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Test Equipment Transportation Using the Traveling Salesman Problem

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Abstract: When transporting testing equipment, corporations often run into complications over the competing interests associated with minimizing both travel time and associated costs. More specifically, it is difficult to quantify the value of time and compare it to the costs associated with a specific mission. There are a multitude of factors which must be considered in the transportation of any equipment, especially when the equipment involves national security. The type of testing associated with each mission further increases the convoluted nature of transporting testing equipment. Some missions do not require a considerable amount of equipment, and therefore, do not need the same manning or funding as other, more extensive mission sets. Furthermore, certain testing missions require longer periods of execution time than others. All relevant aspects of the equipment transportation process make the minimization of costs and travel time difficult to achieve. Nonetheless, the goal of this project was to create a decision-supported methodology in order to lower costs, decrease travel times, and accommodate more customers, following that priority ranking. With testing locations scattered across the nation and broken up into relevant groupings using a K-Nearest Neighbors approach, executing a traveling salesman approach was gleaned to be the optimal equipment transportation methodology. The combination of both resulted in decreased travel time and costs when transporting testing equipment between regional groupings.

Keywords: Traveling Salesman, K Nearest Neighbors, transportation analysis, cost-benefit analysis

1. Introduction

The global positioning system (GPS) was developed in the mid-1970s and has since become the most prevalent method for planning and routing personal travel. This system is reliant upon three technologies: satellites, ground stations, and receivers. These three work together to provide precise locational awareness on the Earth's surface. GPS has proven to be a critical asset of the United States military, which utilizes its capabilities on a daily basis (Dunbar, 2015), and is controlled by the recently created United States Space Force. The Department of Defense uses guidance and navigation systems to execute system testing at home and therefore ensure preparedness abroad. These tests include ensuring the operational capability of warfighting technologies such as the GPS guided missiles on fighter aircraft. Such testing has proven to be extremely relevant in the area of GPS-based guidance and navigation systems in enabling the United States Air Force to maintain and foster its technological edge. Vital to national defense, GPS testing would not be possible without the efforts of testing squadrons throughout the Armed Forces. Along with optimized maintenance and manning efforts, testing squadrons must have deliberate methods of transporting testing equipment in order to conduct as many tests as possible while operating within approved budgets.

The Air Force's central inertial and GPS testing facility, the 746th Test Squadron (TS), is located at Holloman Air Force Base (AFB), NM, and supports up to fifty tests annually with durations of two to fifteen days each. About half of these tests occur locally at White Sands Missile Range (WSMR) or Holloman AFB, while the remainder are conducted at dispersed locations around the country with personnel on temporary duty (TDY) travel. Corresponding TDY costs and durations are based upon several factors, including the number of tests being conducted, the mode(s) of transportation being used to reach each location, and the mission being accomplished. Navigation warfare (NAVWAR) testing uses both high-powered jammers (HPJs) and portable box jammers (PBJs). These tests are typically longer due to set-up, tear-down, and execution requirements. Both HPJs and PBJs are transmission devices used to conceal one's location, and thus are vital components in test execution, and so transporting them to test locations is a necessary expense for these events. Direct-inject (DI) missions require no HPJs or PBJs but do need other smaller GPS-related equipment, reflected in a shorter set up, tear down, and mission execution time.

Ultimately, the costs, in both time and money, associated with traveling to conduct tests have placed stressors on the ability of the 746th to meet a recent growth in demand.

1.1 Problem Statement

Overall demand for the 746th's testing equipment and expertise increased 300% from 2015 through 2017, while demand for on-site testing (i.e. requiring TDY) increased 400% in that same time frame. Unfortunately, the resources and test capacity of the 746th have not expanded to keep up with those increases in demand, requiring creative solutions to close the gap. The 746th primarily transports equipment via ground; however, because travel time places a constraint on the number of tests they can perform, the 746th is evaluating alternative means of transporting personnel and equipment that can increase the proportion of demand that can be met while limiting travel costs. Thus, the question addressed in this paper is, *"What is the optimal way to transport testing equipment in order to minimize cost and travel time while simultaneously maximizing the number of clients accommodated for testing?"*

