EVALUATING BEAT STRUCTURE AND TRUCK ALLOCATION FOR THE TARRANT COUNTY COURTESY PATROL

by

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ABSTRACT

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Non-recurring congestion poses a significant concern to urban freeway drivers. Effective incident management relies on many tools to lessen the overall impact of crashes, road debris, and stalled/disabled vehicles. While many of the tools are based in a region's traffic management center, many urban areas have adopted freeway service patrol (FSP) programs that patrol the freeway network searching for incidents, providing aid to motorists, and assisting with incident management and clearance. While FSP operations can be assessed in terms of response and clearance times, FSP management must consider the beat structure and fleet allocation. This investigation considers response time and fleet allocation.

This study uses both deterministic and probabilistic response time estimations for each beat to assess different fleet allocations. The research's goal is to consider whether the urban network should be segmented into as many beats as possible with individual trucks assigned to each beat or if additional trucks should be allocated to fewer beats.

In an effort to explore the truck allocation problem with field data, the study uses the Tarrant County Courtesy Patrol (CP) as a case study. The Tarrant County CP typically uses a one-beat, two-beat or three-beat configuration with a single truck allocated to each beat. This study explores the merits of adding an additional truck to a beat in the two-beat configuration rather than expanding to the three-beat configuration; remaining in the two-beat configuration shows an improvement in estimated response time of four to nine percent. Although the deterministic case shows better performance for the one-beat configuration rather than changing to a two or three beat configuration, the probabilistic case indicates the superiority of the two-beat configuration. This emphasizes the importance of utilizing a probabilistic approach for evaluation. Furthermore, the two-beat configuration appears to perform better because links that are traversed more frequently tend to have more incident per mile than those for other beat configurations. This finding indicates that the incident distribution should be considered during both beat and tour design.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Objective and Overview

Traffic delay is a continuing concern of urban drivers [1]. On the urban freeway network, a high proportion of this delay is due to unforeseen incidents (e.g., a stalled vehicle, a crash, or an unexpected object or debris on the pavement); these temporary problems restrict the traffic speed and freeway capacity while creating safety concerns. Therefore, removing these problems quickly from the freeway has a critical role in the network's performance and metropolitan areas should use systematic procedures to respond and clear these kinds of issues as soon as possible.

As shown in Figure 1, total delay incurred due to an incident consists of five separate phases: Detection Time, Verification Time, Response Time, Clearance Time, and Discharge Time [2]. The first step is incident detection, which includes many approaches such as using traffic sensors like loop detectors, probe vehicles, video, and cellular phones [2]. Although the detection time generally has a large share of the total delay, collecting and determining the detection time poses a challenge because the traffic management agencies rarely know exactly when an incident occurs. Although there are many incident detection algorithms that develop performance measures based on traffic data inputs, physical infrastructure, and incident rates, their investigation is beyond the scope of this study. These estimates of detection time from incident detection algorithms are one of the best sources of detection time, but their effectiveness depends on the algorithms, data collection, traffic volume, and incident type. The second piece of delay is the verification time, which measures the time between when the incident is reported and the incident occurrence is confirmed by the agency. The verification time highly depends on the detection strategy and camera availability but generally should not take a long time in an urban environment with traffic management facilities.

The response time forms a high proportion of the total delay but could be greatly decreased by using an effective strategy. Response time starts after the incident occurrence is detected and verified and ends when the appropriate action to remove the incident starts on the scene. For patrolling vehicles, the detection, verification and response are not separable and occur together as will be described in the Freeway Service Patrol strategy. Then, clearance time starts when the responsible agency arrives at the scene and continues until the incident is removed from the network. This time is highly dependent on the incident type and severity. Finally, discharge time measures from when the incident is removed from the network until the effect of the incident is completely eliminated and the traffic returns to the normal condition, which is generally dependent on the traffic and facility characteristics such as capacity and flow. Secondary incidents caused due to a primary incident (such as a crash) can increase the discharge time. This study aims to minimize the total response time for the patrolling case, but for patrolling vehicles, the FSP directly performs the detection, verification, and response functions in quick succession. As a result, the response time includes all three phases of incident delay.

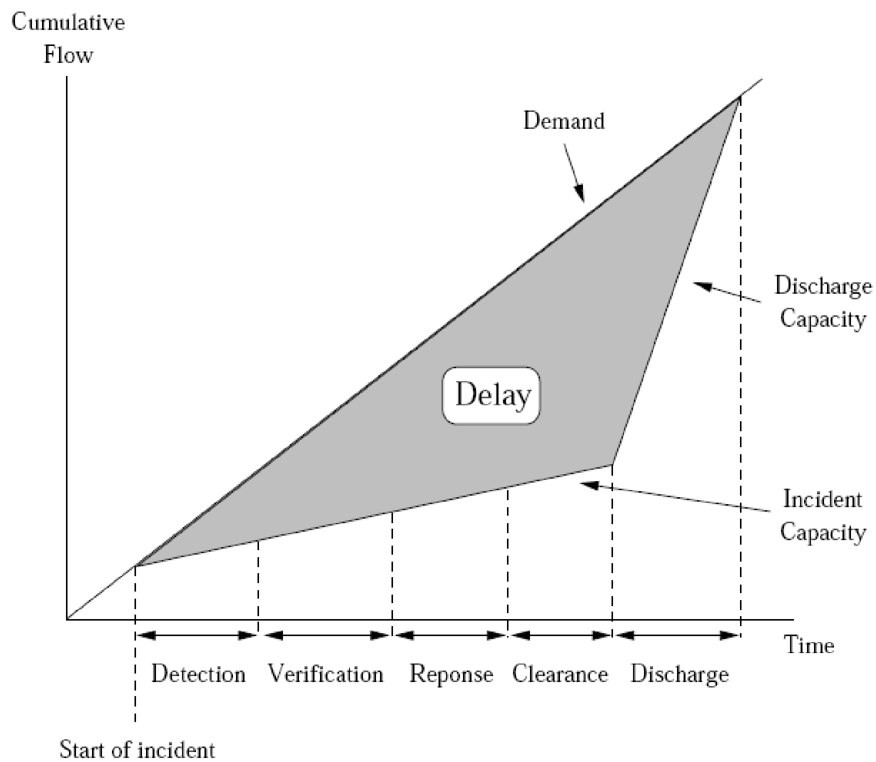

Figure 1 Incident Delay Components, source [2]

Traffic management uses a variety of strategies to respond to nonrecurring congestion. Once an incident is detected, the operating agency may use variable message signs, ramp metering, temporary shoulder use or other strategies to manage the travel demand where the incident is located [3]. However, the key to successful (e.g., improved safety and quicker return to full capacity) incident management is rapid detection, response and clearance as well as on scene management. Many regions have opted to create a fleet of service vehicles to assist with incident management and to respond and clear minor incidents. These vehicles could be dispatched to incidents from a centralized depot, but the detection and dispatch time may be higher than desired [2]. Although by creating several depots on the network the agency can reduce the response time, the construction and operating cost of additional depots may be high, which decrease its attractiveness. A different strategy for improving incident detection is to have the service trucks move into the detection and verification role directly by patrolling the freeways. This system, which is called Freeway Service Patrol (FSP) or Courtesy Patrol (CP), has been widely used in US metropolitan regions like Los Angeles, Chicago, and Dallas-Fort Worth. The most important advantage of this system is actively detecting incidents while patrolling. (FSP and CP both refer to the same system, but FSP is a more general terminology while CP is used in the Dallas-Fort Worth area. During this study, both terminologies are used for the same program.)

This study aims to improve the efficiency of courtesy patrol trucks given fleet size constraints; specifically, should the network be re-structured into more beats or should additional trucks be allocated to existing beats. Although the total incident time in CP operations is a combination of response time, clearance time, and discharge time, this study focuses on the response time. The detection-response time can be adjusted using fleet management and beat structure strategies while clearance time is more a function of incident type and crew, and discharge time is a function of the network traffic characteristics. The determinations of vehicle paths, which are called beats, are typically based on network structure; however, their structure may also consider incident frequency and traffic volume [1]. This study does not focus on the beat structure, but examines the merits of allocating additional trucks to existing beats rather than creating additional beats for the added trucks. Part of the fleet management problem is also to allocate trucks to the beats given a pre-specified beat structure. The study uses response time as the primary measure of effectiveness for evaluating different allocation strategies.

1.2 Literature Review

Ma *et al*. evaluated the effectiveness of FSPs in decreasing the duration of roadway blockage and vehicular delay on 11 miles of freeway and six interchanges of the I-85 corridor in Greenville, S.C. They developed “a customized PARAMICS model for random spatial and temporal crash generation and modeling different numbers of FSPs and response policies through an application-programming interface” [4]. Furthermore, Petty planned a model based on traffic theory in combination with marginal benefit analysis, for determining where to place tow trucks so as to maximize the expected reduction in congestion [2]. Yin proposed a minimax bi-level programming model to determine a fleet allocation that minimizes the maximum system travel time that may result from incidents [5]. These two recent studies presented two distinct strategies to allocate trucks by following two different approaches. The current study is also presenting another strategy to determine the best allocation of trucks by minimizing the total response time.

