ABSTRACT

The Title of Document: A Comprehensive Mixed-Integer Programming Model to Optimize the Performance of Freeway Service Patrol Programs

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Unexpected congestion due to incidents may cause a substantial delay for drivers and reduce the roadway safety. Effective incident management relies on many tools to lessen the overall impact of crashes, road debris, and disabled vehicles. 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.

FSP management must consider the beat configuration, fleet size, and fleet allocation. The beat configuration is how the network is divided into different parts for patrolling, and each part is called a beat. The beat configuration, fleet size, and fleet allocation need to be determined for designing a network for FSP program. However, the literature lacks profound analytical methodologies for this purpose, and a few previous models typically tried to design these elements distinctly while they are strictly interrelated. Therefore, our research presents a comprehensive mixed-integer programming model to design the network for freeway service patrol programs. This model aims to concurrently determine the beat structure, fleet size, and allocation of trucks to beats, to minimize incident delay while the operational cost is considered, as well.

The research uses part of the Tarrant County Courtesy Patrol (CP) network in Texas as a numerical example to examine the model's capability to address different issues in patrol programs and to determine the impact of each factor on the optimal design. Also, to explore the problem with field data and real-size networks, the proposed model and developed heuristics are applied to part of the freeway network in Maryland covered by Coordinated Highways Action Response Team (CHART). Results indicate that a joint model forms a better solution regarding incident delay reduction and operation costs.

A MIXED-INTEGER PROGRAMMING MODEL TO OPTIMIZE THE PERFORMANCE OF FREEWAY SERVICE PATROL PROGRAMS

By

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Dedication

To my beloved family for their endless support

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I would like to thank my adviser Dr. Ali Haghani and all my teachers and collogues who assisted me during my academic career at the University of Maryland, College Park. Furthermore, I appreciate Coordinated Highways Action Response Team (CHART) for providing me with the data and supporting this study.

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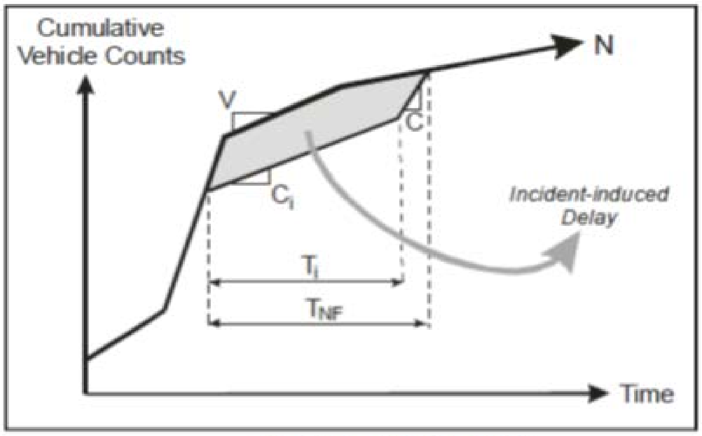
Chapter 1: Introduction

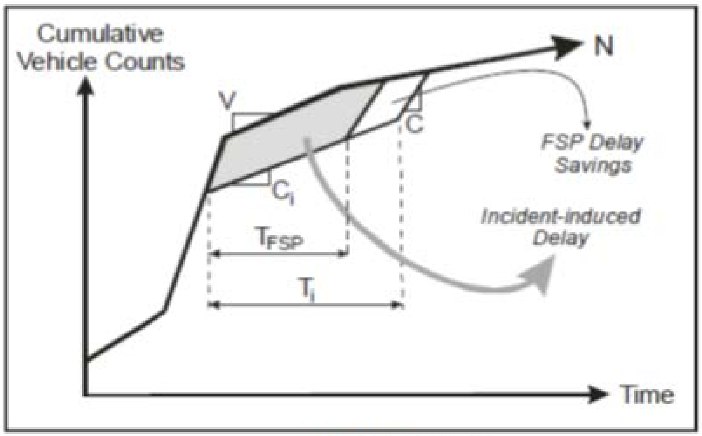
Non-recurring congestion due to incidents is a significant concern of all urban drivers. Unexpected incidents such as a stalled vehicle, a vehicle out of gas, or debris on the pavement cause large traffic delay to all drivers. Quick removal of these incidents from the freeway is necessary to recover the network performance, and as a result, systematized procedures should be implemented to respond and clear incidents as soon as possible. For this purpose, state agencies and transportation professionals have come up with several strategies and programs. Well-planned incident management programs can cause significant delay savings for users by the quick recovery of the freeway capacity. The most important aspect of freeway incident management programs is the rapid removal of the incidents [1].

More than fifty percent of the non-recurring traffic delay caused in urban areas and nearly all incurred delay in rural areas are due to incidents [2]. The total delay incurred due to incidents includes Detection Time, Verification Time, Response Time, Clearance Time, and Recovery Time [3]. Response time is the time since the incident is detected until incident management team arrives at the location to remove the incident. Clearance time starts when the aid process starts until the incident is removed from the freeway and is highly dependent on the incident type. Response time and detection time compose a large part of the total delay but could be significantly decreased by using a proper strategy. Traffic management uses different approaches to quickly respond to unexpected incidents such as using variable message signs, ramp metering, temporary shoulder use or other strategies [4]. Many metropolitan areas implement freeway service patrol (FSP) programs that patrol the freeway network searching for incidents, providing aid to motorists, and assisting with incident management and clearance. This system is in use in many metropolitan regions such as Los Angeles, Chicago, and Dallas-Fort Worth. This incident management program has several benefits among which the most important ones to mention are the reduction in incident delays for traffic users, fuel consumption, air pollutant emissions, and incident response and clearance times [5].

These elements are significantly decreased by implementing patrol programs, and they are usually used as measures of effectiveness to evaluate the performance of the patrol programs. There are additional benefits for patrol programs such as benefits to assisted motorists, benefits to the freeway operators, improved safety, improved average freeway travel speeds and freeway throughput, less number of secondary accidents, and better public perception [5]. According to the estimate reported by USDOT, about 14% to 18% of all crashes are caused because of an earlier incident [2]. The probability of occurring secondary incidents increases as the incident duration for the initial incident increases. Therefore, effective incident management can largely reduce the number of secondary crashes and improve the freeway safety [6]. Figure 1 demonstrates how FSP programs can reduce the traffic delay. In Figure 1, N is cumulative vehicle counts, V is vehicle thru-flow rate, T_i is the duration of the incident (with no FSP in service), T_{FSP} is the duration of the incident with FSP service provided on the beat, T_{NF} is the duration of the incident-induced congestion, C is freeway's (normal) capacity, and C_i is freeway's capacity during the incident [5]. As shown, FSP service reduces the duration of the incident and, as a result, reduces the total incident-induced delay on the network.



