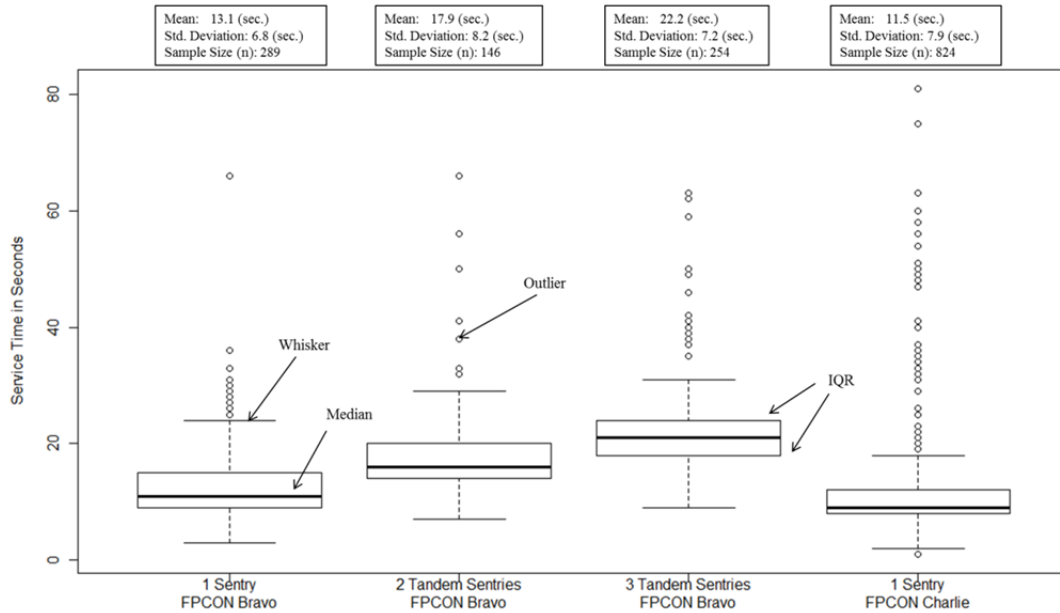

Figure 4.　　Service Time Boxplots Grouped by Number of Tandem Sentries. The median for each group of data is 11, 16, 21, and 9 seconds, respectively

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Table 6 allows us to compare our data with the data collected by NBSD and reported previously in Table 3. Unfortunately, the data collected by NBSD does not include the number of sentries and lanes at each ACP. If we assume three sentries in tandem in each of the three lanes at ACP 6 and full congestion we would estimate from our data analysis a throughput of 1458 (486 × 3), which is 15% above the throughput numbers recorded by NBSD. This is in line with our intuition that our numbers are going to be higher than observed numbers, due to the fact that we ignore idle times, and have a fully saturated queue.

Number of Tandem Sentries	Force Protection Condition	Median Service Time (Sec.)	95% Confidence Interval of the Mean Service Time (Sec.)	95% Confidence Interval of the Throughput (VPHPL)
1	Bravo	11	12.3 – 13.9	260 – 293
2	Bravo	16	16.6 – 19.2	374 – 435
3	Bravo	21	21.3 – 23.1	468 – 507
1	Charlie	9	11.0 – 12.1	298 – 327

Table 6.   Normalized Vehicle Throughput and 95% Confidence Interval based on the Average Batch Service Time

While our throughput values are consistent with those provided by NBSD, we see larger differences when we compare our throughput values with those of Table 1. Our observed throughputs are a considerable amount lower than the published standard in Pamphlet 55-15 (MSDDCTEA, 2009). Table 1 states the standard hourly throughput for a one sentry lane in FPCON Bravo or Charlie is 300 – 450. Our 95% confidence interval for FPCON Bravo in Table 6 is entirely below that range. Our 95% confidence interval for FPCON Charlie in Table 6 overlaps only with the lowest end of this range. Table 1 provides a standard throughput of 400 – 600 cars per hour for tandem sentries. Our 95% confidence interval for two sentries is at the lower end of this range, and the three sentry estimate lies in the middle. In reality, as our data confirms, there will be occasional idle periods even during peak commute hours. Thus, our estimate probably overestimates the actual hourly throughput NBSD can achieve. We conclude that the standard estimate of

throughput rates might be overly optimistic and the actual throughput (at least at NBSD) might be considerably lower. The implication is that if the standard values are used to determine staffing levels, then NBSD is certain to experience significant congestion during peak hours due to being understaffed.

Figure 5 illustrates the difference in our observed throughput estimates and the standard values from Table 1. The dashed boxes represent the different sentry configurations. Notice that our estimated 95% confidence intervals lie well below the standard average ACP throughputs from Table 1.
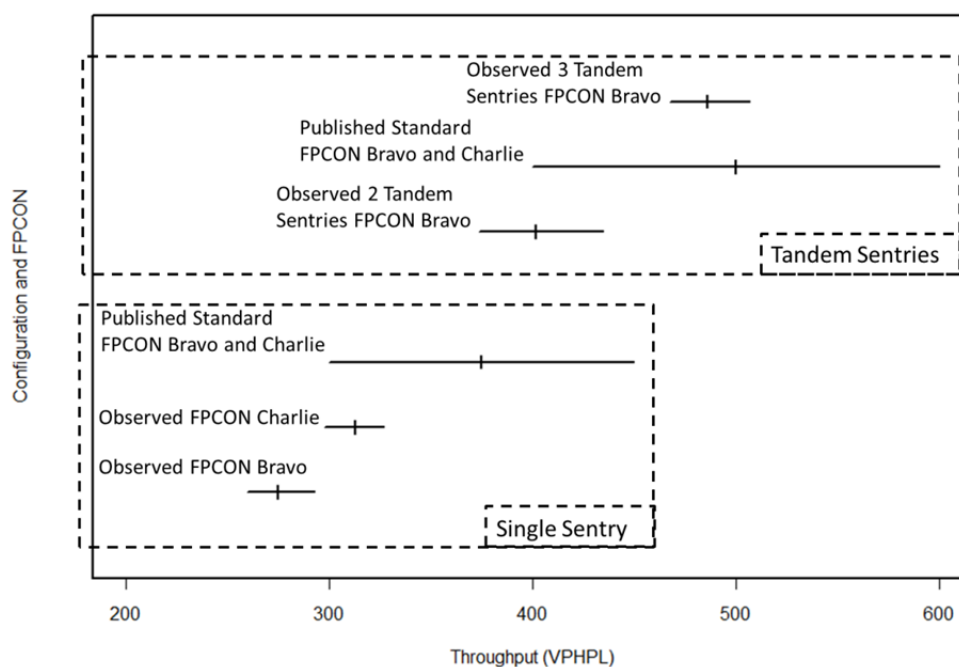
Figure 5.   Throughput Interval Estimates from Tables 1 and Tables 5

The results presented in Figure 4 and Table 6 help us to analyze the impact of FPCON by examining the difference between one sentry in FPCON Bravo and one sentry in FPCON Charlie. We do this by conducting a standard hypothesis test to compare the means between two independent samples. In a hypothesis test, we posit a null hypothesis (H_o) about the properties from which our data was collected and an alternative hypothesis (H_a). We then calculate statistics from our data to test the null hypothesis. If we deem the test statistics calculated to be very unlikely to occur under the null hypothesis, then we

reject the null and conclude the alternative hypothesis as correct. Otherwise, we do not reject the null. Refer to Devore (2009 pg. 284) for more details on hypothesis testing.