Moreover, Levinson *et al*. performed a stated preference analysis to measure the service that the FSP provides to an individual and reported that the Los Angeles FSP has a benefit over cost ratio of about six [6]. Also, Pal and Sinha presented a simulation model to evaluate and improve the effectiveness of freeway service patrol programs. They found fleet size, beat design, dispatch policies, patrol area and hours of operation are parameters that can be changed to improve the performance of the program [1]. This study provided insight for the current study on the appropriate parameters to investigate during the case study, and as a result, most of these parameters are carefully considered during this study. Furthermore, Lou *et al*. developed two non-linear mixed-integer models for deterministic and stochastic integrated FSP beat design and fleet allocation. These models can effectively reduce the expected time for detection, response and clearance of traffic incidents [7]. The current study is developing a simpler model for deterministic and probabilistic fleet allocation by minimizing the total response time. In another study, Yin formulated a model to allocate patrol trucks among beats by optimizing the performance of the FSP system. He also presented a deterministic optimal fleet allocation method to minimize total expected waiting time [8]. This deterministic model represents the foundation for the current study to develop a probabilistic model.

As presented, many studies are done to determine the best allocation of trucks using different approaches and strategies, which confirms the importance of truck allocation in the performance of FSP program. Although Yin presented a deterministic method [8] to minimize total waiting time, this method does not appear to be applicable because incident distribution and truck location at the time of incident occurrence are not considered. This study tries to improve the deterministic model to a probabilistic model and apply the method to a study area to evaluate the performance of the methodology. The model framework is presented in the next chapter.

CHAPTER 2

MODEL FRAMEWORK

2.1 Overview

Generally, motorists incur delay during three different phases of an incident. First, the response time (Including detection and verification times), which is the time between when the incident occurs and patrolling trucks arrive at the scene, and the second, clearance time, which is the time from when trucks arrive at the scene and the problem is completely removed. Lastly, recovery (discharge) time measures the time from the end of clearance until traffic conditions return to normal. Clearance time depends highly on the incident type and could take from a few minutes when a vehicle just needs a gallon of gasoline to several hours for a severe crash. Since an incident has a great influence on the total network and may create delay for all vehicles driving on the network, response time and clearance time should be minimized as much as possible, which likely reduces recovery time and definitely reduces overall delay. This study focuses exclusively on response time and investigates truck allocation to minimize response time.

In tackling these problems, three issues need to be determined. First is the setup of beats, which is how the network is divided into different paths for patrolling. For this purpose, the freeway network should be segmented into different links and assigned to a beat (some links may be included in more than one beat). Second is the fleet size constraint, which describes the number of available trucks, which is dependent on the agency's budget and the expense for each additional truck including driver salary, fuel, and truck maintenance. However, there could be some other parameters influencing the fleet size. As a result, this number is fixed for different fleet allocation scenarios. Finally, the trucks must be allocated to the beats to minimize delay resulting from incidents. This final allocation is the focus of the study, especially for the case when choosing to create more beats and allocate one truck to each beat or allocate additional trucks to existing beats.

CP trucks may become aware of an incident in two ways. In some cases, the truck may be informed by central dispatch, which has detected the incident either by using various incident detection methods and algorithms or communication from other entities such as police department or the traveling public. In this instance, the truck will proceed directly to the scene from its current location (either the depot or a link on its beat). This type of response is called patrol-based dispatch, and is different from depot-based dispatch because, in this method, trucks are still patrolling and only the detection phase is attributable to dispatch. In the rest of the study, patrol-based dispatch is referred to as the dispatch case. In the dispatch case, the number of trucks on each beat has a smaller impact on the response time because the trucks move directly to the incident location. Therefore, in this method, just one truck is allocated to each beat to calculate the response time excluding the detection time. The second method occurs when a truck encounters an incident while patrolling on its beat; this incident detection feature greatly enhances the utility of courtesy patrols. This method relies highly on the number of trucks on each beat because larger headways will increase mean detection-response times. Although only response times (not including detection time) for dispatch are most likely lower than the patrol case, trucks are not always informed of the incidents or are not informed in a timely manner, which may increase total delay. As a result, the total delay, including the detection and the response time, is typically less for the patrolling case than the dispatch case. However, given these differences in the times associated with the dispatch or patrol case, comparing the dispatch and patrol field response data separately will provide a more accurate assessment of current FSP performance.

The response time is different for the patrol and dispatch cases, and each case depends on the incident and truck locations. At first, one may assume that the average response time for each beat may be calculated by averaging the response times for each pair of links i,j on the beat, where the incident occurs on link *i* and the truck is somewhere on link *j*. This approach is appropriate when incident occurrences are uniformly distributed among all links. However, when the probability of incident occurrence varies for each link, this simplified approach provides erroneous results. As a result, the probability of incident occurrence and truck location should be coupled together to obtain a more accurate measure of response time.

2.2 Patrol

Using the deterministic case for FSP incident detection proposed by Yin (2007), one can allocate FSP trucks to the network with the objective of minimizing response time [8]. As a first step, each beat requires determination of a minimum travel time tour, where a tour traverses all links in the beat at least once and returns to its starting node; the time required to complete a tour is called tour time. Define node degree of node *i* as the number of links ending or starting at node *i*, and define the Euler tour as the tour which traverses each link on the network exactly once; a network may not have such a tour. According to the Euler rule, each network could have an Euler tour if and only if all of its nodes have an even node degree. A network that does not possess an Euler tour should be solved for the minimum tour, which traverses each link at least once. Designing such a tour is an Edge-Covering problem and there are some methods to tackle these kinds of problems; one of these is the Chinese Postman Problem Algorithm. To find the minimum tour, the nodes with odd degrees should be determined. Note that their sum is an even number. Then, find the set of pairwise odd-degree nodes, where adding links between those pairwise results in the shortest extra length. Finally, by connecting those odd-degree nodes together, the network is converted to a new network where all of its nodes have an even degree. Then, an Euler tour can be designed in the new network, which is the minimum tour on the initial network, which traverses each link at least once.

The response time during the specified period for each beat is a function of the mean response time for each beat, t_{avg}, which is equal to half the tour time when a single truck is allocated to a beat. Assuming that patrolling speed is constant and congestion does not impact the average standard patrolling speed, one can calculate the tour time by dividing the tour length by the average speed. The number of incidents on each beat is defined as *n*, and the study assumes that incidents do not occur at the same time on the same beat and trucks on the beat are available to provide service. Then, the response time, *R*, for each beat during the study period can be calculated by the following formula:

$$R = nt_{avg} \tag{1}$$

After another truck is added to the beat, the response time is halved because the expected time to detect the incident is halved. Given *X* available trucks to allocate, if the patrolling trucks maintain a constant headway, the beat can be divided into *X* identical sections where there is one truck on each section. As a result, the average distance that the closest truck to the incident needs to traverse is half the length of the section, which is the length of the tour divided by 2*X*. Generally, the response time on each beat can be calculated by the following formula:

$$R = \frac{nt_{avg}}{X} \tag{2}$$

Where *X* is the number of trucks patrolling on the beat, and t_{avg} is equal to half the tour time

So now, the response time on each beat during the pre-specified time period is obtained. But, each beat is part of the overall network whose total response time must be minimized. Then, the following equation can be used to estimate the total response time for the network:

$$R_t = \sum_k \frac{n_k t_k}{X_k} \tag{3}$$

R_t = total response time on the network due to incidents

n_k = the number of incidents on beat k

t_k = the average response time on beat k

X_k = the number of trucks patrolling on beat k

Note that the sum of X_k for all beats is equal to the total number of trucks available to allocate to the whole network. Allocating the trucks to the beats influences the CP performance; thereafter, this task should be done so that it increases the CP efficiency as much as possible. Then, the following objective function and constraints must be solved to determine the truck allocation that minimizes the total response time on the network:

Minimize

$$R_t = \sum_k \frac{n_k t_k}{X_k} \tag{4}$$

$$\begin{aligned} s.t.\quad & \sum_k X_k = Q \\ & X_k \geq 1 \\ & n_k, t_k \geq 0 \\ & X_k, n_k \in integer \end{aligned}$$

Where Q is the total number of trucks

The objective function could be solved by a simple program written in MATLAB software. By solving the above function, the allocation of trucks on each beat can be determined by assuming the incidents are uniformly distributed. However, a uniform distribution is atypical because each link has different traffic characteristics and geometry. As a result, trucks are more likely to detect incidents on high-risk links rather than links that may occasionally have an incident. Here, a more accurate method is presented by considering the distribution of the incidents among the links on the network. In addition, the method takes into account the truck location on the separate links during the study period by considering the link length and frequency of traversing during a complete tour.

The probabilistic case works in a similar way. Function (4) can still be solved to acquire the truck allocation and calculate the total response time, but t_{avg} must be calculated based on the probability of incident occurrence on link i while the truck is on link j. First, one needs to specify the probability of an incident occurrence for each link by considering the total number of incidents on a beat during the study period and the percentage of these occurring on each link. The following formula can be used to calculate the probability of incident occurrence on link *i* on beat *k*:

$$Prob\ (incident_i, b_k)\ =\ \frac{r_i}{n_k} \tag{5}$$

Where n_k is as defined before, r_i is the number of incidents on link *i*, and b_k represents the beat. For incidents occurring on links, that are included in more than one beat, the closest truck on those beats likely will respond to the incident. However, for simplicity, it is assumed that trucks on different beats respond to these incidents equally. Then, if link *i* is included in more than one beat, r_i should be divided based on the number of beats containing link *i*.