Estimation of Incident Delays



FSP Delay Savings

Figure 1 - Incident Delay Reduction by FSP Program [5]

The first patrol program started in Chicago, Illinois in 1960, and currently many metropolitan areas implement patrol programs among which there are:

- H.E.L.P. (Highway Emergency Local Patrol; New York)
- CHART (Coordinated Highways Action Response Team; Maryland)
- HERO (Highway Emergency Response Operators; Georgia)
- Hoosier Helper Program (Indiana)
- Texas's Courtesy Patrol
- California's Freeway Service Patrol

Problem Statement

In tackling FSP problems, three major issues need to be dealt with. First is the beat configuration, which is how the network is divided into different parts for patrolling. Each part is called a beat. For this purpose, the freeway network should be segmented into different links and each link is assigned to at least one beat. The second issue is the fleet size constraint, which determines the optimal number of trucks to fully cover the network while the cost associated with additional trucks is taken into account. Finally, truck allocation, which determines how trucks need to be allocated to beats such that delay caused by incidents is minimized. Patrol trucks become aware of an incident while patrolling on the beat and this procedure highly relies on the beat configuration, and the number of trucks on each beat, because larger headways will increase mean detection-response times. In this research, we propose a mixed-integer programming model to deal with all three major issues in patrol programs along with addressing several additional aspects of the program.

Organization of the Dissertation

The rest of the study is organized as follows. First, in the literature review section, current studies are reviewed, and their contribution to the field is investigated. The problem statement and model framework to tackle the problem are presented in the next section. Methodology section includes the steps to formulate the problem mathematically. Then, the research uses part of the Tarrant County Courtesy Patrol (CP) network in Texas as a numerical example to verify the capabilities of the model. Also, to explore the problem with field data and real-size networks, the proposed model and developed heuristics are applied to a subset of the freeway network in Maryland covered by Coordinated Highways Action Response Team (CHART). In the last sections, the results and conclusions are presented.

Chapter 2: Literature Review

Evaluation Studies

FSP programs are proven to be economically advantageous. Fenno and Ogden found that B/C ratios for FSP programs range from 2.1 to 36.2 nationwide [7]. Also, while incidents may be found via loop detectors or cellular phone calls, patrol trucks are typically closer to potential incident locations and may detect many of the incidents themselves which reduce detection time significantly; for instance, the San Francisco–Oakland FSP located 92% of all incidents itself [8]. Another study by Nee and Hallenbeck [9] shows that for lane-blocking incidents in the Puget Sound region of Washington State, the average response time without FSP was 7.5 min while response time was reduced to 3.5 min with FSP in service. They claim that the patrol programs reduce incident response times by 19% to 77%.

Skabardonis and Mauch [5] proposed a model to estimate the benefit over cost ratio of providing FSP service using empirical data and an additional model was developed to predict the cost-effectiveness of proposed FSP beats which currently provide no FSP service. According to the evaluation studies, patrol program is cost-effective based on MOEs before and after the implementation of the program; and benefits of the program depend on the beat's geometric, traffic characteristics, and the frequency and type of assisted incidents [5]. Moore II et al. [10] claims that secondary incidents in Los Angeles freeways where FSP is implemented occur much less frequent than suggested in the literature. Also, it is shown that reduction in response time is associated with incident duration reduction; for example, Khattak et al. [11] found that a 1-min reduction in response time causes a 0.6- to a 1-min reduction in incident clearance time. Overall, a significant number of studies and performance evaluation studies [12-16] have similarly confirmed the effectiveness of such incident management programs to mitigate incident-incurred congestion [17].

Network Design

Reviewing literature reveals that patrol programs have been explored in several studies. However, the majority of these studies intended to evaluate the overall performance of the program and determine the benefit over cost ratio after the program's implementation, while only a limited number of studies aimed to propose a solid mathematical framework to design the network for patrol programs efficiently. Although the deployment of the response patrol trucks is a critical aspect of the efficiency and performance of the program, the literature lacks profound analytical methodologies for this purpose [1]. Nevertheless, still, some ambiguous methods have been presented to improve the performance of the patrol programs [18]. In following, we review some of the general models for incident response programs, in addition to more particular models suggested for the patrol programs in the literature.

Sherali et al. [19] formulated two mixed-integer models to determine the optimal assignment of multiple response units into multiple incidents considering operation and opportunity costs. Kim et al. [20] developed an integer-programming model to minimize the total incident-incurred delay by optimizing the deployment locations of incident response units. Daskin [21] proposed a mixed-integer model to determine the dispatching policy and routing for incident response units. These studies tried to determine optimal locations and dispatch policy of response units but did not consider patrolling of incident response units. Two studies on Tennessee HELP program [22] and Maryland CHART program [23] are among the first programs that tried to reveal important locations that should be covered in their corresponding networks by using some traffic and incident indexes.

Zografos et al. [1] proposed a districting model to minimize incident-induced delay by determining the optimal locations of emergency response units. This study transforms freeway corridors into sections with the similar demand of incident service and assumes that demand of each section is concentrated at its centroid. Zhu et al. [24] evaluated the performance of the incident response units based on three different strategies for allocation of incident response units. These include whether to allocate response units near high-frequency incident locations, or distribute the units equally over the network, or place them at the traffic operation centers to dispatch to the incident location once an incident occurs. Another study by Zhu et al. [25] developed a methodology to evaluate both patrolling and dispatching strategies for allocating emergency response units based on field data from the I-495/I-95 Capital Beltway. They claim better strategy depends on some critical factors such as incident frequencies, traffic characteristics, and available detection methods.

Petty [3] planned a model based on traffic theory in combination with marginal benefit analysis, for determining where to place tow trucks to maximize the expected reduction in congestion. Yin [26] proposed a minimax bi-level programming model to determine a fleet allocation that minimizes the maximum system travel time that may result from incidents. These two studies presented two distinct strategies to allocate trucks by following two different objectives. Our research is also providing a methodology for determining the best allocation of trucks by minimizing incident duration while operation cost is taken into account.

Pal and Sinha [27] presented a simulation model to evaluate and improve the effectiveness of freeway service patrol programs regarding total vehicle-hours in the system. They presented a sensitivity analysis to show the possible improvements by showing the trend of FSP program performance after changing the fleet size or a minor change in current beat configurations. 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. This study provided insight into our research on the appropriate parameters to investigate during the case study, and as a result, most of these parameters are carefully considered. Pal and

Sinha [28] also proposed a mixed-integer programming model to determine the optimal locations of incident response units to minimize the operation cost.

Khattak et al. [29] presented an approach to determine, evaluate, and compare the most beneficial locations among the candidate facilities to expand the FSP network by analysis of incident indexes (and incident type distribution and incident delay estimation) combined with spatial analysis and average hourly freeway traffic volumes. They assume that high-priority locations are already covered. They do not aim to design beats or allocate trucks and only rank the locations that FSP is more beneficial in case that expansion is desirable.