Let μ_{1b} and μ_{1c} denote the population mean for service times for single vehicle batch processing under FPCON Bravo and FPCON Charlie, respectively. We propose the following null and alternative hypotheses:

$$H_o: \mu_{1b} = \mu_{1c}$$
$$H_a: \mu_{1b} \neq \mu_{1c}.$$

We test whether the claim of equal population averages is plausible in light of available data. The sample size and sample standard deviation corresponding to the FPCON Bravo situation are 289 observations and 6.8, respectively. For the FPCON Charlie case, these values are 824 observations and 7.9. Because we do not know the true standard deviation of the entire population, we use a t-test statistic to generate our *p-values,* which is the probability of observing a statistic. We must also assume that the two samples we are testing are independent, and that the variances of the two populations are equal in order to use the t-test statistic. We calculate the t-test statistic to be 3.14, which is large (in general anything greater than 2 in absolute value is considered large). The probability of observing such a large statistic under the null hypothesis is 0.001748. If the p-value is less than a set significance level (α, typically set to 0.05) the test will reject H_0. We interpret this to mean that the data contradicts the null hypothesis. Because our p-value is so small, we will reject the null hypothesis under a 0.05 significance level. Thus, we can confidently state that the mean service times of the two FPCON groups are different. Surprisingly, not only are the two means different, but the mean service time for FPCON Charlie is lower than for FPCON Bravo. There are several possible explanations for this. It may be due to the newly adopted MEP PLANORD, which attempts to bring only mission essential personnel onto the installation during events such as a crisis or increased level of FPCON. Mission essential personnel typically have vast experience at ACPs and thus are less likely to slow the processing down via abnormal events. Furthermore, during heightened conditions, both drivers and sentries are apt to be more alert and act more efficiently during the processing.

For each of the next four figures (Figure 6 through Figure 9) we consider only the one sentry per lane case for both FPCON Bravo and Charlie. Figure 6 displays a boxplot of observed service times grouped by credential type. It shows the difference in processing times between individuals with CACs and RAPIDGate credentials. For CAC credentials, the mean service time was 12.7 seconds with a median of 11 for FPCON Bravo, and 10.8 seconds with a median of 22 seconds for FPCON Charlie. For RAPIDGate credentials, the mean service time was 23.2 seconds with a median of 9 seconds under FPCON Bravo, and 30 seconds with a median of 21 seconds for FPCON Charlie. The RAPIDGate batches have small sample sizes; however the results align with our intuition. We expect that it takes more time to process a RAPIDGate credential than a CAC. We observe that it takes approximately 20 seconds longer to process a RAPIDGate then a CAC in FPCON Charlie, and only an additional 10 seconds for the same comparison in FPCON Bravo. This suggests that the sentries are more meticulous during FPCON Charlie in processing non-CAC users. Also note that the distribution for service times are much tighter (in terms of the IQR) for CAC users. We would expect the processing times for CAC users to be more consistent because these interactions occur the vast majority of the time, although the small sample sizes drive some of these results.
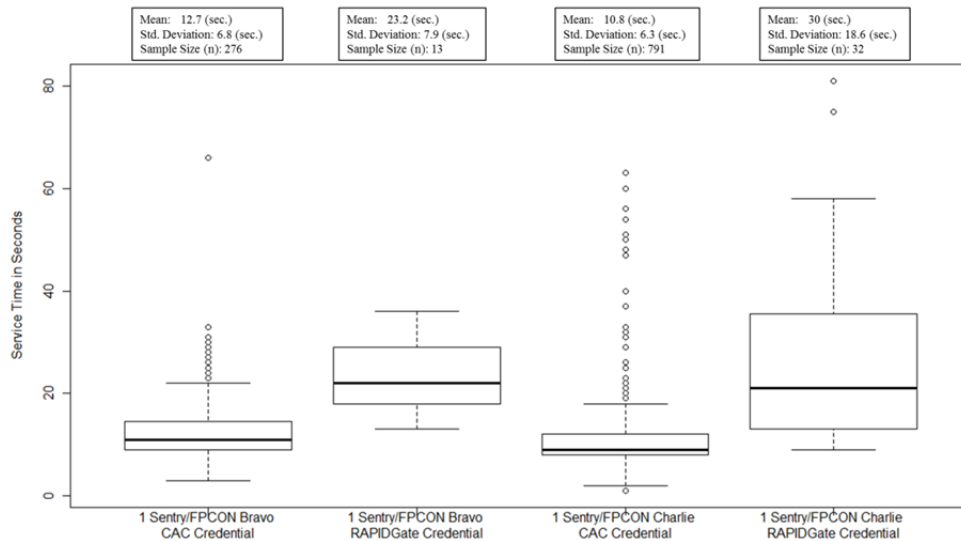

Figure 6.   Mean Service Times According to Credential Types. The median for FPCON Bravo service times is 11 and 22 seconds, while the median for FPCON Charlie is 9 and 21 seconds