1.2 Related Work

To inform our analysis and recommendations, research was focused in the areas of cost-benefit analysis, transportation methodologies, activity schedules, and sensitivity analysis. Recently, Cui and Levinson (2018) broke down the classification, framework, and cost-benefit analysis for a transportation problem. They discussed the quantification of a utility function for transportation methodologies and identified each cost aspect to consider for different forms of travel, providing a roadmap for prioritizing relevant constraints and factors. Merlin (2017) examined how best to increase the accessibility of four major metropolitan areas through scientific methodology. He defines accessibility as most commonly associated with lower vehicle miles traveled (VMT) and posits that increases in proximity, and therefore a reduction in VMT, would result in increased accessibility and relaxed budget constraints for organizations, thereby demonstrating that proximity is an important factor to analyze when considering air travel. These concepts help to shape the parameters and objective function in the modeling approaches described below.

Ishutkina and Hansman (2008) used holistic analysis to find the relationship between air transportation and economic activity. The authors showed that as the air transportation system became saturated, the cost of delays had an unfavorable impact on economic activity, reflective of a similar detrimental impact in the transportation of test equipment. This article highlights benefits and drawbacks of air transportation, with the effects of air traffic delays being notable for their detrimental impact on meeting customer requirements. Miller and Roorda (2003) proposed a new prototype activity-scheduling model, the Toronto Area Scheduling Model for Household Agents. This model generated activity schedules and travel patterns for a typical weekday for individuals within a household. Operationalizing a household decision-making model in this manner helped assess the frequency, duration, and start time for each activity type and location. A key takeaway is to schedule activities based upon previous observations.

Lastly, Frey and Patil (2002) compiled a collection of ten different sensitivity analysis methods across three different categories: mathematical, statistical, and graphical. Investigating food-safety risk models, they compared each method and ultimately determined that there was no best approach; instead, they argued each method has its own strengths and weaknesses, and recommended the best use for each method. Jia and Ierapetritou (2004) took this a step further and applied uncertainty to mixed integer linear programming sensitivity analysis. They explored a primarily deterministic model but included aspects of uncertainty to address various risk factors.

2. Methodology

To determine the most cost-efficient and client-serving manner to transport testing equipment, several modeling methodologies were utilized to answer the research question. A K-nearest-neighbor (KNN) approach was applied to create regional groupings of testing locations. From there, a traveling salesman problem (TSP) analysis was executed to find the optimal route between testing locations within each grouping. Finally, a cost-benefit analysis (CBA) was performed to provide information on whether it was preferable to fly or drive to regional groupings considering both time and money. In order to execute this sequential approach, we required a variety of historical data.

2.1 Data

The 746th provided comprehensive data in order to create the most accurate view of their operations. This dataset encompasses the most recent test missions of the 746th. The data provided for each mission includes departure, arrival, and execution dates; number of jammers; test location; mission type; number of customers served; number of 746th civilian, military, and contractor personnel; number of vehicles used; stopover locations; and military and civilian personnel costs. There were 108 data points provided, each representing a unique mission which provided a small, yet sufficient, dataset from which to project travel characteristics.

Various data cleaning activities were performed prior to a preliminary analysis using Microsoft Excel. First, the total test execution length for each event was calculated from the "Execution End" and "Execution Start" fields. Next, the dataset was sorted by location name and mission type. The mean and standard deviation of execution time was also determined, as well as sample size for each testing location, separated by mission type. Finally, a simple hypothesis test was executed to determine if it was important to differentiate between mission types within the dataset. To complete this task, a set of hypotheses, using mean execution times with respect to mission types ($\bar{x}$), were created and evaluated at a 95% confidence level. More specifically, a t-statistic was calculated and compared it to a t-critical value to determine if the null hypothesis (Equation 1) should be rejected in favor of the alternative (Equation 2).

$$H_0: \bar{x}_{NAVWAR} = \bar{x}_{DI} \tag{1}$$
$$H_1: \bar{x}_{NAVWAR} \neq \bar{x}_{DI} \tag{2}$$

Because the t-statistic was much greater than the t critical value, the null hypothesis could be rejected and therefore the two mission sets must be distinguished from one another due to unequal mean execution times.