Yin [30] formulated a model to allocate patrol trucks among beats by optimizing the performance of the FSP system. A mixed integer nonlinear programming model is formulated to minimize the expected loss with respect to a set of high-consequence scenarios of incident occurrence. Also, Daneshgar [31] presented a model based on two deterministic and probabilistic approaches to estimate the average response time to optimize patrol program performance by minimizing the total response time and determining the best beat configuration among existing beat structures in Tarrant County, Texas. Also, as a base for our study, Daneshgar [32] developed a joint mixed-integer model to determine the beat configuration and fleet size assuming single depot and based on minimization of total response time without presenting a heuristic algorithm to solve the problem for large size networks. Generally, one of the issues in several earlier studies [33-35] is that their methodologies only consider the major incidents [17] while our proposed model can fairly consider incidents with different severities and approximately take the clearance time into account as a factor.

Contribution

Among few studies to design the network for patrol programs, nearly all of them attempt to either design the beats or allocate trucks into the pre-designed beats and perform these two steps separately while these are truly interrelated. Therefore, our research aims to present a model to merge these problems and determine the beat configuration, fleet size, and truck allocation together. According to the literature, only one study by Lou [36] attempted a similar strategy. The current study aims to present an improved and comprehensive model, and as a result, here, we explain what is completed in Lou's work and explain significant contributions that are made by the current study. Lou presented a non-linear model to determine beat configuration and fleet allocation with the objective of minimizing the overall average incident response time. However, in developing this non-linear model, many simplistic assumptions are made such as assuming the number of beats is given, or a total number of trucks (fleet size) is assumed. They proposed a non-linear model [36] which aims to minimize only the response time as part of the total delay and does not consider truck's expenses. Our research aims to present a comprehensive mixed-integer programming model to design the network for freeway service patrol programs. This model aims to concurrently determine the optimal beat configuration along with the optimal fleet size and trucks allocation to minimize incident-incurred delay while the operational cost is taken into account, as well.

Chapter 3: Model Framework

Consider a directed graph, *G(N,A)*, representing a network of freeways where N and L represent sets of nodes and links, respectively. We assume t_{ij} is the travel time, and f_{ij} is the number of incidents during the planning horizon, for each link ij. There are two major decision variables in the model that need to be determined. The first variable is X_{ij}^{b} which determines whether link ij is covered by beat b and the second decision variable is V_b which determines the number of trucks that must be assigned to each beat b. As a result, the fleet size can be determined, too. The following notations are used in the model:

$G(N, L) = \ Network\ of\ freeways$

$N = Set\ of\ nodes\ in\ network\ G$

$L = Set\ of\ \ links\ ij\ in\ network\ G$

$LL = \ Set\ of\ \ links\ ij\ in\ netwotk\ G\ plus\ dummy\ links\ from\ the\ hypothetical\ origin$
$\quad node\ to\ each\ node$

$B = Maximum\ possible\ number\ of\ patrol\ beats$

$$X_{ij}^{b} = \begin{cases} 1 & if\ link\ ij \in L\ is\ covered\ by\ beat\ b \\ 0 & Otherwise \end{cases}$$

$P_s\ = Probability\ of\ patrol\ trucks\ being\ busy\ on\ another\ incident\ at\ the\ time\ of\ an$

$incident\ occurance$

$f_{ij} =\ Total\ number\ of\ incidents\ on\ link\ ij$

$f_{ij}^{p} =\ Number\ of\ incidents\ on\ link\ ij, detected\ by\ patrol\ trucks$

$f_{ij}^{d} =\ Number\ of\ incidents\ on\ link\ ij, not\ detected\ by\ patrol\ trcuks$

$t_{ij} = Travel\ time\ on\ link\ ij$

$V_b = Number\ of\ patrol\ trcuks\ assigned\ to\ beat\ b$

$\alpha = Coefficient\ to\ monetize\ the\ benefit\ of\ incident\ duration\ reduction$

$\beta = Coefficient\ to\ monetize\ the\ nonservice\ time\ spent\ by\ trucks\ to\ travel\ between$

$beat\ and\ depot$

$R_{ij}^{b} = Average\ response\ time\ in\ case\ of\ an\ incident\ on\ link\ ij\ in\ beat\ b$

$S_{ij}^{b} = Average\ service\ time\ for\ an\ incindent\ on\ link\ ij\ in\ beat\ b$

$S_{ij}\ = Average\ service\ time\ for\ an\ incident\ on\ link\ ij\ assuming\ only\ one\ truck$

$provides\ the\ assist$

$C_{ij}^{b} =\ Varibales\ defined\ to\ resolve\ non-linearity\ of\ the\ model: S_{ij}^{b}X_{ij}^{b}$

$C_m = Hourly\ cost\ of\ truck\ m$

$hr = Patrol\ trucks\ operating\ hours\ per\ day$

$day = Number\ of\ opearting\ days\ during\ the\ planning\ horizon$

$V =\ Maximum\ number\ of\ trucks\ allowed\ to\ be\ assigned\ to\ each\ beat$

$T =\ Maximum\ total\ number\ of\ available\ trucks\ (maximum\ possible\ fleet\ size)$

$D =\ Number\ of\ depots$

$U^b_{ijklme} = Binary\ varibles\ defined\ to\ resolve\ non-linearity\ of\ the\ model{:}\ X^b_{ij}X^b_{kl}V^b_{me}$

$W^b_{ijkl} =\ Binary\ varibles\ defined\ to\ resolve\ non-linearity\ of\ the\ model:\ X^b_{ij}X^b_{kl}$

$O^b_{ijme} =\ Binary\ varibles\ defined\ to\ resolve\ non-linearity\ of\ the\ model:\ X^b_{ij}V^b_{me}$

$r^d_{ij}\ =\ Shortest\ ditsance\ from\ depot\ d\ to\ link\ ij$

$SD^b_d\ =\ Shortest\ Distance\ from\ depot\ d\ to\ beat\ b\ (Min\ r^d_{ij}|X^b_{ij} = 1)$

$$y^b_i = \begin{cases} 1 & if\ node\ i\ is\ covered\ by\ beat\ b \\ 0 & Otherwise \end{cases}$$

$V^b_{me}, Z^b_e = Binary\ variables\ defined\ to\ determine\ V_b$

$Q^b_{ij}\ = Variables\ defined\ to\ assure\ connectivity\ of\ beats$

$S^k_{ijb}\ , C^k_{ijb}, a^1_{ijk}, a^2_{ijk} =\ Dummy\ variables\ defined\ to\ calculate\ S_{ij}$

$h_{ij}^{b} = \ Binary\ variable\ defined\ to\ assign\ beats\ to\ depots$

$I_{ij}^{n} = Normalized\ importance\ factor$

Most of the papers in the literature assume that patrol trucks are immediately available and never busy on another case at the time of an incident occurring. However, our research tries to capture this possible scenario fairly. Here, P_s is defined as the probability that in a time of an incident, patrol trucks on the same beat could be busy in another case. One way to calculate P_s is to explore the historical incident log data and determine the number of scenarios that the truck serving an incident was initially attending another case at the time of the subject incident occurrence. This data may be available if patrol trucks record log data about incidents they serve.