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Figure 7 presents our findings when we group service times by the occurrence of an abnormal event. For observations where abnormal events occurred under FPCON Bravo, the mean and median service time is 22.5 seconds. When no abnormal event occurred in FPCON Bravo, the mean service time is 12.9 seconds with a median of 11 seconds. When abnormal events occurred in FPCON Charlie the mean service time is 13.2 seconds with a median of 12 seconds. For the remainder of observations in FPCON Charlie, the mean service time was 11.5 seconds with a mean of 9 seconds. As expected, the mean service time increases for an abnormal event. However, the difference is much greater for FPCON Bravo than Charlie. We should not read too much into this difference because the sample size for abnormal events in FPCON Bravo is only 8. However, one possible explanation is that in FPCON Charlie only mission essential personnel arrive, and so perhaps any abnormal interactions between sentries and these individuals are resolved quickly.
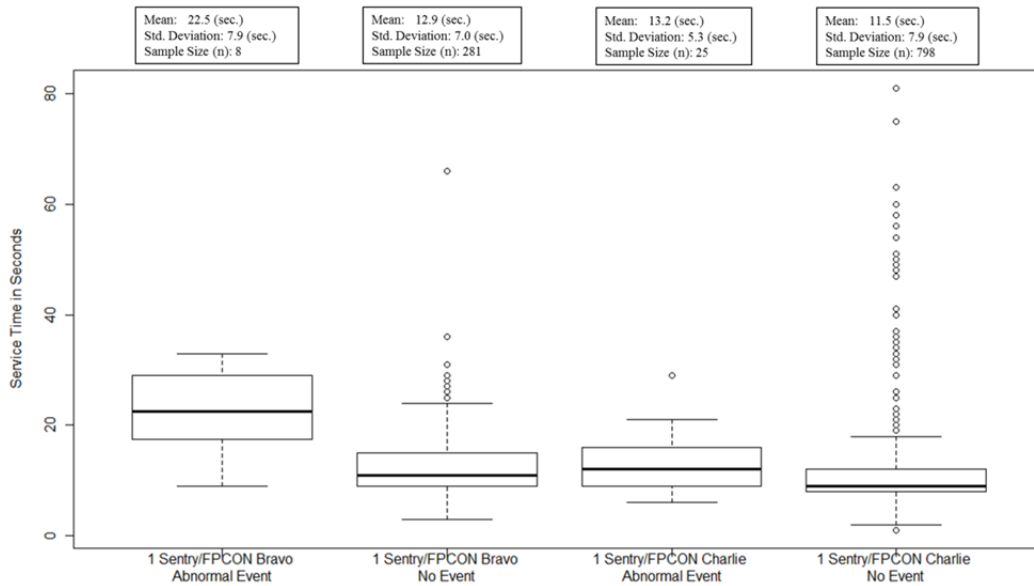
Figure 7.   Mean Service Times According to Abnormal Event Occurrences.
The median for each subset is 22.5 and 11 seconds for FPCON Bravo,
and 12 and 9 seconds for FPCON Charlie

Figure 8 presents a boxplot of service times grouped by motorcycles or privately owned cars and trucks that access NBSD. A handful of commercial vehicles did access the ACP under observation, which we ignore for Figure 8. Most commercial vehicles will enter via ACP 6A due to the dedicated inspection equipment located there. For FPCON Bravo motorcycles averaged 20.5 seconds for their service time with a 16 second median, while cars and trucks averaged 12.8 seconds for their service times with a median of 11 seconds. For FPCON Charlie, motorcycles had a mean service time of 30.2 seconds with a median of 25 seconds. Cars and trucks had a considerably lower value for their mean (10.9 seconds) and median (9 seconds). As expected, it takes longer to process motorcycles because of the equipment removal required. Also the difference between processing times for cars and motorcycles is greater for FPCON Charlie than FPCON Bravo because the sentries have to be more thorough in their vetting process.
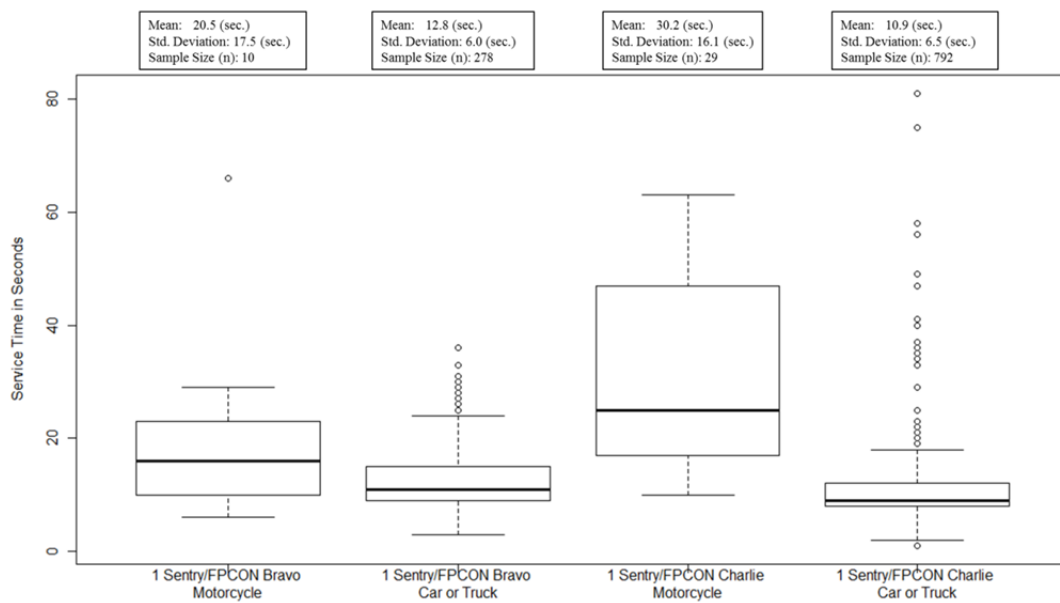
Figure 8.   Mean Service Times According to Vehicle Type. The median under
FPCON Bravo is 16 and 11 seconds. For FPCON Charlie:
25 and 9 seconds, respectively

Figure 9 groups the service times by the number of occupants in each vehicle. As described in Section B, 90% of the vehicles entering the installation contained one individual. In Figure 9, we distinguish between vehicles with one individual and vehicles with multiple individuals. While sentries can process individual drivers in 12.6 seconds on average (11-second median) in FPCON Bravo, the addition of more individuals lengthens the average service time to 17.9 seconds (17.5-second median). FPCON Charlie presents similar behavior with individual drivers being processed in 10.4 seconds on average (9-second median) and the presence of additional individuals increasing the average to 19.9 seconds (16-second median). As we have seen with several other figures in this section, the difference between service times for vehicles with multiple individuals and vehicles with a single individual is greater for FPCON Charlie than Bravo, which suggests more thorough vetting of additional individuals by the sentries during FPCON Charlie. We also see a much smaller variation in the service time distributions for one individual compared to the distributions for vehicles with multiple individuals.