Another factor that should be considered in the estimation of the response time is the truck location. This can be determined by using the probability that the truck is on a particular link when an incident occurs on the same beat that the truck is patrolling. This probability depends on the link length and the number of times that the truck traverses the link during a tour on the beat. Then, by assuming constant speed, this probability can be calculated using the following formula:

$$Prob\ (truck_j, b_k)\ =\ \frac{f_j d_j}{\sum_j f_j d_j} \tag{6}$$

Where:

f_j = the number of times that truck traverse on the link *j* during a tour on beat *k*

d_j = the length of the link j

Now, two important probabilities of incident occurrence and truck location are acquired, but these two must be combined to get the probability of incident occurrence on a link while the truck is on a specified link. A matrix can be constructed that shows the joint probability of incident occurrence on link *i* when the truck is on any link *j*. Since the probabilities of incidence occurrence on link *i* and truck presence on link *j* are independent, the resulting joint probability for any cell in this matrix is the product of the aforementioned probabilities.

$$Prob\left(incident_i, truck_j, b_k\right) = Prob\left(incident_i, b_k\right) * Prob\left(truck_j, b_k\right) = \frac{r_i}{n_k} * \frac{f_j d_j}{\sum_j f_j d_j} \quad (7)$$

All variables are as defined before.

Now, to calculate t_{avg} for the beat, the event (incident and truck location) probability for each *i,j* pair must be multiplied by the travel time for the event's link pair; this process must be completed for the entire matrix of possible events, which results in another matrix whose sum of the cells is the average response time on the beat.

The deterministic t_{avg} for each beat can be calculated more easily by finding the mean of the travel times between all link pairs. However, this result is unlikely to be as accurate as the probabilistic approach whose t_{avg} for beat *k* could be obtained using the following equation:

$$t_k = \sum_i \sum_j Prob\left(incident_i, truck_j\right) * t_{ij} \quad (8)$$

Where

$t_k = t_{avg}$ for beat *k*

t_{ij} = average travel time from link *i* to link *j* on the tour

Note that t_{ij} is different from t_{ji} for the patrol case. Different strategies could be used to calculate average distance from link *i* to link *j.* The common strategy adopted in this study is to calculate distance between mid-points of the links and keep the links small to decrease the calculation error.

The shortest tour that covers all of the links at least once is known as an Edge-Covering problem. Kwan Mei-Ko, 1968, presents a simple algorithm for solving the Edge-Covering problem. As described before, the solution requires that the odd-degree nodes be connected together such that all nodes are even and the additional cost to traverse these connections is minimized.

2.3 Dispatch

In the dispatch case, the study assumes that the trucks are informed of the incident by the depot. Then, the truck on the beat where the incident occurred will move directly toward the scene from its current location. The process for the dispatch case is similar to the one presented for the patrol case, but the main difference is the calculation of travel times from link *i* to link *j*. To calculate the response time for the dispatch case, the shortest path between links *i* and *j* can be used because the tour need not be followed. The calculation of the probabilities is about the same because the only difference is that the dispatch method is only concerned with the link and not the entire tour; therefore, this method does not distinguish between the first time and subsequent times that a link is traversed during a tour. One should note that for the dispatch case, this calculation of the response time does not include the detection time, while in the patrol case, detection time is included in the response time because the detection time and the response time occur together. A direct comparison between the results obtained for the patrol case and the dispatch case requires the detection and verification times be added to the calculated response time. The total detection time during the study period may be acquired by multiplying the average detection time for the study area by the number of incidents during the study period. One may find the average detection time for the dispatch case by referring to previous research or a data collection strategy such as an incident detection algorithm. However, calculation of the detection time for the dispatch case is beyond the scope of this study.

CHAPTER 3

CASE STUDY

3.1 Study Area

The techniques discussed in the previous section are applied to the Tarrant County CP. The Tarrant County CP covers eight freeways including IH-20, IH-30, IH-35, IH-820, SH-360, SH-121, US-287, and SH-183 serving cities such as Fort Worth, Arlington, Richland Hills, Euless, and Haltom City. The Tarrant County CP, which is operated by the Tarrant County Sheriff's Office, uses a depot located at the Texas Department of Transportation Fort Worth District Office. The Tarrant County CP has three typical beat configurations. The three-beat configuration is labeled Setup A (Figure 2), while the two-beat configuration is labeled Setup B (Figure 3), and the one-beat configuration is labeled Setup C. Setup C covers all freeway links in the network in only one beat. The Tarrant County freeway network includes eight different highways, which are divided into different links where the freeways intersect. As a general rule, the study assumes that the probability of incident occurrence is uniform along each link because the link is not crossed by another freeway, and as a result, the traffic characteristics do not change significantly, though geometric conditions may change. This assumption implies that variations in incident probability along a link will be captured more accurately by using shorter links. In addition, since the links' midpoints are used to estimate the travel times between the links, shorter links reduce the error associated with incident and truck location along a link. Therefore, some of the longer links between freeway interchanges in the Tarrant County network are subdivided due to their length. For example, links 822 and 823 (See Figure 4) are not crossed by any major highway on the network but the total length of these two links is about 14 miles, which may create inappropriate error if treated as a single long link. This process of subdividing the links could be continued to create even shorter links.