Patrolling Response Time

Incidents usually cause a substantial delay for urban drivers and increase travel times. They cause about 50% to 60% of the congestion in urbanized areas [11]. Delay experienced by urban drivers due to incidents may significantly decrease if incidents are identified, responded to and removed as soon as possible. Response time reduction is highly dependent on incident management strategies. Well-designed patrol programs can significantly reduce the response time and delay experienced by users. As a result, considering the response time reduction in FSP network design is a must. Please note in patrol programs, response time typically includes detection and verification time when incidents are detected by patrol trucks themselves. Given V_b as the number of patrol trucks allocated to each beat *b*, assuming that patrol trucks keep a constant headway, the average response time on each beat could be calculated as below:

$$R^b = \frac{\sum_{ij\in L} t_{ij} X_{ij}^b}{2V_b} \qquad (1)$$

Where X_{ij}^bdetermines whether link *ij* is included in beat *b* and V_b is the number of trucks patrolling in beat *b* and t_{ij} is the average travel time on link *ij*. For the purpose of having a linear term, response time could be re-calculated as follow:

$$R^b = \frac{\sum_{ij\in L} t_{ij} X_{ij}^b}{2V_b} = \frac{\sum_{ij\in L} t_{ij} X_{ij}^b}{2}\ [1 - \sum_{m=1}^{T} \sum_{e=2}^{e=V}\ (\frac{1}{e-1} - \frac{1}{e}) V_{me}^b] \qquad (2)$$

Equation (2) initially calculates the average response time based on one truck on the beat *(V_b =1)* and reduces the response time for each additional truck assigned to the beat. Given equation (2) we may calculate the following statement:

$$\sum_{ij\in L} X_{ij}^b R_{ij}^b \ = \sum_{ij\in L} X_{ij}^b\ \frac{\sum_{kl\in L} t_{kl} X_{kl}^b}{2} \left[1 - \sum_{m=1}^{T} \sum_{e=2}^{e=V}\ (\frac{1}{e-1} - \frac{1}{e}) V_{me}^b\right] = \frac{\sum_{ij\in L} \sum_{kl\in L} t_{kl} X_{kl}^b\, X_{ij}^b}{2} -$$

$$\frac{\sum_{ij\in L} \sum_{kl\in L} t_{kl} X_{kl}^b\, X_{ij}^b}{2}\ \sum_{m=1}^{T} \sum_{e=2}^{e=V}\ (\frac{1}{e-1} - \frac{1}{e}) V_{me}^b =$$

$$0.5[\sum_{ij\in L} \sum_{kl\in L} t_{kl} X_{kl}^b\, X_{ij}^b - \sum_{ij\in L} \sum_{kl\in L} \sum_{m=1}^{T} \sum_{e=2}^{V} (\frac{1}{e-1} - \frac{1}{e})\ t_{kl}\, X_{kl}^b\, X_{ij}^b V_{me}^b] \qquad (3)$$

All variables are as defined before. Note that each truck could be allocated only to one beat and for each beat $V_b = \sum_m \sum_e V_{me}^b$. Equation (3) is presented to linearize the statement $X_{ij}^b R_{ij}^b$ which will be applied in the objective function.

Non-Patrolling Detection: Response Time

The above calculations for the average response time are for the case once the incident is detected by patrol trucks while patrolling on their assigned beat on a regular route. However, sometimes there are cases where other sources detect incidents and trucks are informed to respond. As a result, patrol units do not need to follow the regular route to detect the incident and could respond to the incident in their assigned beat using the shortest path. Table 1 lists the difference between patrolling detection and non-patrolling detection scenarios. Assuming that incidents are responded only by patrol trucks on the same beat, the average response time for non-patrolling, R_n^b**,** could be estimated similar to the patrolling response time but the average non-patrolling response time is roughly about half of the estimated average patrolling response time. This happens because in the non-patrolling case the closest truck in the beat is sent to the location while in the patrol case trucks are not aware of the incident and need to detect the incident on their way ahead, as shown in Figure 2.

Table 1 - Patrolling vs. Non-Patrolling Detection

	Detection	Path to Incidents
Patrolling Detection	Patrol Trucks	Patrol Route
Non-Patrolling Detection	Others	Shortest Path

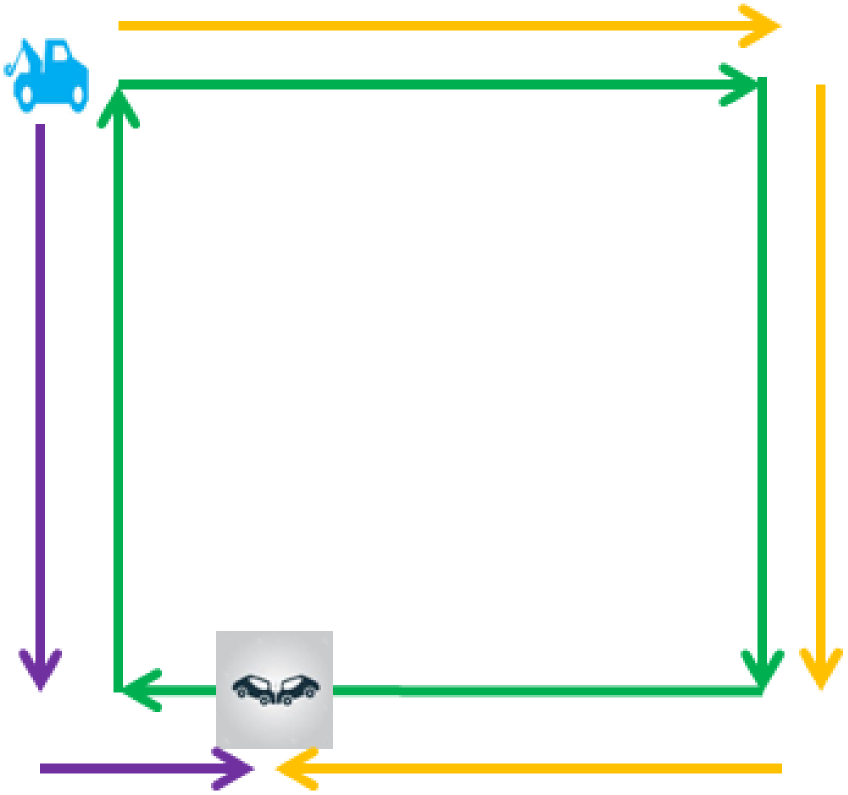


Figure 2 - Patrolling vs. Non-Patrolling Detection Response

Given V_b as the number of trucks allocated to each beat b, assuming the patrolling trucks keep a constant headway, and time spent to turn around is negligible, the average non-patrolling response time on each beat can be calculated as below:

$$R_n^b = \frac{\sum_{ij\in L} t_{ij} X_{ij}^b}{4V_b} = \frac{\mathrm{R}^{\mathrm{b}}}{2} \tag{4}$$

Assume we have a beat with four trucks patrolling on. As shown in Figure 3, once an incident occurs, depending on its location and how it is detected, one of the patrol trucks may respond to the incident. Trucks 1 through 4 respond to the incidents in the red, green, blue, and yellow area, respectively. Apparently, the coverage area for each unit is different depending on whether the incident is detected by patrol trucks or by other sources which informed the patrol trucks. Please note these areas constantly change relevant to the location of patrol trucks, at the moment.