Figure 9.   Mean Service Times According to the Number of Occupants per Vehicle. The median for each subset is 11 and 17.5 seconds for FPCON Bravo, and 9 and 16 seconds for FPCON Charlie

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E. REGRESSION MODEL

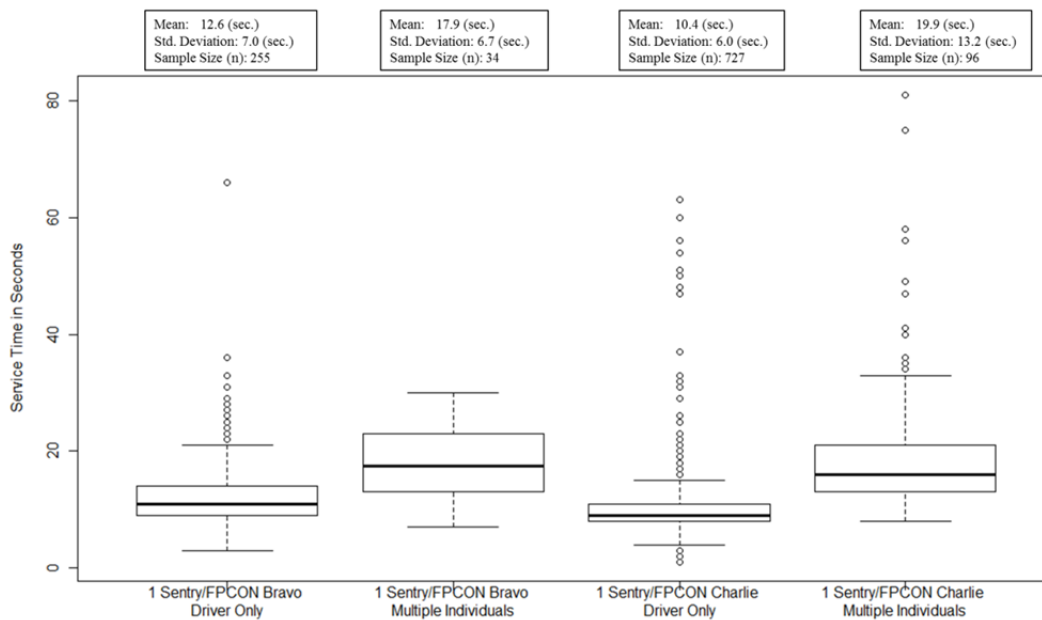We formulate a linear regression model to examine the relationship between the service time in seconds and the factors described in this chapter. We focus on the number of sentries and the FPCON level. We defined an indicator variable to be 1 if the batch occurred during FPCON Bravo. Based on the additional analysis presented in the chapter, we also include three additional indicator variables: whether an abnormal event occurs, whether a RAPIDGate credential was used, and whether the batch included a motorcycle. Finally, we include the number of individuals in the vehicle as an independent variable. Table 7 presents the coefficients for our regression model.

Model Coefficients:				
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	4.90	1.07	4.55	5.85E−06
FPCON Bravo (Indicator)	1.91	0.04	4.81	1.64E−06
Normal Event (Indicator)	−4.20	0.99	− 4.22	< 2e−16
Number of Sentries	4.42	0.25	17.51	< 2e−16
RAPIDGate Credential Used (Indicator)	8.80	0.74	11.94	< 2e−16
Vehicle Motorcycle (Indicator)	15.50	0.92	16.79	< 2e−16
Number of Individuals in Vehicle	4.61	0.30	15.41	< 2e−16

Table 7.   Linear Model Regression Output. Coefficient estimates are in seconds

The independent variables appear in the first column of Table 7 and the coefficient value appears in the second column. For the four indicator variables, the coefficient can be interpreted as a time penalty (or bonus if negative) given an occurrence of the associated variable. For example, fixing all other variables, the model predicts that it will take the sentries on average 15.5 seconds more to process a motorcycle than a privately owned car or truck. Similarly, on average a standard processing interaction will take 4.2 seconds less when a normal event is associated with it. For each additional sentry, which corresponds directly to the number of vehicles in a batch, the service time increases by 4.4 seconds. The service time increases by 4.6 seconds for each additional

individual in the vehicle. The p-value appears in the final column in Table 7. Small p-values provide strong evidence that there exists a statistical relationship between the given independent variable and the service time. As seen, all of our independent variables are significant. An R-squared value measures the fraction of the total variability in service times that our model captures. The R-squared for this regression is 0.505, which means our model captures about half of the variability. This means that while not a poor model, there are certainly factors our regression does not capture. Overall, the regression results align with our intuition and the analysis in the rest of this chapter.

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III. QUEUING MODEL

Based on the experience of the SECO and the empirical evidence described in Chapter II, tandem sentries clearly produce diminishing returns in terms of throughput. In this section, we build a queuing model to account for this behavior. In this chapter, we focus on one single processing lane. Our single lane queuing model defines a mathematical representation of a tandem queue to determine the throughput as a function of the number of sentries. We formulate the single lane queuing model in Section A and prove in Section B that the throughput for this model for tandem sentries exhibits decreasing returns. In Section C, we illustrate with examples, and finally, in Section D we examine whether this model is consistent with data we collected.

A. SINGLE LANE

Consider the case where a single lane contains n sentries in tandem and each sentry processes one vehicle at a time. We assume a sufficiently congested system so that we can ignore situations where an individual sentry is idle. A batch of n vehicles arrive to the sentries for processing. Only after the sentries process all n vehicles and the vehicles exit the access control zone can the next batch of vehicles move into the access control zone. We assume the time it takes the ith sentry to process a vehicle is a random variable denoted X_i. Let i index individual sentries, $i=1,2,..n$. Because the entire batch is processed only after each individual vehicle is processed, we model the service time for a batch of n vehicles as the random variable:

$$T_n = \max_{i=1,2,...n} X_i.$$

For analytic tractability, we assume that the X_i are *independent and identically distributed (IID)* random variables. Certainly, this is not true in practice; some sentries are more efficient or meticulous than others. Future work may specify service time distributions that depend upon whether the sentry is part of the Force Protection Department or from another command. We next derive the *cumulative distribution function* (*CDF*) of T as follows:

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$$P(T_n < t) = P(\max_{i=1,2,...n} X_i < t)$$

$$= P(X_i < t, \; \forall i)$$

$$= \prod_{i=1,2,...n} P(X_i < t) \quad \text{assume independent}$$

$$= P(X_i < t)^n \quad \text{assume identical distribution}$$

$$= F(t)^n.$$

where F is the CDF of service time X_i.

B.   ANALYSIS

We now show that according to our model, the throughput for a processing lane with n sentries in tandem will be less than a corresponding system where the sentries are spread among n independent one sentry processing lanes. The average time to process a batch of n vehicles is $E[T_n]$. When $n=1$, we have the special case $E[T_1] = E[X_i]$. On average n vehicles proceed onto the installation every $E[T_n]$ time units and thus the average throughput rate is $n/E[T_n]$. The throughout for a one sentry lane is $1/E[X_i]$, and so for n independent one sentry processing lanes, the total throughput is $n/E[X_i]$. Therefore, the throughput for the tandem system is less than the throughput for n independent processing lanes because $n/E[T_n] < = n/E[X_i]$. This follows because $E[X_i] <= E[T_n]$. In general, this inequality will be strict; only when the service times X_i are deterministic will $E[X_i] = E[T_n]$. Thus, we have shown that the tandem sentry setup is less effective than independent processing lanes.