Once it was determined that mission types differed in mean execution times, the location, mission type, and execution dates were used to create predictive confidence intervals around expected mission execution lengths. The confidence intervals were useful in the execution of a TSP model (Section 2.4) and for predicting per diem, travel, and transportation costs.

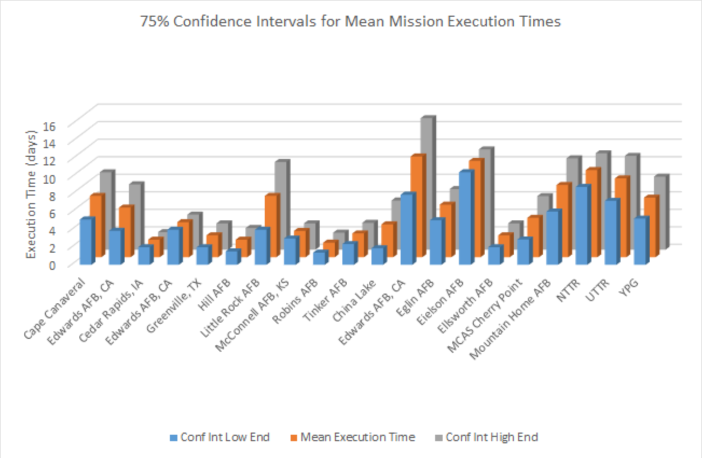

Figure 1. Confidence Intervals for Mission Execution Duration

Due to the assumption that all testing equipment can be used for a maximum of 60 consecutive days before returning to Holloman AFB to undergo maintenance (Section 2.2), both travel and execution times were considered in the construction of an optimal route within the TSP model. The defined confidence intervals provided mission length ranges, and those values were injected directly into the model. Confidence intervals (Figure 1) were created at a 75% confidence level because there were too few data points to create intervals at a higher confidence level; doing so produced infeasible travel times that included negative values. Figure 1 depicts the mean execution times and their associated high and low confidence levels. The blue (front) bars represent the lower limits of the confidence levels, the grey (back) bars are upper limits, and the orange (middle) bars represent mean execution times.

Many of the other entries in the dataset—including the number of HPJs/PBJs, number of personnel, number of vehicles, and travel times—supplemented by additional information gathered from the U.S. General Services Administration (GSA) website were used to establish travel cost estimates (Section 2.5). For each testing location (based on zip code) in the original dataset we compiled the lodging rates by month, the total daily meal and incidental expenses (M&IE) rates, and the first/last day of travel per diem rates from January 2021 through September 2021. The city-pair airfare rates between the locations in each region and between each location and Holloman AFB were also obtained; the airports used for each location were the closest that were part of the GSA's city-pair program.

2.2 Assumptions

Several assumptions were made in order to construct a holistic model. First, all testing equipment could only be used for sixty consecutive days before it was required to return to Holloman AFB for maintenance. Additionally, for DI missions, all require fewer than 24 hours to set up, while the NAVWAR missions require one to two days to set up. Both mission types required the same respective amount of time for clean-up as previously stated. This assumption was provided by the 746th who ensured that these estimates were accurate. This assumption had to be made to account for all timing that would impact the 60-day maintenance constraint.

In terms of travel, the first assumption was that upon arrival in a region the 746th will drive between locations regardless of the mode used to reach the region, and the maximum number of miles driven in a day is 480. The second was that the team will always start driving to/from a region or between test locations with a full tank of gas. The final assumption was that the costs of transporting testing equipment via commercial air, which are unknown at this time, were comparable to the additional costs that would be incurred from towing the equipment while driving.