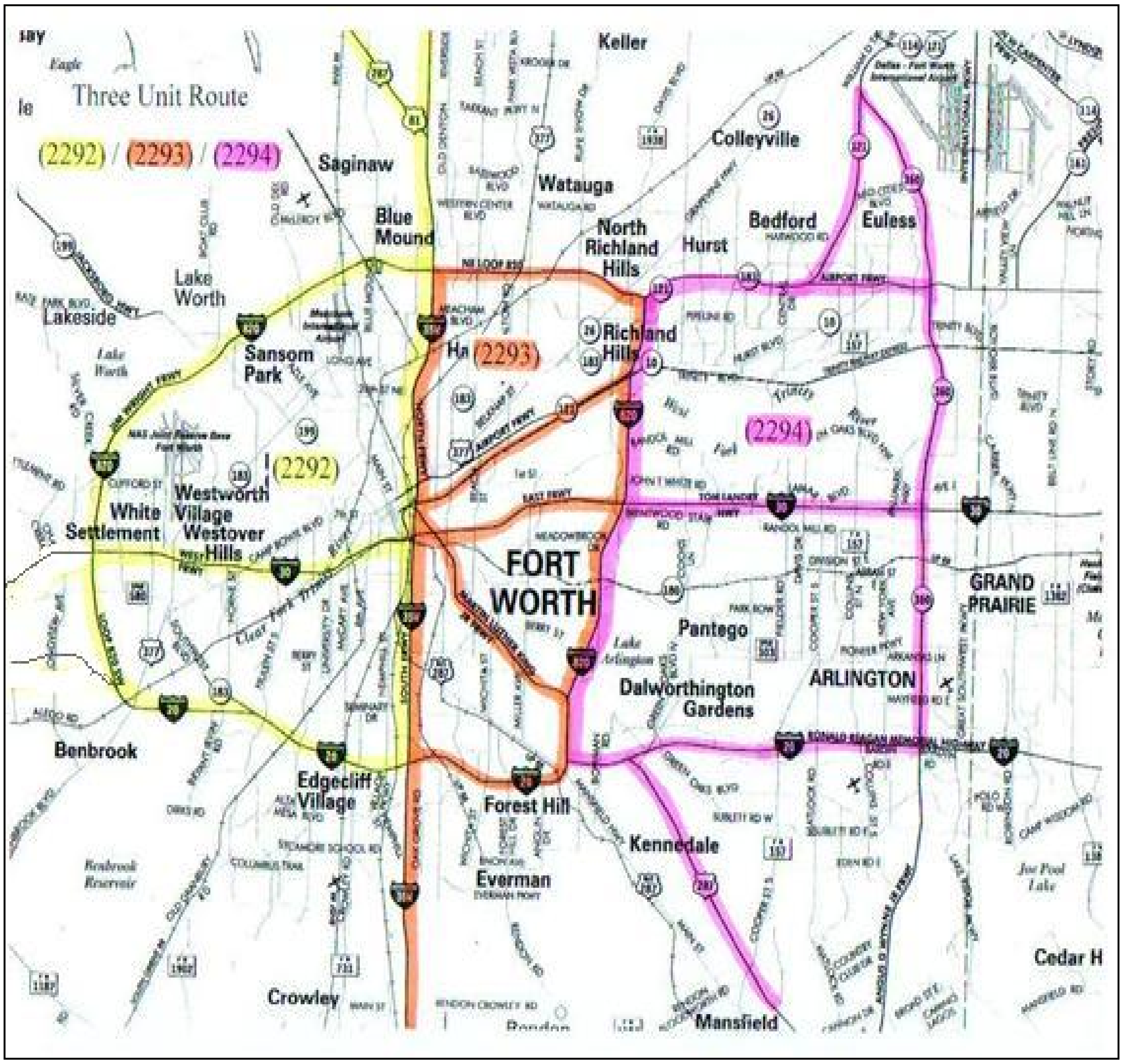

Figure 2 Setup A, Three-Beat Configuration for Tarrant County CP Trucks

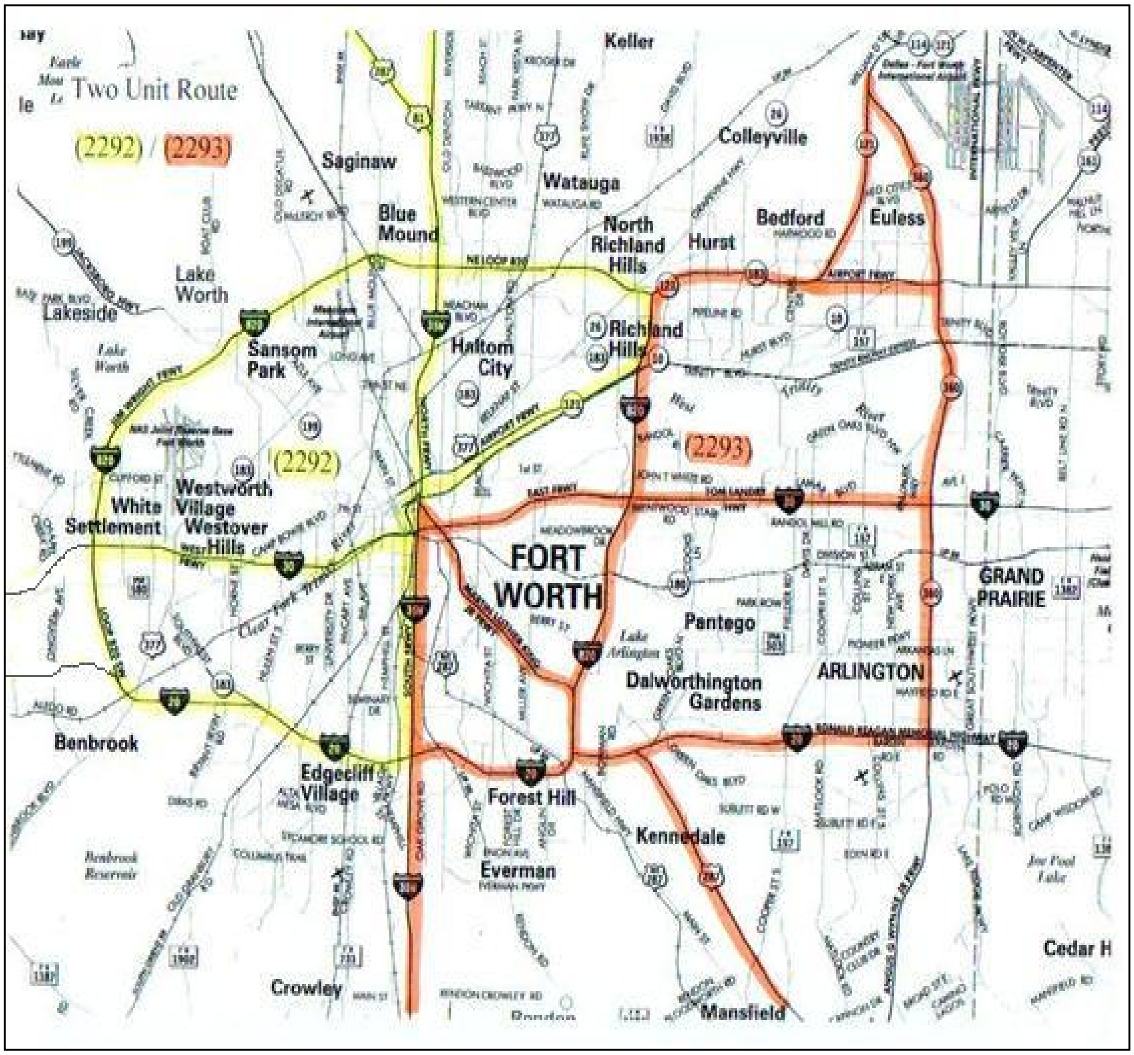

Figure 3 Setup B, Two-Beat Configuration for Tarrant County CP Trucks

As shown in Figure 4, all of the freeway links are presented below:

- I-20: 201-202-203-204
- I-30: 301-302-303
- I-35: 351-352-353-354-355-356
- I-820: 821-822-823-824-825-826-827-828
- State Hwy 360: 362-362-363
- State Hwy 121: 1211-1212
- U.S. Hwy 287: 2871-2872-2873
- State Hwy 183: 1831-1832

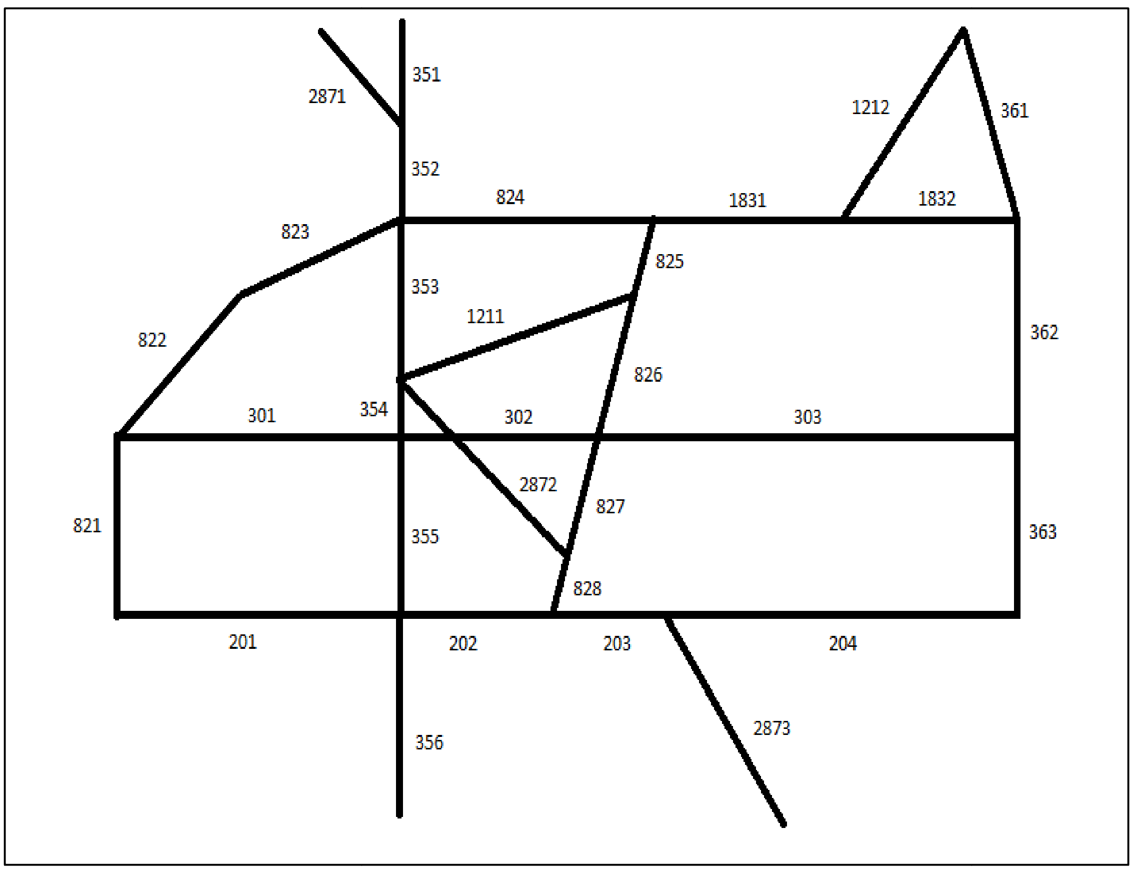

Figure 4 Schematic Diagram of the Tarrant County CP Links

As shown in Figure 2, setup A has three beats named 2292, 2293, and 2294, and Figure 3 shows that setup B has two beats named 2292 and 2293, while setup C beat 2292 covers all links. The Tarrant County CP keeps a log of the incident data such as location and type on data sheets. As shown in Figure 5, the incident data log identifies which truck (vehicle number) has been patrolling on a beat (route number) for a specified date and shift. It also shows the history of assists provided during the period including assists start and end time, the incident type (code in Figure 5) and location as well the characteristics of the stopped vehicle. Unfortunately, the CP does not identify the current beat configuration and uses the same numbers for each beat setup. For example, beat 2292 for setup A just covers about one-third of the network, while beat 2292 for setup B covers half of the network, but the data sheets just record the beat number not the beat configuration. To clarify the actual beat configuration the beats are renamed A-2292, A-2293, A-2294, B-2292, B-2293, and C-2292. Thankfully, the data sheets also indicate the approximate location of the incident on the network, which facilitates determining the incident distribution on the links and the beats. Unexpectedly, in patrolling, Tarrant County CP trucks do not follow any tour and move randomly on the beat; however, this study still designs Edge-Covering minimum tours based on link length. These are shown in Figures 6, 7, and 8 for beats A-2292, A-2293, and A-2294, and in Figures 9 and 10 for beats B-2292 and B-2293, and in Figure 11 for beat C-2292, respectively. Note that on some beats the depot is not on the tour; therefore, each truck must connect to the tour from the depot (at the beginning and end of each shift) and these connections appear in the following tour figures. In the tour design, it is assumed that the links are bi-directional and trucks can detect and respond to an incident on the opposing side of the patrolling direction (links are not considered median-separated). The travel time to change patrol direction and respond is considered negligible when compared to overall response time, because most likely the trucks will have interchanges available within each link to execute a U-turn.