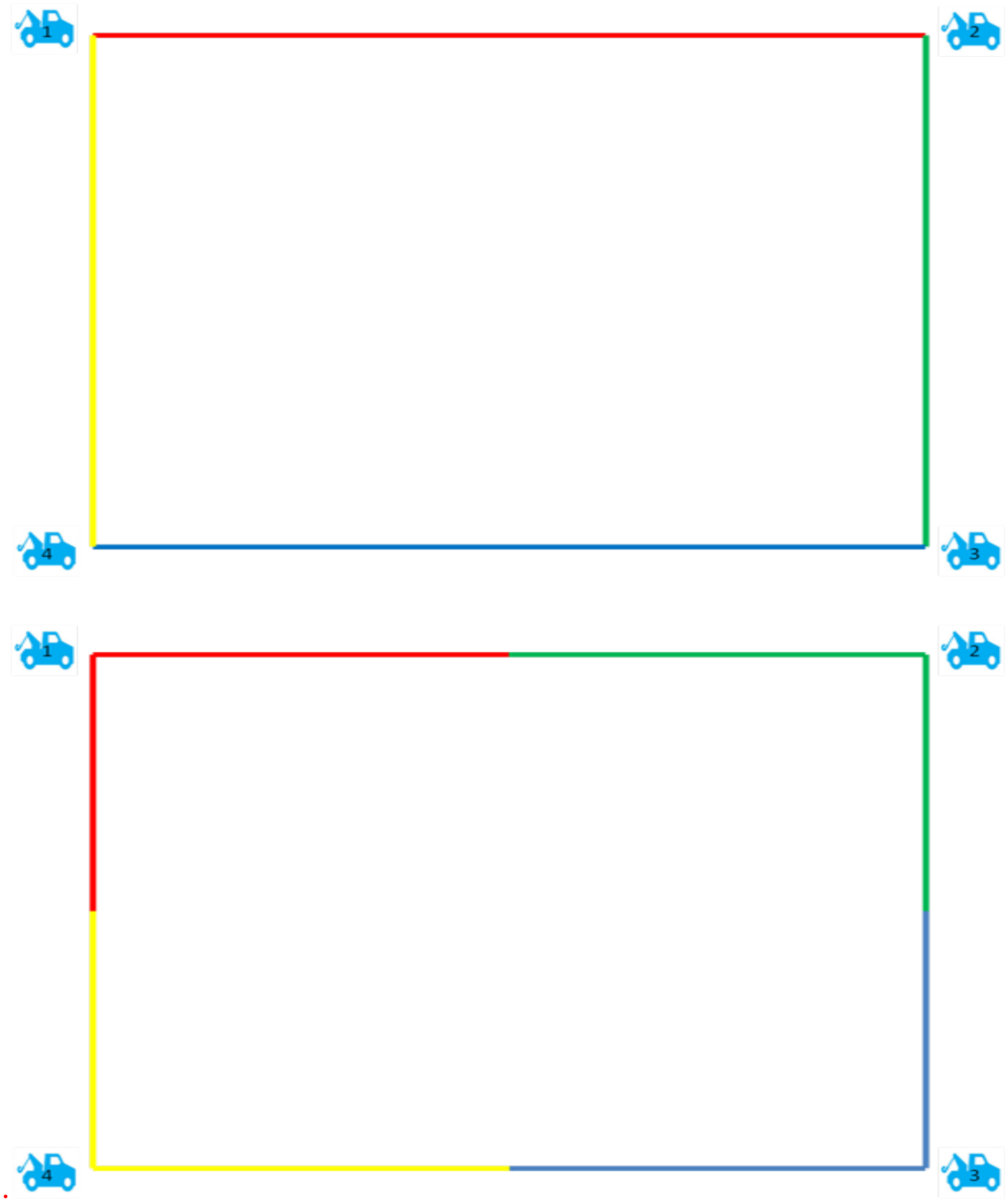


Figure 3 - Truck Coverage for Patrolling Detection (Top) vs. Non-Patrolling Detection (Down)

Service Time

Response time is dependent on the performance of incident management systems such as patrol programs. On the other hand, clearance time is more dependent on the incident severity and the service provided at the incident scene. However, designing the network for patrol programs solely based on the response time minimization, regardless of incidents severity, may not result in optimal performance. Assume a network where a part of it typically has major severe incidents because of traffic characteristic and its geometric design, while the rest of the network may have the same number of incidents but with less severity. It is obvious that more frequent patrolling is required on high-risk links although the distribution of incidents is similar. Exactly how an effective patrol program can reduce the clearance time is not a major focus of this study. However, as will be explained subsequently, this study attempts to somehow consider the clearance time in the model such that areas with a higher likelihood of severe incidents are covered more frequently.

For this purpose, here, service time is defined to be the time spent on the incident scene only by patrol trucks and does not include the time spent and service provided by the dispatch system or other emergency units such as fire trucks, ambulances, and police vehicles, to clear the incident. It is reasonable to assume that increasing the number of patrol trucks may decrease the service time and as a result may reduce incident clearance time. Service time is the same as clearance time if the incident is cleared only by patrol trucks. Note that in many cases, especially disabled vehicles or minor incidents, the incident is completely cleared by the patrol system. Other emergency vehicles only assist in severe incidents and crashes. According to the CHART's performance evaluation report in 2012 [37], CHART (Coordinated Highways Action Response Team) responded to more than 63500 emergency cases while in about 65% of the cases, assistance was provided to disabled vehicles and only 35% of the cases were collisions.

If we assume only one patrol truck stops at each incident and other patrol trucks continue their patrolling on the beat regardless of the current incident, then, service time is independent of the number of trucks on each beat. However, typically each truck on its patrolling stop at the incident location, even if another truck is already there and that help from an additional truck may shorten the service time duration. Reduction in service time by additional trucks depends on several factors such as incident severity and type of required service. So, a comprehensive study may be required to determine the patrol program's service time reduction by additional trucks. However, it may be an acceptable assumption to consider that, for example, an incident that needs 18 minutes of service by a single truck may be cleared in 9 or 6 minutes, if there were two or three trucks available, respectively, providing the service at the same time. If we assume that assist from each additional truck makes half the rest of the service time, then:

$$S_{ij}^{b} = \sum_{k=1}^{k=V-1} min\{R_{ij}^{b}\,,\ max\left[\left(\frac{S_{ij}-0.5k(k-1)R_{ij}^{b}}{k}\right),0\right]\} +\ max[(\frac{S_{ij}-0.5V(V-1)R_{ij}^{b}}{V}),0] \qquad (5)$$

Figure 4 shows how additional trucks may reduce the service time. First truck starts clearing the incident, and once the second truck gets there, the rest of the service is provided by two trucks which reduce the rest of the service time to half of what was in the case of only having one truck. The same happens once the third truck or more arrive at the place. This time is only the time that aid is provided by the patrol trucks and does not include any time spent by other systems to clear the incident. In Figure 4, case (a) occurs when only one truck is at the incident scene while in case (b) a second truck and in case (c) a third truck joins the first truck to remove the incident.