C.   EXAMPLES

We now present two examples to illustrate the diminishing returns of tandem configurations.

1.   Exponential Service Times

We first model the service times of individual sentries X_i as exponential random variables with rate parameter u. The CDF for X_i is $F(t) = 1 - e^{ut}$ and thus the distribution of T_n is:

$$P(T_n < t) = (1 - e^{-ut})^n.$$

Solving $E[T_n]$ for the exponential case yields:

$$E[T_n] = \int_0^\infty 1 - (1 - e^{-ut})^n dt$$

$$= \frac{1}{u} \sum_{i=1}^n \binom{n}{i} \frac{(-1)^{i-1}}{k}.$$

Table 8 lists the values for $E[T_n]$ for several sentries (n), as well as the per car processing time $E[T_n] / n$, and the hourly throughput. We use the FPCON Bravo scenario with one sentry (mean service time = 13.1 seconds) to build the last column of Table 8. In this case, the rate u = 275/hr.

n	$E[T_n]$	$E[T_n]/n$	Throughput for u = 275 ($n/E[T_n]$)
1	1/u	1/ u	275
2	3/2 u	3/4 u	367
3	11/6 u	11/18 u	450
4	25/12 u	25/48 u	528
5	137/60 u	137/300 u	602
6	49/20 u	49/120 u	673

Table 8.   Expected throughput for *n* sentries when individual service times are IID exponentials with parameter *u*

2. Two Types of Vehicles

We also explore the case where there may be two specific categories of vehicles that have their own service times. As discussed previously, drivers either present CAC or RAPIDGate credentials to the sentries. Figure 6 of Chapter II shows the significant difference in the service times between those vehicles with CAC credentials and those with the RAPIDGate credentials. In this case, we make the assumption that X_i takes on one of two deterministic values, either a (for CAC credentials) or b (for RAPIDGate credentials), depending on the category of the vehicle:

$$P(X_i = a) = p$$
$$P(X_i = b) = 1 - p.$$

Under our assumptions, $a < b$ and the *maximum* time to process a batch of n cars has the following *probability mass function* (*PMF*):

$$P(T_n = a) = p^n$$
$$P(T_n = b) = 1 - p^n.$$

The expected time to process the batch of size n is then:

$$E[T_n] = b - p^n(b - a).$$

As n increases the expected service time goes to b. The throughput for n sentries is:

$$\frac{n}{E[T_n]} = \frac{n}{b - p^n(b - a)}.$$

Using the data from Chapter II for the FPCON Bravo one sentry case, we have $p = 0.96$ (96% of vehicles have a CAC), $a = 12.7$ seconds, and $b = 23.2$ seconds. Table 9 presents the results for several values of n. We list a and b above in seconds, but in Table 9 we transform it to the hourly throughput. Comparing Tables 6, 8, and 9, we see that our observed throughput values in Table 6 fall between the exponential case in Table 8 and the binary case of Table 9.

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n	Throughput for $a= 12.7$, $b= 23.2$, and $p= 0.96$ ($n/E[T_n]$)
1	274
2	532
3	776
4	1008
5	1230
6	1442

Table 9.　Expected throughput for n sentries when individual service times depend upon credential type.

D.　COMPARING THE MODEL TO DATA

We have postulated a model that intuitively describes the behavior of batch processing and exhibits the decreasing returns to throughput that appears in the data. In this section, we perform statistical tests to determine how well our model captures the actual behavior of the NBSD system.

We have an empirical service time distribution for the two sentry tandem configuration and the three sentry tandem configuration. We describe the characteristics of these distributions in Chapter II. We define Y_2 and Y_3 to be the random variables associated with these distributions. Recall from Chapter II that $E[Y_2] = 17.9$ and $E[Y_3] = 22.2$. We want to compare Y_2 and Y_3 to the corresponding distributions predicted by our model, T_2 and T_3. In order to generate T_2 and T_3 we first need the time for one sentry to process one vehicle X_i. We utilize the empirical service time distribution for the one sentry case in FPCON Bravo to define X_i. We collected 289 observations for one sentry under FPCON Bravo, and thus X_i corresponds to a discrete random variable that takes on each of its 289 values with equal probability. Recall from Chapter II that $E[X_i] = 13.1$. To generate the distribution of T_2 from X_i we generate all 289^2 combinations of pairs from X_i and define T_2 to be the maximum of the two values. T_2 takes on each of these values with probability $1/289^2$. We construct the distribution for T_3 in an analogous

fashion. We call T_2 and T_3 generated in this way the *synthetic distributions*. In Figure 10, we present the actual observed service times for tandem sentries (Y_2 and Y_3) and the synthetic service times generated by our model (T_2 and T_3). The synthetic data for two sentries in tandem (T_2) has a mean service time of 16.6 seconds and a standard deviation of 8.2 seconds. The synthetic data for three sentries in tandem (T_3) has a mean service time of 18.9 seconds with a standard deviation of 8.9 seconds. We next perform statistical tests to compare the actual and synthetic distributions.
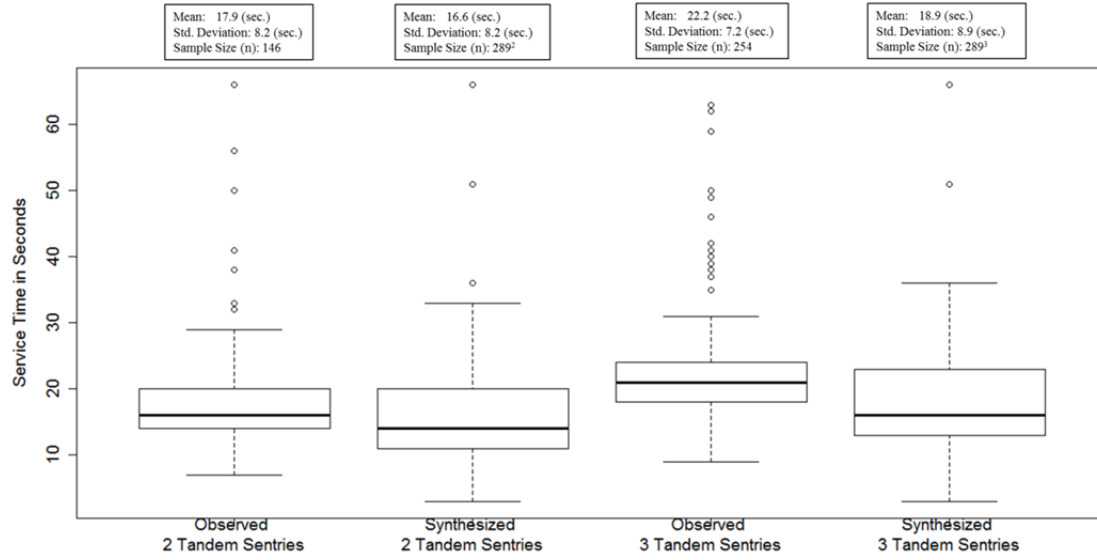
Figure 10.   Boxplots of Service Time Distributions for Observed and Synthetic Two and Three Tandem Sentry Configurations. The median for each group of data is 16, 14, 21, and 16 seconds, respectively