Courtesy Patrol Shift Events Log

Vehicle Number: 2578	Route Number: 2292 2293 2294 2295 2296	10-7 Out of service 10-8 In service 10-9 Repeat 10-12 Stand-by
Date: 10/27/10	Operator: Davis	10-19 Return to 10-20 Location 10-21 Call by phone 10-22 Disregard
Shift: A	Co-Operator: Dixon Crane	10-23 Arrived at scene 10-41 Beginning Tour of Duty; 10-42 Ending Tour of Duty 10-45 Animal Carcass
10-41: 0600	10-42: 1349	10-46 Stranded Motorist 10-50 Accident 10-97 Check Radio Signal
Begin Mileage: 61770	End Mileage: 62011 Total Shift Mileage: 241	10-2 Radio Signal Good T-Transport D-Debris SC-Satellite Check; 1594- Used when we give Fuel

20-3
30-6
121-4
360-3
820-2
18

Time Dispatched	10-7	10-8	Code	Location	License Plate L/P	State	Vehicle Make/Type	Gal. Gas	Reason for Stop/Corrective Action/REMARKS/Cancelled Time
	0643	0644	46	30E @ 820	499YYB	TX	Kia	–	Abandoned / Tagged
	0647	0648	46	30E @ Cooks Ln	X22 LGS	TX	Honda	–	Flat / no spare / Help Encoute cc
	0837	0838	46	20E @ Bowman Springs	DYT 405	TX	Pontiac	–	Abandoned / Tagged
	0849	0850	46	20E @ 360N	NXH201	TX	Lincoln	–	Abandoned / Tagged
	0908	0908	46	30bn @ Trinity	93DDRL6	TX	Chevrolet	–	Abandoned / Tagged
	0915	930	46	360S @ Norewood	GBN219	TX	Ford	1	1594
	0933	0934	46	360N @ FAA	RTV109	TX	Nissan	–	Abandoned / Tagged
	0947	0948	46	121S @ mid cities	X72PTH	TX	Nissan	–	Abandoned / Tagged
	0949	0949	46	121S @ mid cities	C84 CB4 3268	TX	Ford	–	Abandoned / Tagged
	0955	1006	46	121S @ Bedford Rd	TDK683	TX	Nissan	–	Flat / Changed
	1009	1012	46	121S @ Recint Line	JGT2272	TX	Chrysler	–	Abandoned / Tagged
	1023	1027	46	30E @ Cooks Ln	BJS 4284	TX	Mitsubishi	–	Abandoned / Tagged
	1030	1032	46	30W @ East chase	BR8 P603	TX	Mercury	–	CC / Trying to sync BlueTooth
	1039	1109	L	30 @ East Chase	–	–	–	–	Lunch
	1113	1123	46	30 @ Fielder	72LW26	TX	Toyota	–	Flat / changed

A-Adam B-Boy C-Charles D-David E-Edward F-Frank G-George H-Henry I-Ida J-John K-King L-Lincoln M-Mary
N-Nora O-Ocean P-Paul Q-Queen R-Robert S-Sam T-Tom U-Union V-Victor W-William X-X-ray Y-Young Z-Zebra