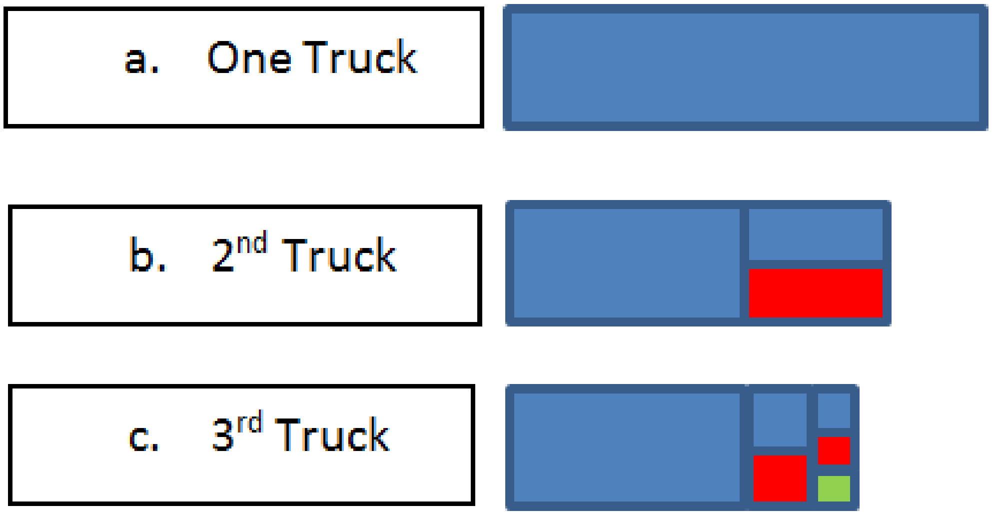


Figure 4 - Additional Trucks Reduce the Service Time

The contribution of service time and in general, clearance time in the model depends on the operational details and how additional trucks may reduce the rest of the service time. However, based on the operational conditions, the model could be updated accordingly.

The above formulation in statement 5 is based on the fact that every additional truck may create an impact and reduce the service time while this may not be a practical assumption. For different case studies and scenarios, we may come up with a maximum number of trucks that may impact the service time. For example, assume that three trucks are the maximum number of trucks which can reduce the service time. For this scenario, Table 2 represents the service time based on the incident type and number of trucks on the beat. In Table 2, R and V_b are the average incident response time, and number of trucks on the beat, respectively. Also, S_{ij} is the average service time for the incidents on link *ij*, assuming only one patrol truck provides the assist.

Table 2 - Service Time for each Link *ij* in beat *b*: Additional Trucks Cause Service Time Reduction

	$\boldsymbol{S_{ij} < R}$	$\boldsymbol{R < S_{ij} < 3R}$	$\boldsymbol{S_{ij} > 3R}$
$\boldsymbol{V_b = 1}$	S_{ij}	S_{ij}	S_{ij}
$\boldsymbol{V_b = 2}$	S_{ij}	$\frac{S_{ij}}{2} + \frac{R}{2}$	$\frac{S_{ij}}{2} + \frac{R}{2}$
$\boldsymbol{V_b \geq 3}$	S_{ij}	$\frac{S_{ij}}{2} + \frac{R}{2}$	$\frac{S_{ij}}{3} + R$

Please note that it has been claimed by some studies that reduction in response time generates a reduction in clearance time, as well. Khattak et al. [8] found that a 1-min reduction in response time causes a 0.6 to a 1-minute reduction in incident clearance time. Therefore, another approach to consider the impact of patrol programs on clearance time reduction, (and subsequently to include clearance time as part of the inputs into the model to design the network), is to estimate the average reduction in clearance time caused by reduction in incident response time and determine the savings regardless of the number of patrol units. Although the number of patrol units in each beat, might seem an irrelevant factor in this approach, actually locations with more severe incidents (incidents which require longer clearance times) will be assigned more patrol trucks to reduce the response time further and as a result, reduce the clearance time. As a result, locations with more severe incidents will be assigned an additional number of patrol trucks.

Parameters

It is necessary to convert benefits achieved by incident duration reduction, caused by the patrol program, into monetary value to have equivalent statements in the objective function. For this purpose, first, the traffic delay avoided by the incident duration reduction through the patrol program (in veh-hrs) need to be determined. Figure 1 shows how FSP programs save the incident delay.

A few approaches are presented in the literature to estimate delay savings. Sun et al. [38] presented a method to estimate the total delay under traffic incident management (TIM) and non-TIM, and, as a result, delay saving could be estimated. This method requires input data on incident duration, volume, and reduced capacity. Also, Khattak and Rouphail [39] developed a method to estimate delay savings as a function of volume-to-capacity ratio, knowing the area type, the number of blocked lanes, and estimated incident duration.

Then, given the total delay avoided for the volume on the network and the value of time, the monetary value of incident duration reduction could be calculated. The value of time multiplied by the total avoided delay for the traffic volume on the network determines the cost savings caused by the patrol program. However, this approach may not be practical as it requires a comprehensive evaluation study for the subject network based on each scenario. Then, the second approach is to rely on the value of delay avoided by incident duration reductions that are reported in the literature. Referring to FSP program evaluation studies, the delay avoided by patrol programs could be obtained based on different scenarios of incident duration reduction, traffic volume, and incident types. The avoided delay is mainly dependent on these factors, and as a result, a few different values for the parameter could be obtained based on different ranges of these influencing elements. Then, the upper bound, lower bound, the average value or an appropriate value based on the subject scenario could be applied. Mathematical details on how to calculate the parameter are provided in the numerical example section.

Importance Factor

An importance factor, I, may be introduced for each link based on the road characteristics such as volume, capacity, road type, location, safety, and security. The introduction of this factor helps to cover the roads with a higher priority more frequently. Each of these characteristics could be categorized to a small set of standard ranges. Then, a classification table is defined based on the combination of these categories of different characteristics, and each class is assigned an importance factor value. Therefore, each road will be assigned an importance factor value based on its class. For the objective function, we may need to normalize these importance factors such that for each link k:

$$I_k^n = \frac{nI_k}{\sum_j I_j} \tag{6}$$

Objective Function

In this research, we propose a mixed-integer programming model to determine the optimal beat configuration, fleet size, and allocation of patrol trucks to beats for patrol programs while incident delay, including response time and service time by the patrol program, plus the cost associated with the program is minimized. Please note that in patrol programs incidents are typically detected by patrol units, and, as a result, response time simultaneously includes detection and verification time. The first term in the objective function, to minimize the response time and service time, starts as follows:

$$Min \sum_{b=1}^{B} \sum_{ij\in L} X_{ij}^{b} f_{ij} (R_{ij}^{b} + S_{ij}^{b} + P_s \frac{S_{ij}^{b}}{2}) \tag{7}$$

This term minimizes the total response and service time during the planning horizon. The statement in the parenthesis estimates the average response and service time for each link and this statement is multiplied by the number of incidents in each link during the horizon, f_{ij}, to calculate the total delay.