We apply a two-sample Kolmogorov-Smirnov test to compare the synthetic and observed distributions. The Kolmogorov-Smirnov test defines a distance between the cumulative distribution function of two distributions and tests whether the distance is large in some sense. For more details, see Sheskin (2004, pg. 453–459). For the three sentry case, the test produces a p-value of less than 2.2e-16 allowing us to assert that the distributions are different. The p-value for the two-sentry case is slightly higher 1.096e-06, but we still reject the hypothesis that the distributions are the same at a 0.05 alpha level.

These tests show conclusively that a statistical difference between the service times of our observed and synthetic datasets exists. There are several possible reasons for this. The amount of data collected is very small compared to the total amount of traffic that arrives at NBSD. Another factor that may influence why our theoretical model does not fit the data well is the time required to fill and empty the access control zone. The observed data accounts for this movement of vehicles into position, but the theoretical model does not adequately account for this. When there is one sentry, a vehicle only has to move one vehicle length to get into the proper position. However, the lead vehicle must travel three vehicle lengths to get into position for the three sentry case. Furthermore, the second and third vehicles in the batch may experience slight delays before the driver reacts and pulls up to the proper position. This extra time is not accounted for in our model. Thus, we would expect the observed distributions to have larger service times than we would predict with our theoretical model. This occurs in both the two-sentry and three-sentry cases. For two sentries in tandem, the observed average service time, $E[Y_2] = 17.9$, is one second more than our synthetic distribution, $E[T_2] = 16.6$. For three sentries in tandem, the observed average service time is $E[Y_3] = 22.2$, which is three seconds more than the average service time according to our synthetic distribution, $E[T_3] = 18.9$. The differences between the observed averages and the theoretical averages increase as we go from two to three sentries. This is consistent with the potential flaw in the model described above. We would expect the extra delays from moving through the access control zone to increase with the number of sentries. There are other possible reasons why our model does match the observations. For example the characteristics of the batches depend upon the number of sentries (see Table 5). However, we feel these differences would have a minor impact on the comparison. In the next chapter, we use only the observed distributions, so we do not investigate the model's shortcomings further. Future work may explore analytical representations, however, and thus we will need to determine the cause of the discrepancy between the model and observed data, its real-world impact, and whether we can reduce it via model refinements. Our initial intuition is that the difference would not have a significant impact on our results.

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IV. OPTIMAL STAFFING CONFIGURATIONS

We now consider the staffing decision faced by the SECO every day: which ACPs should be opened, how many lanes should be opened at each ACP, and how many sentries should be placed in each lane. In this analysis, we assume that all lanes are equivalent and independent. Thus, the throughput in a lane at ACP 6 will be the same as one at ACP 9. The total throughput of two lanes will just be the sum of the throughputs at each individual lane. For example, if one sentry processes 300 VPH in one processing lane, then we can assume that if the SECO were to open another sentry processing lane, the total throughput of both lanes would be 600 VPH. Similarly, if two sentries in tandem can produce a throughput of 500 VPH, then having two lanes with two sentries in tandem each will produce a total throughput of 1000 VPH. We assume throughout that there is no server idleness and so there is essentially an infinite backlog of vehicles. This assumption is reasonable during the morning commute, but it should be relaxed in future work.

A. THE NAVAL BASE SAN DIEGO SYSTEM

We described the NBSD system in Chapter I, but review the main points here. In Table 2 of Chapter I, we list six ACPs. ACP 6A processes only commercial vehicles, so we ignore it for our analysis. Currently, NBSD has closed ACP 7 for renovation, so we ignore ACP 7 for this analysis due to its status, although including it in future analyses will be straightforward. Thus, we only consider the current operational ACPs at NBSD: 2, 6, 9, and 13. We assume ACP 2 has one processing lane, ACP 6 has three processing lanes, ACP 9 uses contraflow and has four processing lanes, and ACP 13 has two processing lanes. Based on conversations with the SECO we define an order in which the SECO will open the ACPs: 6 then 9 then 13 then 2. We assume that all lanes can hold up to three sentries in tandem, except for the lane in ACP 2, which only supports up to two sentries in tandem.

The SECO has a finite number of sentries he or she can assign to various ACPs. However, not all sentries will necessarily process vehicles in lanes at the ACPs. To open

an ACP the SECO may need to station sentries around the ACP for additional security purposes. Other sentries may exclusively process pedestrian traffic. These sentries do not process any vehicles, and thus they do not increase the vehicular throughput at ACPs. However, these sentries count against the limited pool of sentries the SECO can use for vehicular processing. We refer to the sentries required to open a gate that do not process vehicles as the *overhead* to open an ACP. We only consider the overhead to be personnel, but it could also be specific equipment. The overhead will probably depend upon the FPCON; at higher FPCON levels we would expect the overhead to increase.

The SECO faces a tension. On one hand, he prefers to have as many ACPs open as possible to limit the amount of tandem processing, which we have shown is not as efficient as opening new processing lanes. However, opening additional ACPs reduces the number of sentries available for processing because of the overhead cost to open an ACP. In Table 10, we present the optimal number of ACPs to open as a function of the number of sentries available (the rows) and the number of overhead sentries required to open each ACP (the columns). The throughput rate for the optimal staffing configuration appears in each cell of the table. We shade the cells to show the number of ACPs the SECO will optimally open for the given situation. As stated earlier, we assume the SECO first opens ACP 6, then ACP 9, then ACP 13, then 2. White cells correspond to the SECO opening ACP 6 only. Dark grey cells correspond to the SECO opening ACPs 6 and 9. Light grey cells correspond to the SECO opening ACPs 6, 9, and 13. Black cells correspond to the SECO opening all four ACPS: 6, 9, 13, and 2. We also state in each cell the optimal sentry configuration as a triple (i, j, k), where $i, j,$ and k correspond to the number of one sentry, two sentry tandem, and three sentry tandem lanes, respectively. The blank cells at the bottom signify that all lanes at all ACPs have the maximum number of sentries in tandem (three sentries per lane for ACPs 6, 9, and 13, and two for ACP 2), and thus adding more sentries is infeasible. Currently, NBSD can support 29 sentries processing vehicles onto NBSD assuming no overhead cost per ACP. Due to space considerations, we do not present all sentry levels between 1 and 41 in Table 10.