2.3 Test Location Grouping

Before conducting a cost-benefit analysis, reasonable, if not optimal, regions in which to group test events first needed to be defined. Historical testing locations were grouped into regions based on their geographic proximity to one another using a method similar to a K-Nearest-Neighbor (KNN) approach. Typically, the KNN methodology identifies/classifies an unknown data point by grouping it with other data points so as to minimize the total separation between points across all K groups. Using a similar approach, a model was created that would find a testing location's K nearest neighbors (other nearby testing locations) and assign it to a regional grouping. The two processes differ in that the testing locations being compared had no original classification, and therefore could not initially be assigned to regional groupings. Instead, regions were created based on which testing locations were closest to one another. The geographic coordinates were compiled for each testing location, then the "as the crow flies" distance between each location was computed and each testing location's nearest neighbors to the "kth" factor was determined. In this case, k was assigned to 14, as this represented half of the number of testing centers, which accounted for all bases that were likely to be grouped together. More directly, k acts as a parameter which allows us to view a testing location's k number of nearest neighbors. Setting k to 14 allowed us to analyze a base's nearby neighbors and excluded those which automatically could be assumed to not fall within its regional grouping, due to their remoteness. Furthermore, because different mission types require different equipment and personnel, regional groupings were created such that solely DI or NAVWAR mission types were included across all locations within the regional groupings.

2.4 Test Location Routing

The TSP is a computational methodology that determines the shortest route to visit a given set of locations exactly once, starting and ending at the same location; this approach was used to emphasize the scheduling perspective of the CBA. Total travel time was minimized within a region, rejecting any solution whose total time exceeded the 60-day maintenance requirement, and used to inform the travel costs in the CBA. Based on the geographical location of testing sites, their associated groupings, and the TSP model, an optimal path was produced between testing centers within each region using the following optimization model. The decision variables were defined as:

$$x_{ij} = \begin{cases} 1 \; if\ test\ location\ j\ is\ visited\ immediately\ after\ test\ location\ i \\ 0 \; otherwise \end{cases}$$

The objective function simply minimizes the total distance traveled, as shown in Equation 3.

$$Minimize\ \sum_i \sum_j d_{ij} x_{ij} \tag{3}$$

where,

$$d_{ij} = \{distance\ between\ test\ locations\ i\ and\ j\}$$

The key result of this model was the order by which the testing locations should be visited within each region, as shown in Table 1 in Section 3 below.

2.5 Cost-Benefit Analysis: Ground Transportation Versus Commercial Aircraft Transportation

A cost-benefit analysis is used to select the best option from a group of comparable choices. This analysis requires consideration of each option's relative benefits compared to their costs as a result of implementation. Following completion of the TSP, the 746th must consider whether they should continue the use of ground travel to the regional groupings optimized by the TSP, or if they should utilize commercial air travel more frequently.

To complete this analysis, a variety of assumptions were made, which can be found in Section 2.2 above. Ultimately, those assumptions aided in the execution of a relevant and concise cost-benefit analysis. The most important of those assumptions was that since the mode of travel within a regional grouping was driving, the cost of travel, test execution, per diem, etc., stayed constant throughout the duration of a trip. Such an assumption ultimately contributed to a cost-benefit analysis which compared the amount of money saved traveling by car to each regional grouping, as compared to the time saved when traveling by air. This preference is fluid and depends on the priorities of the 746th when completing a certain grouping of equipment tests. The following equations were used to calculate the costs of both air and ground travel. It is important to note that "air cost to [or from] the region" accounts for only the costs of commercial airline tickets for all necessary personnel. Similarly, "ground cost" to the region includes only the cost of travel, in terms of mileage and gas. Maintenance costs were not included in these calculations because the 746th uses rental vehicles for TDY travel.

$$\mathit{Per\ Diem} = (\mathit{first\ and\ last\ day\ rate} + (\mathit{M\&EI\ rate} * \mathit{travel\ days}) + \big((\mathit{travel\ Days} - 1) * 96\big) * (\#\ \mathit{of\ military} + \#\ \mathit{of\ contractors} + \#\ \mathit{of\ civilians}) \tag{4}$$

$$\mathit{Gas\ Price} = ((\mathit{diesel\ price} * (\frac{1}{\mathit{MPG\ of\ trucks}}) * \mathit{distance}) * \#\ \mathit{of\ trucks}) + ((\mathit{gas\ price} * (\frac{1}{\mathit{MPG\ of\ sedans}}) * \mathit{distance}) * \#\ \mathit{of\ sedans}) \tag{5}$$

$$\mathit{Airfare\ Price} = \mathit{airfare} * (\#\ \mathit{of\ military} + \#\ \mathit{of\ contractors} + \#\ \mathit{of\ civilians}) \tag{6}$$

$$\mathit{Total\ Air\ Travel\ Cost} = \mathit{air\ cost\ to\ the\ region} + \mathit{air\ cost\ from\ the\ region} + \mathit{per\ diem} \tag{7}$$

$$\mathit{Total\ Ground\ Travel\ Cost} = \mathit{ground\ cost\ to\ the\ region} + \mathit{ground\ cost\ from\ the\ region} + \mathit{per\ diem} \tag{8}$$