Figure 5 Tarrant County CP Incident Data Log

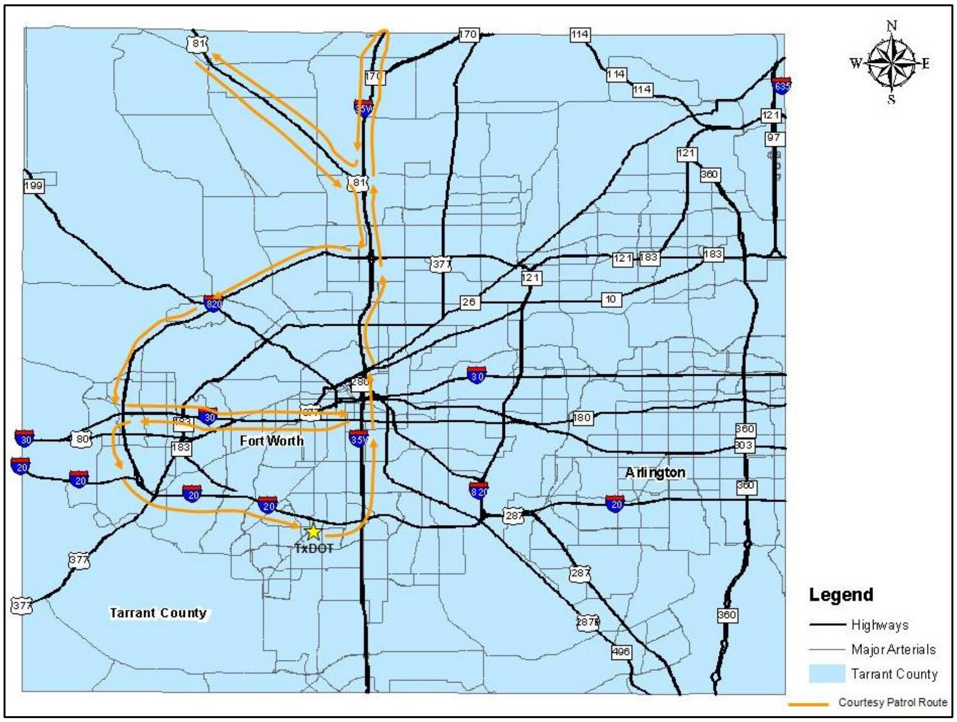

Figure 6 Tour of beat A-2292 for Tarrant County CP Trucks

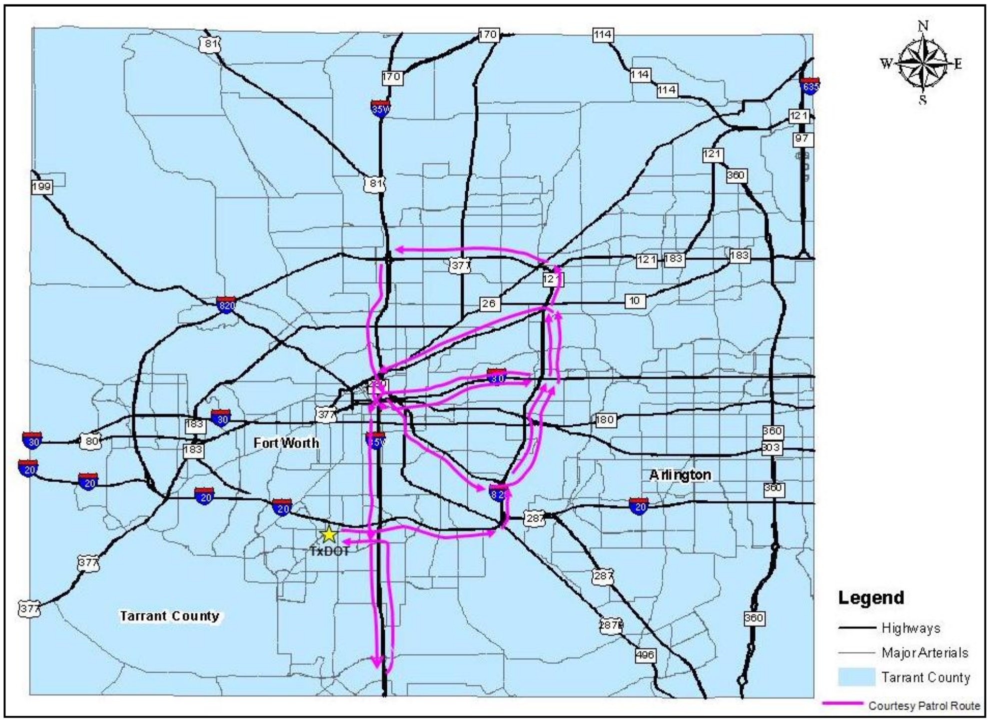

Figure 7 Tour of beat A-2293 for Tarrant County CP Trucks

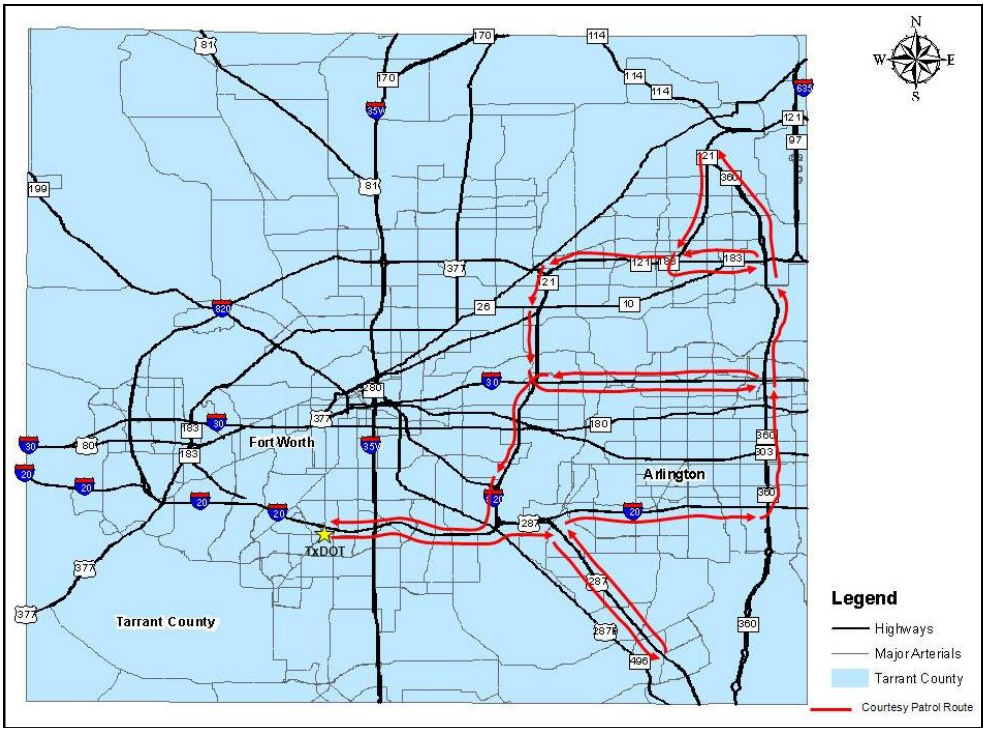

Figure 8 Tour of beat A-2294 for Tarrant County CP Trucks

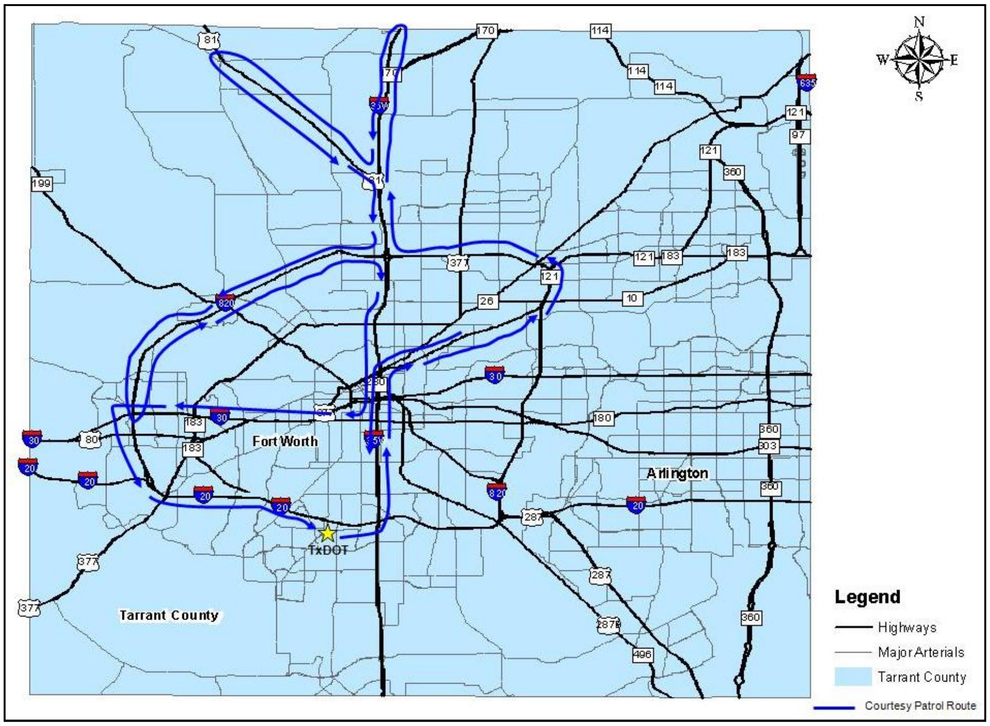

Figure 9 Tour of beat B-2292 for Tarrant County CP Trucks

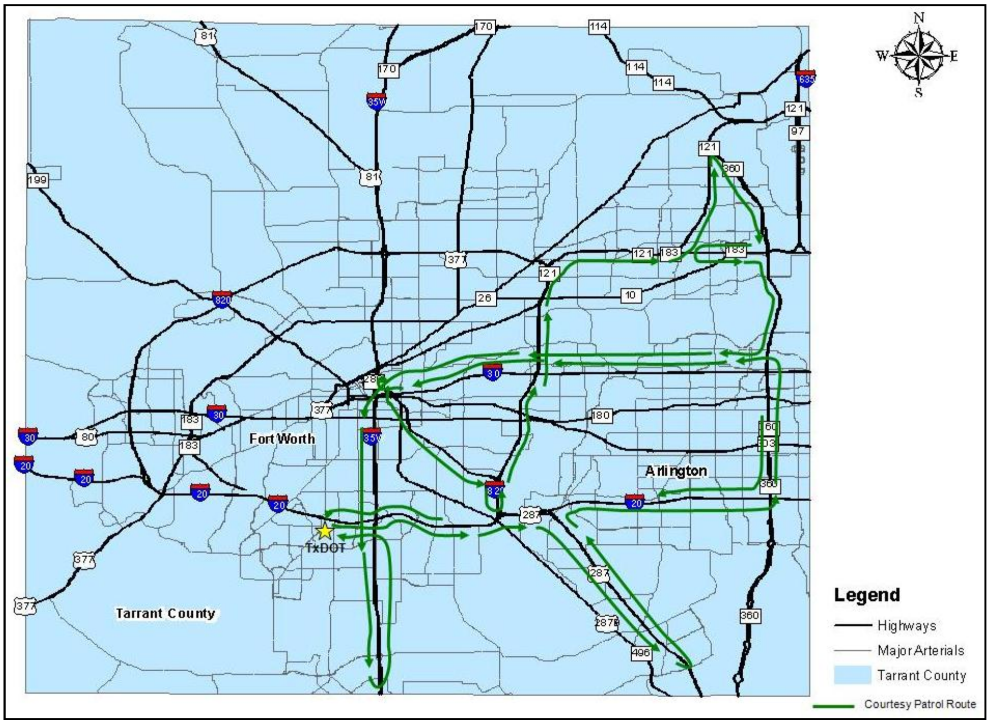

Figure 10 Tour of beat B-2293 for Tarrant County CP Trucks

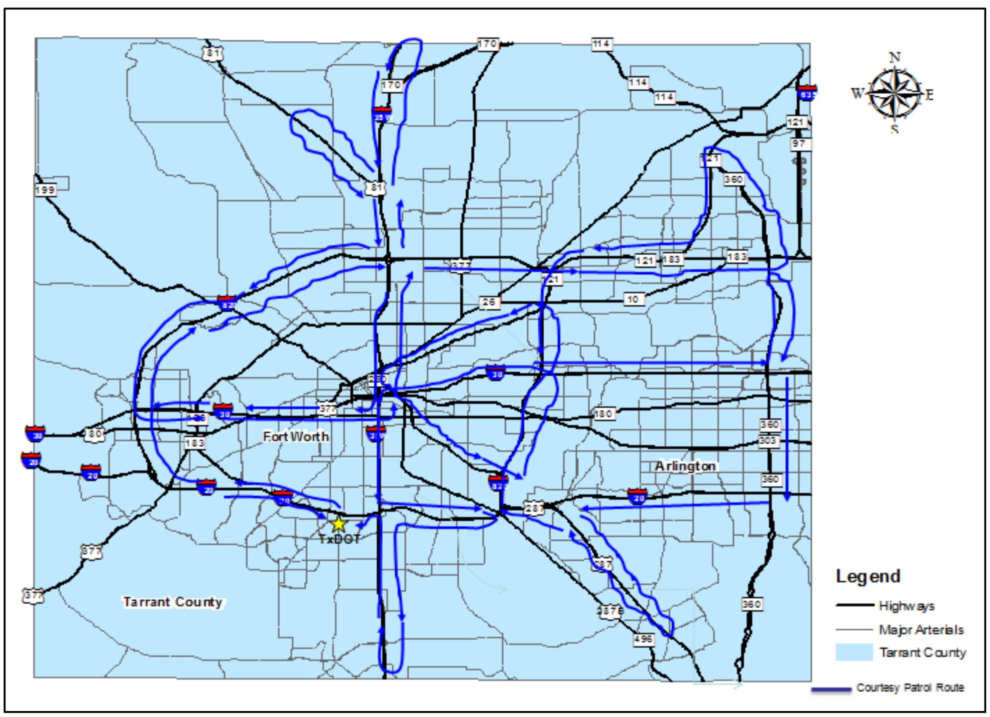

Figure 11 Tour of beat C-2292 for Tarrant County CP Trucks

As mentioned, the Tarrant County CP maintains a log during each shift in each truck. The crews record in these logs the incident location and type as well as the time that aid is provided. Although there may be some locational data errors in the crew records, these errors should remain relatively negligible when considering the overall network. The study investigates the CP logs for October 2010 since October represents a typical month in terms of traffic volume (i.e. there are not significant holidays). No effort is made to separate the incidents based on the detection method (dispatch or patrol) because this data is not available nor is it critical when developing the incident database; however, when evaluating patrol detection versus other detection this data would be critical. As a result, the incidents for the month are evaluated as two cases, either all dispatch response or all patrol response to estimate the total response time for each case.

The study calculates the response times for the patrol case by determining the distances from each link *i* to any link *j* on the tour and using the standard patrolling speed (55 mph for the Tarrant County CP) to compute the travel time. The link midpoints are used to estimate the average distances but there may be some superior strategies, which provide better estimation of the average distances of any point on link *i* to any point on link *j.* The mid-point assumption is most appropriate as link length decreases. Note for the patrolling case, the travel time from link *i* to link *j* may not be equal to time from link *j* to link *i*, but the sum of these two times are equal for all *i*,*j* pairs and equal to the total tour time. By excluding turning time, the dispatch case travel time from link *i* to link *j* is equal to travel time from *j* to *i*, and it uses the shortest path between the links. The shortest path times between each *i*,*j* pair are found using Google map with an average speed of at least 60 mph (The typical speed limit for Tarrant County freeways) for the dispatch case, which is more than the 55 mph patrol speed because the truck crews are not attempting to detect incidents while on route to a dispatch call. The study does not investigate the impact of congestion on the response time, and as a result, the standard patrolling speed and dispatch speed could be used to compute all the travel times.

3.2 Result

As shown in Tables 1 through 6, the total number of incidents on each link and the number of times each link is traversed during a tour is determined for the different beats. If a link is included on two beats, the incidents on that link are equally divided between the two beats. In the patrol case, if a link is traversed twice in a tour, the probabilities for the first and the second pass are exactly the same but the travel times are different. Also, the link probabilities of both incident occurrence and truck location for the different beats are shown in Tables 1 through 6; these probabilities are combined to find the event probability matrix. Since these two events are independent, the probability matrix's element *ij* is a product of the probability of incident occurrence on link *i* and probability of truck presence on link *j*.

By using the probability and travel time matrices, the average response times for all beats are obtained and shown in Table 7 for the dispatch case and Table 9 for the patrol case. The total estimated response times during October 2010 are shown in Tables 8 (dispatch case) and 10 (patrol case). As shown, the results are presented for both the deterministic and probabilistic approaches to emphasize the influence of both incident and truck distributions.