| | | Overhead to Open ACP | | | |
| | | (Number of Sentries) | | | |
		0	1	2	3
	1	275 (1,0,0)	Infeasible	Infeasible	Infeasible
	2	550 (2,0,0)	275 (1,0,0)	Infeasible	Infeasible
	3	825 (3,0,0)	550 (2,0,0)	275 (1,0,0)	Infeasible
	4	1100 (4,0,0)	825 (3,0,0)	550 (2,0,0)	275 (1,0,0)
	5	1375 (5,0,0)	952 (2,1,0)	825 (3,0,0)	550 (2,0,0)
	6	1650 (6,0,0)	1100 (4,0,0)	952 (2,1,0)	825 (3,0,0)
	7	1925 (7,0,0)	1375 (5,0,0)	1079 (1,2,0)	952 (2,1,0)
	8	2200 (8,0,0)	1650 (6,0,0)	1206 (0,3,0)	1079 (1,2,0)
	9	2475 (9,0,0)	1925 (7,0,0)	1375 (5,0,0)	1206 (0,3,0)
	10	2750 (10,0,0)	2052 (6,1,0)	1650 (6,0,0)	1290 (0,2,1)
	11	2877 (9,1,0)	2200 (8,0,0)	1925 (7,0,0)	1374 (0,1,2)
	12	3004 (8,2,0)	2475 (9,0,0)	2052 (6,1,0)	1650 (6,0,0)
	13	3131 (7,3,0)	2602 (8,1,0)	2179 (5,2,0)	1925 (7,0,0)
Number Available Sentries	14	3258 (6,4,0)	2750 (10,0,0)	2200 (8,0,0)	2052 (6,1,0)
	15	3385 (5,5,0)	2877 (9,1,0)	2475 (9,0,0)	2179 (5,2,0)
	16	3512 (4,6,0)	3004 (8,2,0)	2602 (8,1,0)	2306 (4,3,0)
	17	3639 (3,7,0)	3131 (7,3,0)	2729 (7,2,0)	2433 (3,4,0)
	18	3766 (2,8,0)	3258 (6,4,0)	2750 (10,0,0)	2560 (2,5,0)
	20	4020 (0,10,0)	3512 (4,6,0)	3004 (8,2,0)	2814 (0,7,0)
	21	4104 (0,9,1)	3639(3,7,0)	3131 (7,3,0)	2898 (0,6,1)
	22	4188 (0,8,2)	3766 (2,8,0)	3258 (6,4,0)	2983 (5,4,0)
	23	4272 (0,7,3)	3893 (1,9,0)	3385 (5,5,0)	3110 (4,5,0)
	26	4524 (0,4,6)	4188 (0,8,2)	3766 (3,7,0)	3491 (1,8,0)
	29	4776 (0,1,9)	4440 (0,5,5)	4104 (0,9,1)	3786 (0,7,2)
	30		4524 (0,4,6)	4188 (0,8,2)	3870 (0,6,3)
	33		4776 (0,1,9)	4440 (0,5,5)	4122 (0,3,6)
	34			4524 (0,4,6)	4206 (0,2,7)
	36			4691 (0,2,8)	4374 (0,0,9)
	37			4776 (0,1,9)	4440 (0,5,5)
	38				4524 (0,4,6)
	40				4649 (1,0,9)
	41				4776 (0,1,9)

Gate 6	Gate 6, 9	Gate 6, 9, 13	Gate 2, 6, 9, 13

Table 10.   Throughput in Vehicles per Hour for Optimal Configuration of ACPs.
The triple (*i, j, k*) in each cell represents the optimal number of lanes

We now describe how we construct this table. For a given configuration, we compute the total throughput using the following formula.

$$Throughput = (275 \times i) + (402 \times j) + (486 \times k)$$
where i = number of single sentry lanes
j = number of 2 tandem sentry lanes
and k = number of 3 tandem sentry lanes.

The maximum throughput occurs with 29 sentries spread out over 9 three tandem sentry lanes and 1 two tandem sentry lane at ACP 2. This produces a throughput of 4776= (1×402) + (9×486), which appears in the last cell of each column. In what follows, we assume the sole objective of the SECO is to maximize throughput. For a given number of ACPs open, the SECO should distribute the sentries as uniformly as possible across all the lanes because this will maximize the throughput. Let us look at the eleven-sentry case. For no overhead, the SECO should open all ACPs (black cell), which yields ten lanes. Thus, the SECO should assign one sentry to nine lanes and two sentries to one lane, producing a throughput of 2877 = (9×275) + (1×402). For a single-sentry overhead, the SECO should open ACPs 6, 9, and 13 (light grey cell), which yields nine lanes. The SECO should assign three sentries as overhead at the three ACPs, yielding eight processing sentries. Eight lanes each have one sentry, producing a throughput of 2200 = (8×275). For an overhead of two sentries, the SECO should open ACPs 6 and 9 (dark grey cell), which yields seven lanes. The SECO should assign four sentries as overhead at the two ACPs, yielding seven processing sentries. Seven lanes each have one sentry, producing a throughput of 1925 = (7×275). With an overhead of three sentries, the SECO should open only ACP 6 (white cell), which yields three lanes. The SECO should assign three sentries as overhead at the ACP, yielding eight processing sentries. Two lanes have three sentries and one lane has two sentries, producing a throughput of 1374 = (1×402) + (2×486). This example illustrates the potentially significant impact of the overhead. The throughput decreases by over 50% from no overhead (2877) to three overhead sentries per ACP (1374).

The shades in the table show that as the overhead increases the SECO is best served by opening a new ACP and more likely to stack his sentries in tandem. With no

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overhead or a one-sentry overhead the SECO should open a new ACP as soon as feasibly possible. For example, with no overhead, the SECO should open ACP 9 as soon as four sentries are available. In the case where each ACP requires one sentry in overhead, the SECO should open ACP 9 as soon as six sentries are available. With three overhead sentries, the SECO should delay opening ACP 9 because of the larger overhead cost. The first realistic opportunity the SECO has to open a second ACP (ACP 9) is when he has 10 sentries available. This corresponds to six overhead sentries at ACPs 6 and 9, three processing sentries at ACP 6 and one processing sentry at ACP 9. This would produce a throughput of 1100 = (4×275). However, it is more efficient for the SECO to only open ACP 6 and use three sentries as overhead and seven processing sentries spread over the lanes of ACP 6. The throughput for this configuration is 1290 = (2×402) + (1×486). The SECO should not open another ACP until twelve sentries are available. This corresponds to six sentries as overhead at ACP 6 and 9 and six single sentry process lanes, which yields a throughput of 1650 = (6×275). If instead the SECO only opens ACP 6, he would have three overhead sentries and three processing lanes of three sentries in tandem, which would produce a lower throughput of 1458 = (3×486).