The above objective function is non-linear and non-convex but could be linearized. For this purpose, we make the following transformations. First, as shown before, the response time and the service time can be transformed into linear expressions as shown below:

$$\begin{aligned}
&\sum_{b=1}^{B} \sum_{ij\in L} X_{ij}^{b} f_{ij} (R_{ij}^{b} + S_{ij}^{b} + P_s \frac{S_{ij}^{b}}{2}) = \sum_{b=1}^{B} \sum_{ij\in L} X_{ij}^{b} f_{ij} S_{ij}^{b} (1 + \frac{P_s}{2}) + \sum_{b=1}^{B} \sum_{ij\in L} X_{ij}^{b} f_{ij} R_{ij}^{b} = \\
&\sum_{b=1}^{B} \sum_{ij\in L} X_{ij}^{b} f_{ij} S_{ij}^{b} (1 + \frac{P_s}{2}) + 0.5 \sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L} f_{ij} t_{kl} X_{kl}^{b} X_{ij}^{b} - \\
&0.5 \sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L} \sum_{m=1}^{T} \sum_{e=2}^{V} f_{ij} t_{kl} (\frac{1}{e-1} - \frac{1}{e}) X_{kl}^{b} X_{ij}^{b} V_{me}^{b}
\end{aligned} \tag{8}$$

Statement (8) is presented to linearize statement (7). The first term in equation (8) estimates the total service time while the second and third terms calculate the total response time during the horizon. See statement (3) for the response time calculation.

In the second step to linearize the model, a new set of binary variables are introduced. The model is non-linear due to cross multiplication of some binary variables, but this non-linearity could be resolved by introducing a new set of binary variables and replacing each cross product $\prod_{j \in Q} X_j$ by a new variable X_Q such that [40]:

$$X_j \geq X_Q \quad for\ all\ j \in Q \tag{9}$$

So, the following changes are made in the model:

$$X_{ij}^{b} X_{kl}^{b} V_{me}^{b} = U_{ijklme}^{b} \tag{10}$$

$$X_{ij}^{b} X_{kl}^{b} = W_{ijkl}^{b} \tag{11}$$

$$X_{ij}^{b} V_{me}^{b} = O_{ijklme}^{b} \tag{12}$$

$$X_{ij}^{b} S_{ij}^{b} = C_{ij}^{b} \tag{13}$$

These dummy variables are introduced to linearize the model. All variables are as defined before.

In the following, expression 14 is added up to the objective function to capture the operating costs during the planning horizon. Also, to assign each beat to a depot, in case that multiple depots are available, statement 15 is suggested.

$$\sum_{b=1}^{B} \sum_{m=1}^{T} \sum_{e=1}^{V} C_m V_{me}^{b} * (hr * day) \tag{14}$$

$$\sum_{d=1}^{D} \sum_{b=1}^{B} SD_d^b \tag{15}$$

Statement 15 determines the total shortest distances between each beat b and its corresponding depot *d;* and, in the objective function, parameter β is added up to monetize this term. Also, parameter α is introduced to convert incident duration reduction and, as a result, traffic delay savings to monetary value. Finally, importance factors are added up to take into account the road priorities based on influential characteristics. So, the proposed formulation including the objective function and constraints forms as follows:

Min

$$\alpha[\sum_{b=1}^{B} \sum_{ij\in L} f_{ij} C_{ij}^{b} I_{ij}^{n} (1+\frac{P_s}{2}) + 0.5 \sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L} f_{ij} t_{kl} I_{ij}^{n} W_{ijkl}^{b} -$$

$$0.5 \sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L} \sum_{m=1}^{T} \sum_{e=2}^{V} f_{ij} t_{kl} I_{ij}^{n} (\frac{1}{e-1} - \frac{1}{e}) U_{ijklme}^{b}]$$

$$+\sum_{b=1}^{B} \sum_{m=1}^{T} \sum_{e=1}^{V} C_m V_{me}^{b} (hr * day)$$

$$+\beta \sum_{d=1}^{D} \sum_{b=1}^{B} SD_d^b \qquad (16)$$

Subject to:

$$U_{ijklme}^{b} \leq X_{ij}^{b} \qquad for\ each\ ij \in L, kl \in L, m = \{1..T\}, e = \{1..V\}, b = \{1..B\} \qquad (17)$$

$$U_{ijklme}^{b} \leq X_{kl}^{b} \qquad for\ each\ ij \in L, kl \in L, m = \{1..T\}, e = \{1..V\}, b = \{1..B\} \qquad (18)$$

$$U_{ijklme}^{b} \leq V_{me}^{b} \qquad for\ each\ ij \in L, kl \in L, m = \{1..T\}, e = \{1..V\}, b = \{1..B\} \qquad (19)$$

$$W_{ijkl}^{b} \leq X_{ij}^{b} \qquad for\ each\ ij \in L, kl \in L, = \{1..B\} \qquad (20)$$

$$W_{ijkl}^{b} \leq X_{kl}^{b} \qquad for\ each\ ij \in L, kl \in L, = \{1..B\} \qquad (21)$$

$$W_{ijkl}^{b} \geq X_{ij}^{b} + X_{kl}^{b} - 1 \qquad for\ each\ ij \in L, kl \in L, = \{1..B\} \qquad (22)$$

$$R^{b} = 0.5 \left[\sum_{ij\in L} t_{ij} X_{ij}^{b} - \sum_{ij\in L} \sum_{m=1}^{T} \sum_{e=2}^{V} (\frac{1}{e-1} - \frac{1}{e}) t_{ij} O_{ijme}^{b}\right] \qquad (23)$$

$$O_{ijme}^{b} \leq X_{ij}^{b} \qquad for\ each\ ij \in L, m = \{1..T\}, e = \{1..V\}, b = \{1..B\} \qquad (24)$$

$$O_{ijme}^{b} \leq V_{me}^{b} \qquad for\ each\ ij \in L, m = \{1..T\}, e = \{1..V\}, b = \{1..B\} \tag{25}$$

$$\sum_{b=1}^{B} \sum_{e=1}^{V} V_{me}^{b} \leq 1 \qquad for\ each\ m \tag{26}$$

$$\sum_{m=1}^{T} \sum_{e=1}^{V} V_{me}^{b} = V_{b} \qquad for\ each\ b \tag{27}$$

$$\sum_{m=1}^{T} V_{me}^{b} = Z_{e}^{b} \qquad for\ \ each\ e = \{1..V\}, b = \{1..B\} \tag{28}$$