For the dispatch case, since the trucks move directly to the incident location, the number of trucks on each beat has less impact on the response time. Therefore, the dispatch case uses three scenarios based on the number of beats on each setup where the first scenario allocates only three trucks to three beats of setup A, and another allocates two trucks to the two beats of setup B, while the last scenario allocates one truck to the only beat of setup C. As can be seen in Table 8, the total response times for the dispatch case are much lower than the patrol case because the incident is detected and reported to dispatch, therefore, the time laid between incident occurrence and dispatch (Detection Time) cannot be determined. Apparently, increasing the number of trucks improves the CP performance as a measure of total response time but the total cost of extra trucks and value of response time should be considered to find the optimum fleet size and beat configuration for the dispatch case.

Table 1 Probability of Truck and Incident Presence on the Links of Beat A-2292

Link	201	301	351	352	353	354	355	821	822	823	2871
Times link traversed (f_i)	1	2	2	2	1	1	1	1	1	1	2
Truck Location%	10.9%	22.6%	19.1%	7.2%	6.6%	1.0%	6.4%	4.0%	7.8%	7.9%	6.5%
Number of incidents (r_i)	127	174	16	37	51	48	68	23	53	80	9
Incident Occurrence%	18.5%	25.4%	2.3%	5.4%	7.4%	6.9%	9.9%	3.4%	7.7%	11.7%	1.3%

Table 2 Probability of Truck and Incident Presence on the Links of Beat A-2293

Link	202	302	353	354	355	356	824	825	826	827	828	1211	2873
Times link traversed (f_i)	1	2	1	1	1	2	1	1	2	2	1	1	1
Truck Location%	6.2%	15.3%	7.0%	1.1%	6.8%	15.3%	7.9%	2.2%	7.9%	12.6%	2.0%	8.7%	7.1%
Number of incidents (r_i)	96	158	51	48	68	88	36	9	23	21	10	29	35
Incident Occurrence%	14.4%	23.7%	7.6%	7.1%	10.2%	13.2%	5.4%	1.3%	3.4%	3.1%	1.5%	4.3%	5.2%

Table 3 Probability of Truck and Incident Presence on the Links of Beat A-2294

Link	203	204	303	361	362	363	825	826	827	828	1212	2874	1831	1832
Times link traversed (f_i)	1	1	2	1	1	1	1	1	1	1	1	2	1	2
Truck Location%	2.1%	9.4%	19.5%	7.3%	6.2%	6.3%	2.0%	3.5%	5.6%	1.8%	7.2%	15.3%	5.9%	8.0%
Number of incident (r_i)	51	159	184	24	81	79	9	23	21	10	31	14	15	30
Incident Occurrence%	7.0%	21.8%	25.2%	3.3%	11.1%	10.8%	1.2%	3.1%	2.8%	1.4%	4.2%	1.9%	2.1%	4.1%

Table 4 Probability of Truck and Incident Presence on the Links of Beat B-2292

Link	201	301	351	352	353	354	355	821	822	823	824	825	2871	1211
Times link traversed (f_i)	1	1	2	2	1	2	1	1	2	2	1	1	2	1
Truck Location%	8.8%	9.1%	15.4%	5.8%	5.1%	2.3%	5.2%	3.2%	12.6%	12.8%	6.0%	1.7%	5.3%	6.7%
Number of incident (r_i)	127	174	16	37	101	48	68	23	53	80	36	9	9	29
Incident Occurrence%	15.7%	21.5%	2.0%	4.6%	12.5%	5.9%	8.4%	2.8%	6.5%	9.9%	4.4%	1.1%	1.1%	3.6%

Table 5 Probability of Truck and Incident Presence on the Links of Beat B-2293

Link	202	203	204	302	303	354	355	356	825	826	827	828	361	362	363	2872	2873	1212	1831	1832
Times link traversed (f_i)	1	1	1	2	2	1	1	2	1	1	1	2	1	1	1	1	2	1	1	2
Truck Location%	3.7%	1.4%	6.3%	9.2%	13.0%	0.9%	4.1%	9.2%	1.3%	2.4%	3.8%	2.4%	4.9%	4.1%	4.2%	5.0%	10.2%	4.8%	3.9%	5.3%
Number of incident (r_i)	96	51	159	158	184	47	68	88	8	45	41	20	24	81	79	35	14	31	15	30
Incident Occurrence%	7.5%	4.0%	12.5%	12.4%	14.4%	3.7%	5.3%	6.9%	0.6%	3.5%	3.2%	1.6%	1.9%	6.4%	6.2%	2.7%	1.1%	2.4%	1.2%	2.4%

Table 6 Probability of Truck and Incident Presence on the Links of Beat C-2292

Link	201	202	203	204	301	302	303	351	352	353	354	355	356	821	822	823	824	825	826	827	828	361	362	363	2871	2871	2873	1211	1212	1831	1832
Times link traversed (f_i)	1	2	1	1	1	1	1	2	2	1	1	1	2	1	2	2	1	1	2	2	1	1	2	1	2	1	2	1	1	2	1
Truck Location%	3.9%	4.2%	0.8%	3.6%	4.1%	2.6%	3.7%	6.9%	2.6%	2.3%	0.5%	2.3%	5.3%	1.4%	5.7%	5.8%	2.7%	0.8%	2.7%	4.3%	0.7%	2.8%	4.8%	2.4%	2.47%	2.9%	5.9%	3.0%	2.8%	4.5%	1.5%
Number of incident (r_i)	127	96	51	159	174	158	184	16	37	101	95	136	88	23	53	80	36	17	45	41	20	24	81	79	9	35	14	29	31	15	30
Incident Occurrence%	6.1%	4.6%	2.4%	7.6%	8.4%	7.6%	8.8%	0.8%	1.9%	4.9%	4.6%	6.5%	4.2%	1.1%	2.6%	3.8%	1.7%	0.8%	2.2%	2.0%	1%	1.1%	3.9%	3.8%	0.4%	1.7%	0.7%	1.4%	1.5%	0.7%	1.4%

The dispatch case shows good response times for these minor incidents with a mean response time less than 14.5 minutes for all beats. As shown in Table 7, the mean response time is 14.24 minutes for the deterministic and 14.52 minutes for the probabilistic case when one truck is covering the whole network. The mean response times decrease considerably, about 25 percent, when changing from the one-beat configuration to the two-beat configuration, but they only decrease slightly when switching from the two-beat to three-beat configuration. The decrease is typically about five percent, but one of the new beats shows a thirty percent decrease due to its compact size. The network density appears to be the best indicator of decreasing mean response times for the dispatch case.

Table 7 Number of Incidents and
Average Response Time, Dispatch Case

Setup	Beat	n_k	t_k Deterministic (min)	t_k Probabilistic (min)
A	A-2292	685	11.40	10.86
	A-2293	670	8.99	8.52
	A-2294	729	12.20	11.65
B	B-2292	810	10.65	11.21
	B-2293	1274	12.08	12.35
C	C-2292	2084	14.24	14.52

The total study period response time for different scenarios of fleet size for both the deterministic and probabilistic approaches of the dispatch case are highlighted in Table 8. If one truck is allocated to dispatch for the whole network, the total response time is about 500 hours (30263 min) in just one typical month of operation. By adding one more truck to the network and switching from a one-beat configuration to two-beat configuration the total response time may reduce by 90 hours in a month, which could be worth the cost of one extra truck (A definitive conclusion requires an analysis of network benefits versus truck cost). On the other hand, continuing to increase the fleet size so that three trucks are allocated to the three-beat configuration results in only a 50 hour decrease in the total response time, which indicates there are diminishing returns for adding more trucks, which means an optimal allocation must be determined based on the truck and congestion costs.

Table 8 Total Study Period Response Time, Dispatch Case

Dispatch-deterministic				Dispatch- probabilistic			
Setup	Beat	No. Of Trucks	Total Response Time (min)	Setup	Beat	No. Of Trucks	Total Response Time(min)
A	A-2292	1	7814	A	A-2292	1	7438
	A-2293	1	6022		A-2293	1	5709
	A-2294	1	8896		A-2294	1	8494
Total		3	22732	Total		3	21641
B	B-2292	1	8629	B	B-2292	1	9079
	B-2293	1	15390		B-2293	1	15743
Total		2	24019	Total		2	24822
C	C-2292	1	29666	C	C-2292	1	30263
Total		1	29666	Total		1	30263

As shown in Table 9 for the patrol case, the mean response time is 128.7 minutes for the deterministic and 120.4 minutes for the probabilistic case when one truck is patrolling the whole network. Similar to the dispatch case, the mean response times decrease considerably, about fifty percent, when switching from the one-beat configuration to the two-beat configuration. Furthermore, the mean response times decrease when the two beats are split into three beats, but for the patrol case the decrease is considerable, twenty to thirty-five percent. Smaller beats appear more important for the patrol case because the smaller beats speed incident detection as well as response as the tour lengths decrease. Also, the incident density or tour length of the new beat tends to indicate the magnitude of the improvement over the larger beat structure.

For this network, the patrolling incident detection adds about thirty minutes for setup A, between forty to fifty minutes for setup B, and more than one hundred minutes for setup C, to the incident response when compared to the dispatch case.