The SECO may have some target throughput he wants to achieve. He can use Table 10 to determine how many sentries he needs to achieve this throughput. For example, suppose the SECO has an overhead of two sentries and he needs to process 2,000 vehicles per hour into the installation. The SECO could refer to the two sentry overhead column and find the first row in which the throughput exceeds 2,000 vehicles per hour. In this case, we see that twelve sentries produce a throughput of 2,052 vehicles per hour. The SECO would open ACPs 6 and 9 and assign four sentries as overhead and the remaining eight sentries across the seven processing lanes.

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V.   CONCLUSIONS

This thesis examines the challenge of bringing large numbers of vehicles into a secure location. Reducing congestion and increasing throughput is important and will continue to be important in the future as most military installations see large numbers of personnel attempting to gain access. This problem applies not only to NBSD, but also to many military installations throughout the world. The number of installations impacted by significant congestion will only increase in the coming years as populations grow and cities and towns expand. Congestion creates an opportunity for terrorism, as many potential targets sit vulnerable in traffic. Congestion also generates economic costs both directly for the military and indirectly on the surrounding communities. Personnel stuck in congestion cannot perform their duties and if the congestion impacts the surrounding roadways then local businesses may suffer. As force protection departments try to balance increasing throughput while maintaining the integrity of the installation, understanding the components of an ACP and how they interact with each other will be an important research topic in the coming years.

This thesis presents an analysis of the key factors that drive congestion at the ACP. These factors include the configuration of sentries, the FPCON level, the type of vehicle, the credentials used, and the number of individuals in a vehicle. Our data analysis performed in Chapter II quantifies the impact of these factors. The time for a sentry to process a RAPIDGate credential is about double the processing time of a vehicle with a CAC credential. Similarly, the time to process a motorcycle is about 50% more than the time to process a privately owned vehicle or truck. While the fraction of vehicles that use RAPIDGate or are motorcycles is relatively small, it might be worthwhile for security personnel to examine measures that could speed up the processing of these types of vehicles.

Our data analysis in Chapter II confirms the experiences of the SECO in that having multiple sentries in tandem has a diminishing return on throughput. That is, putting two or three sentries in tandem in the same lane does not double or triple the throughput in that lane. In fact, we observed that the actual throughputs are significantly

lower than other published standards. This implies that if the current standards are used for determining staffing levels, then NBSD will certainly experience significant congestion during peak commuting hours.

In Chapter III, we present a mathematical model to explain this. While the model does not accurately predict specific service time values, it does provide the logic and insight for why increasing the number of sentries in tandem has diminishing returns. This is a very important result for decision makers. If decision makers expect that putting two sentries in tandem will double throughput, then they will significantly overestimate throughput and understaff ACPs, and congestion will increase as a result.

In Chapter IV, we present the optimal staffing configuration for NBSD as a function of the number of sentries in tandem. This provides a baseline for the SECO for determining when to open ACPs and lanes, and how to most effectively staff them to increase throughput. Table 10 in Chapter IV can inform decision makers of the expected gains they will experience in throughput as a function of the number of sentries available and the amount of overhead required to open each ACP. This baseline recommendation table will hopefully prove valuable to the SECO. However, the underlying throughput values used to construct the table are based on some simplifying assumptions and we hope that future work will add more complexity to the analysis and provide an analog to Table 10 that has more accurate throughput values.

Based on our observations and conversations with the SECO, we assumed that during the morning commute there was an infinite backlog of cars attempting to access NBSD. In queuing nomenclature, we assumed that the arrival rate of customers was much greater than the service rate of the servers. Future research should more precisely capture this arrival process. Personnel do not arrive at a constant rate; the arrival rate increases through the morning peak and then ebbs after around 0800. A more thorough analysis would not only consider the ACPs, but also the surrounding roadways leading into NBSD. There are only a handful of large road arteries feeding into NBSD and thus future researchers might need to incorporate traffic models or perhaps network flow models to adequately represent how personnel travel from their residences to NBSD.

Our initial plan was to model many of the arrival intricacies just mentioned. We planned on collecting data on the commuting properties of NBSD personnel to more accurately capture the arrival process. We had discussions with NBSD and NPS Information Technology personnel about developing an automated data collection software application for smartphones. This application would safely and securely collect specific non-identifiable information on where personnel commute from, their arrival time, and the time the personnel wait in congestion before a sentry processes them onto the installation. One of the potential benefits of such an application would be that we could deploy it to essentially any installation. Future research could thus analyze other installations in a similar fashion using the specific data associated with each installation. This application could also provide information to the personnel as they commute by giving estimated wait times at each ACP. This could ease congestion around installation by more uniformly spreading arrivals across ACPs. While we were not able to develop and deploy this application in time for the thesis, our hope is that it will eventually be deployed and future work can take advantage of this wealth of data.

In our analysis, we ignored other aspects of the arrival process that future work could consider. For example, a trolley cuts right across the main thoroughfare leading into ACP 6. In discussion with the SECO, we learned that the morning trolley can significantly impact congestion because it cuts the flow of traffic into the ACP. This congestion then sits on city streets and can even back up onto surrounding freeways. Future researchers could examine the impact of changing the trolley frequency from, for example, every four minutes to every six minutes. An analysis of this type would require a combination of the arrival data from the smartphone application, simulation, and perhaps network models to determine how changing the trolley schedule could help ease congestion outside the installation. Another potentially interesting analysis would consider the impact of connecting the wet side and dry side of NBSD with a vehicular bridge across Harbor Drive. Currently, personnel residing on the dry side of the installation must leave controlled land, drive less than two miles and be reprocessed into the wet side. As approximately 4,000 personnel live on the dry side, they contribute a nontrivial amount to the total number of morning arrivals to the wet side. Building a

bridge would be costly, but it would eliminate the need to reprocess these personnel and could potentially reduce congestion significantly.

While there is much work to be done to enhance the basic analysis in this thesis, we have taken an important first step. We performed statistical analysis of actual processing data at NBSD to present a picture of the characteristics of commuting personnel and the factors that impact the processing times. We then developed a theoretical model for the processing times and provided recommendation for staffing configurations to maximize throughput onto NBSD.

However, this analysis considers congestion solely from the perspective of service times and under the assumption that there is consistent demand for service at each ACP such that sentries are never idle. As a result, our estimates of throughput capability are apt to be overestimates, meaning that congestion could be even worse than projected. In order to get a more complete understanding of the way in which fluctuations in vehicle arrivals affect congestion, future work should focus on collecting data associated with vehicle commuting and arrival patterns.

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