3. Results

This modeling approach produced three key results: regional groupings of testing locations, the optimal routes within each of those regions, and the cost-benefit comparison of air versus ground travel to and from each region. Table 1 summarizes the first two results, combining the KNN approach that defined the regions and the TSP model that optimized the travel path within that region. Two of the regional groupings, Southeast (SE) and Southwest (SW), were split in order to accommodate the maintenance constraint and to address the different missions (NAVWAR vs. DI). Table 1 depicts both the locations that are included in each region (or sub-region) and the optimal path to visit each test location within that region. Each route begins and ends at Holloman AFB.

The third result—the cost-benefit analysis—is summarized in Table 2, which demonstrates the total cost of flying or driving to and from a regional grouping in both monetary and time valuations. In Table 2, costs are rounded to the nearest dollar and per diem costs were taken from the GSA website. The last two columns are the most important aspects, as they show how much extra money was spent (saved in red), and how many travel days would be saved, should air travel be utilized.

Table 1. Regional Groupings and Optimal Travel Routes

Region	Mission	Route	Miles
SW 1	NAVWAR	NV Test/Train Range – China Lake – Edwards AFB– 29 Palms – Yuma Proving Ground	2,065
SW 2	DI	Ft. Huachuca – Palmdale – Hill AFB	2,690
NW	NAVWAR	Ellsworth AFB – Mountain Home AFB – UT Test/Training Range – Idaho National Lab	2,520
MW	DI	Tinker AFB – McConnell AFB – Cedar Rapids – Little Rock AFB – Greenville – Ft. Worth	2,885
SE 1	NAVWAR	Camp Shelby – Eglin AFB – MCAS Cherry Point – Redstone Arsenal	4,200
SE 2	DI	Melbourne – Cape Canaveral – Robins AFB	3,615
NE	DI	Norfolk – NAS Patuxent River – Dover AFB	4,315

Table 2. Air and Ground Cost Comparison, by Region

Region	Air To	Air From	Per Diem	Air Cost	Ground To	Ground From	Per Diem	Ground Cost	Ground Savings ($)	Air Savings (Days)
SW 1	$3,250	$3,040	$870	$7,160	$1,693	$1,306	$3,950	$6,949	$211	2
SW 2	$625	$2,050	$454	$3,129	$297	$343	$2,019	$2,659	$470	2
NW	$4,100	$3,470	$825	$8,395	$1,870	$2,114	$3,845	$7,829	$566	2
MW	$1,050	$2,005	$435	$3,490	$248	$228	$1,975	$2,450	$1,040	2
SE 1	$2,330	$4,720	$825	$7,875	$2,435	$4338	$9,885	$16,658	($8,783)	6
SE 2	$1,270	$1,490	$473	$3,233	$447	$577	$4,408	$5,432	($2,199)	5
NE	$1,310	$1,550	$413	$3,273	$797	$825	$6,453	$8,074	($4,801)	8

4. Recommendations and Potential Future Research

Considering the results of both the KNN and TSP models while also addressing the CBA, our recommendations are to fly only to the Southeastern (SE 1 and SE 2) and Northeastern (NE) regional groupings. For these, flying will save the 746th both time and money. The 746th should drive to the other regions as the two days saved are not worth the incurred costs, based on the valuations of time and money provided by the 746th.

Due to the nature of the small amount of data provided, there were several assumptions that had to be made throughout the course of this project. The first future application of this model would be to apply it to a much larger dataset. It is recommended, although out of the scope of this analysis, that the 746th compile data more completely for all testing missions executed. Another proposed application would be to expand the model for not only the 746th, but also other equipment testing squadrons in the Air Force and Department of Defense. Finally, determining the costs of transporting testing equipment by air, and basing future projections off historical data may produce a more complete analysis, which may sway the determination of whether it is more optimal to fly or drive to regions.

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