Table 9 Number of Incidents and
Average Response Time, Patrol Case

Setup	Beat	n_k	t_k Deterministic (min)	t_k Probabilistic (min)
A	A-2292	685	46.91	40.60
	A-2293	670	44.29	39.05
	A-2294	729	49.31	43.41
B	B-2292	810	57.98	49.51
	B-2293	1274	73.80	59.98
C	C-2292	2084	128.67	120.36

For the patrol case, as shown in Table 10, a comparison is made between the three setups given two, three, four, and five trucks available for assignment. Highlighted numbers in Table 10 show the minimum total response time and emphasize the best setup for different scenarios of fleet size for both the deterministic and probabilistic cases. By solving the objective function (4) for the total available trucks, the study determines the best setup and truck allocation, which creates the smallest total response time. Table 10 also includes the total response time based on the total number of incidents during the study period (October 2010) for both the deterministic and probabilistic approaches for each fleet size. The probabilistic approach's consideration of incident location is more accurate than the deterministic approach, but both approaches are provided to assess the importance of using the more complex approach. In the dispatch case, the probabilistic approach shows around a five percent difference from the deterministic approach while in the patrol case, the probabilistic results are up to twenty percent different than the deterministic. This difference occurs because the incident location is unknown in the patrol case and must be found while it is known for the dispatch case. As a result, the probability of incident and truck presence, which are critical elements to detect the incident, does not affect the result for the dispatch case while playing a significant role in the patrol case.

Table 10 Total Study Period Response Time, Patrol Case

No of trucks	Setup	A-2292	A-2293	A-2294	B-2292	B-2293	C-2292	Total Response Time, Deterministic (min)	Total Response Time, Probabilistic (min)
2	A							NA	NA
	B				1	1		140986	116510
	C						2	134077	125415
3	A	1	1	1				97754	85623
	B				1	2		93976	78305
	C						3	89385	83610
4	A	1	1	2				79781	69801
	B				2	2		70493	58255
	C						4	67039	62708
5	A	2	1	2				63714	55894
	B				2	3		54823	45520
	C						5	53631	50166

As shown in Table 10, the result shows two different conclusions for the deterministic and probabilistic cases. For the deterministic case, setup C gives the smallest total response time and setup B has the second smallest total response time while setup A has the highest total response time for all fleet sizes. This result shows that in this case study it would be better to allocate more trucks on a single beat rather than restructuring the setup and creating additional beats.

On the other hand, the probabilistic case concludes that setup B is the best for all fleet sizes, while setup A once more is the worst alternative. This difference in fleet allocation between the deterministic and probabilistic highlights the importance of using the probabilistic approach. It may appear that this outcome contradicts the primary result obtained from the deterministic case, but there is an important aspect that reasonably explains this outcome. In the probabilistic case, another factor that influences the performance is the rate of incident occurrence per mile (incident density) on links traversed more than once during the tours. Overall, there are 31 links on the whole network that must be traversed at least once, but to complete the tours, some links should be traversed more than once during the tour, which will be denoted as Extra Links. Since setup B covers extra links that have a high rate of incidents while traversing about the same extra length as setup C, its response time will be lower. To compare the efficiency of the extra links covered for each setup, the Incident per Extra Length ratio is defined, as shown in Table 11. The Incident per Extra Length ratio determines the ratio of incidents on extra links to the length (in miles) of extra links on each setup; higher ratios appear desirable because trucks tend to be closer to more important network links. As presented in Table 11, this ratio for setup B is about 10.4, which is considerably higher than the 8.9 of setup C. This appears to be the reason for the higher total response time in setup C than setup B for the probabilistic case while in the deterministic case the result is inverse. However, this discrepancy may be addressed by making the tour consider incident frequency as well. This could be done by defining an incident index multiplied by the length of the links and design the tour based on the new measure instead of only length. This factor should be relevant to the number of incidents on each link. The new measure to establish the minimum edge-covering tour is based on the length per incident of each link.

Table 11 Incidents Coverage per Extra Mile Covered, Patrol Case

<table>
<tr><th>Setup</th><th>Beat</th><th>Links</th><th>Extra Links</th><th>Length (mi)</th><th>Extra Mile</th><th>Incidents on Extra Links</th><th>Incidents per Extra Mile</th></tr>
<tr><td rowspan="3">A</td><td>A-2292</td><td>15</td><td rowspan="3">18</td><td>86</td><td rowspan="3">86.6</td><td rowspan="3">753</td><td rowspan="3">8.7</td></tr>
<tr><td>A-2293</td><td>17</td><td>81.2</td></tr>
<tr><td>A-2294</td><td>17</td><td>90.4</td></tr>
<tr><td rowspan="2">B</td><td>B-2292</td><td>20</td><td rowspan="2">15</td><td>106.3</td><td rowspan="2">70.6</td><td rowspan="2">737</td><td rowspan="2">10.4</td></tr>
<tr><td>B-2293</td><td>26</td><td>135.3</td></tr>
<tr><td>C</td><td>C-2292</td><td>43</td><td>12</td><td>235.9</td><td>64.9</td><td>575</td><td>8.9</td></tr>
</table>

Total Links = 31
Total Miles = 71

In conclusion, when the fleet size is two, setup A may not be used but between setup B and setup C it is shown that setup B has a better performance for the probabilistic approach. Consistently, for larger (three, four, and five) fleet sizes, the two-beat configuration outperforms the three-beat configuration even though the mean response rates for a single truck decreases. This discrepancy occurs because the additional truck can be added to the beat where it will have a greater impact rather than merely dividing the network into smaller beats. The comparison between setup B and setup C shows that for all fleet sizes, for the deterministic approach setup C presents a better performance while for the probabilistic approach setup B results in smaller total response time, and the difference between the outcomes is because of the different incident to extra length ratios. This ratio is highly dependent on the designed tour. As a result, re-designing the tour by considering incident distribution to cover the high-risk links, as extra links, may result in better performance of setup C. However, given the current beat and tour structure, setup B should be used for any fleet size. Increasing the fleet size from two to three trucks reduces the total study period response time by thirty-three percent for Setup B, twenty-eight percent for setup C, and twenty-six percent for setup A. When the fleet size is set at four and five trucks, the total response time for the study period continues to decrease. The cost of changing the fleet size must be compared not only to the decrease in response time, but to the network delay that is avoided by the increased number of trucks. This comparison is beyond the scope of this study because this study is only attempting to assess beat allocation rather than optimal fleet size. For all three increased fleet sizes, setup B with two beats has a smaller total minimum response time than setup A with three beats, and setup C with one beat. This result indicates that for the given incident distribution and the designed tour, setup B should be used for the patrol case regardless of the fleet size.

CHAPTER 4

CONCLUSION

4.1 Conclusion and Future Research

In a Freeway Service Patrol system, three major elements influence its performance. First, the desirable beat structure, which in this study is pre-designed, and current beat structures are evaluated. Second, the fleet size which is the number of available trucks to allocate. This study tries to evaluate program performance given a fixed number of available trucks. Third, determine the allocation of available trucks to designed beats. This is the primary goal of this study for each fleet size. When increasing the fleet size of patrolling CP trucks, generally there are two alternatives for adding additional trucks to the network: increasing the number of beats (by changing the beat structure) and allocating just one truck to each beat or increasing the number of trucks but continue to use the current beat structure. CP fleet management can directly impact response time, which is the performance measure that this study investigates. In this case study, the beat structures (setups A, B, and C) are fixed by a previous design, but the number of trucks allocated to each beat may vary. While a redesign of beat structure may yield some small improvements over the current design, it appears unlikely to affect the most important generalizable research conclusions and remains beyond the scope of this study.

The patrol case result shows that setup B with two longer beats works better than setup A with three smaller beats for all fleet sizes when evaluating total detection-response time during the study period. Furthermore, setup C with one beat, without considering the incident distribution, works better than setup A and setup B, because fewer extra links need to be traversed in a setup with fewer beats. In addition, the fact that setup B has the best performance in the probabilistic case, but not the deterministic case, displays that the incident distribution must be considered when creating FSP beats and tours to guarantee higher coverage for high-risk links than low-risk links. One strategy may be to include the incident distribution in tour design so that they are based on both length and incident rate instead of just link length. Expanding the incident database beyond October 2010 will increase the strength of the results and potentially encourage other analysis of CP incident response. The benefit of using fewer beats for the patrol case is only shown for the current Tarrant County CP beat structure and designed tours; this finding may be less significant if the beats or tours are redesigned. Unfortunately, the sparse density of the freeway network may make formation of "ideal" beat structures that can match the targeted benefits of adding trucks to existing beats difficult. These conclusions still require examination of how beat structure, overall network size, beat size and incident intensity affect them and these factors' importance on response time.

Additional future research on this topic should include the clearance and discharge time as part of the total delay calculation; then, the trucks can be distributed to the network such that the total network delay is minimized. Another approach could be to combine design of the beat structure as well as determination of the best allocation of trucks to solve the problem in just one step because they are clearly interrelated. Furthermore, to improve this study, to minimize total response time, one should address how to deal with multiple incidents when CP resources are already deployed at other scenes. Also, a new approach could be to minimize the maximum total response time. In this instance, one may apply the same method but need to use maximum travel times between links instead of average travel times. Additional complications such as considering the incident type and link volume, which affect the CP's ability to decrease delay, or decreasing patrol and response speeds on congested links should also be added to the analysis. By including these complications, additional structural questions can be considered such as changing beat structures or patrol tours based on incident density and time-of-day (peak vs. off-peak). As urban freeway networks continue to become more congested, CPs offer one approach for reducing network delay, and thus require more investigation to maximize their impacts.

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BIOGRAPHICAL INFORMATION

Farzad Daneshgar received his Bachelor of Science in Civil Engineering in 2010 from Sharif University of Technology, Iran. In August 2010, he started his academic career at the University of Texas at Arlington, and enrolled for a Master of Science in Transportation Engineering.

During his academic career in UTA he has worked on some projects about Sustainability and Work Zone Safety and Delay. He has also submitted two papers to TRB 91st. His main research interests are: Operations Research, Urban Transportation Planning, Network Modeling, Transportation Planning and Logistics, and Travel Demand.

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