$$Z_{e}^{b} \geq Z_{e+1}^{b} \qquad for\ \ each\ e = \{1..V\}, b = \{1..B\} \tag{29}$$

$$C_{ij}^{b} \leq MX_{ij}^{b} \qquad for\ each\ ij \in L, b = \{1 \ldots B\} \tag{30}$$

$$C_{ij}^{b} \geq S_{ij}^{b} - M(1 - X_{ij}^{b}) \qquad for\ each\ ij \in L, b = \{1 \ldots B\} \tag{31}$$

$$S_{ij}^{b} = \sum_{k=1}^{k=V-1} C_{ijb}^{k} + S_{ijb}^{V} \qquad for\ each\ ij \in L, b = \{1 \ldots B\}, k = \{1..V\} \tag{32}$$

$$S_{ijb}^{k} \geq \left(\frac{S_{ij} - 0.5k(k-1)R^{b}}{k}\right) \qquad for\ each\ ij \in L, b = \{1 \ldots B\}, k = \{1..V\} \tag{33}$$

$$S_{ijb}^{k} \geq 0 \qquad for\ each\ ij \in L, b = \{1 \ldots B\}, k = \{1..V\} \tag{34}$$

$$C_{ijb}^{k} \leq R_{ij}^{b} \qquad for\ each\ ij \in L, b = \{1 \ldots B\}, k = \{1..V\} \tag{35}$$

$$C_{ijb}^{k} \leq S_{ijb}^{k} \qquad for\ each\ ij \in L, b = \{1 \ldots B\}, k = \{1..V\} \tag{36}$$

$$R_{ij}^{b} - C_{ijb}^{k} \leq Ma_{ijk}^{1} \qquad for\ each\ ij \in L, b = \{1 \ldots B\}, k = \{1..V\} \tag{37}$$

$$S_{ijb}^{k} - C_{ijb}^{k} \leq Ma_{ijk}^{2} \qquad for\ each\ ij \in L,\ b = \{1 \ldots B\}, k = \{1..V\} \tag{38}$$

$$a_{ijk}^{1} + a_{ijk}^{2} = 1 \qquad for\ each\ ij \in L,\ k = \{1..V\} \tag{39}$$

$$SD_d^b \geq X_{ij}^b * r_{ij}^d - M\left(1 - h_{ij}^b\right) \quad \text{for each } ij \in L,\ b = \{1 \dots B\} \tag{40}$$

$$\sum_{ij \in L} h_{ij}^b = 1 \quad \text{for each } b \tag{41}$$

$$h_{ij}^b \leq X_{ij}^b \quad \text{for each } ij \in L,\ b = \{1 \dots B\} \tag{42}$$

$$\sum_{b=1}^{B} X_{ij}^b = 1 \quad \text{for all } ij \in L \tag{43}$$

$$X_{ij}^b = X_{ji}^b \quad \text{for all } ij \in L \tag{44}$$

$$\sum_{b=1}^{B} y_i^b \geq 1 \quad \text{for each } i \in N \tag{45}$$

$$y_i^b \leq \sum_{j \in N, ij \in L} X_{ij}^b + \sum_{j \in N, ji \in L} X_{ji}^b \leq M y_i^b \quad \text{for each } i \in N \text{ and } b \tag{46}$$

$$\sum_{j \in N, ij \in L} Q_{ij}^b - \sum_{j \in N, ji \in L} Q_{ji}^b = -y_i^b \quad \text{for each } i \in N, ij \in LL \text{ and } b = \{1..B\} \tag{47}$$

$$Q_{ij}^b \leq M X_{ij}^b \quad \text{for each } ij \in LL \text{ and } b = \{1..B\} \tag{48}$$

$$\sum_{ij \in (LL-L)} X_{ij}^b = 1 \quad \text{for each } b = \{1..B\} \tag{49}$$

$$\sum_{ij \in L} X_{ij}^b \leq MV_b \quad \text{for each } b = \{1..B\} \tag{50}$$

In the above model, the objective function minimizes the monetized value of the total response and service time during the time horizon plus the costs associated with the program. In the model, constraints 17 through 22 define a new set of binary variables to resolve the non-linearity of the model as explained in the previous section. Constraint 23 presents the average response time formulation, and constraint 24 and 25 define a binary variable, O, to linearize the formulation for average response time and are added to make sure of the value of this dummy variable. The average response times are calculated based on the assumption that there is a constant headway between patrol units, and assuming an average patrolling speed. Although patrol units may drive faster or slower depending on the traffic condition, we assume an average patrolling speed as the model is intended for planning purposes. Besides, the network could be designed based on several average patrolling speeds for different traffic conditions (for example, peak hours vs. non-peak hours). Also, please note that patrol units may use shoulders or other special access routes to avoid the potential congestion on their way to the incident scene. Constraint 26 makes sure that each vehicle is assigned not more than once; constraint 27 calculates the total number of trucks in each beat, and constraints 28 and 29 are added to calculate number of patrol trucks in each beat, V_b. Constraints 30 through 39 are added to estimate the average service time on each beat. Please note that constraint 32 calculates the average service time and the rest of the constraints are added to linearize this calculation. Please note the formulation to calculate the service time is a general formulation based on the assumption of unlimited impact of additional trucks. Constraints 40 through 42 are added to assign beats to depots and determine the shortest distance between depots and their corresponding beat to deal with multi-depot problem.

The rest of constraints, constraint 43 through 50, are general constraints of the model. Constraint 43 ensures that exactly one beat covers each link. This constraint could be modified depending on the practical implementations such that more than one beat could cover each link or the patrol system may not even cover some links that are served by the dispatch system. However, in practice, it is not common to cover links with several beats as it could cause disturbance for response units and requires additional coordination (although it may be beneficial hypothetically). Also, all links must be covered by patrol units unless there is a dispatch system to cover links with low incident rates once an incident occurs. Therefore, in the proposed model, since it is intended for patrolling purposes only, it is assumed that each link must be covered by exactly one beat. In general, in patrol programs, emergency units are normally much closer to potential incident locations and may find and immediately respond to numerous incidents themselves which significantly reduces detection and response times while dispatch system could be used for low intensity links which continuous patrolling may not be beneficial.

Constraint 44 ensures that link *ij* is covered by the same beat that covers link *ji*. This constraint could also be relaxed such that links on different direction of the same segment are covered by different beats. However, yet again in practice, there are many parts of the network in which patrol units may be able to observe the other side while covering one side of the road. Therefore, to take advantage of this, and avoid confusion between patrol units on different beats, it is more beneficial to cover both sides of the road by the same beat and patrol crew. Constraint 45 ensures that at least one beat covers each node. Constraint 46 states that if there is any link covered by beat *b* starting or ending at node *i* then node *i* is included in beat *b*. Constraints 47 through 50 ensure connectivity of nodes covered by the same beat.

In the above objective function, to take into account the number of incidents responded but not detected by patrol trucks, we may update the first and second terms in the objective function as below:

$$\alpha[\sum_{b=1}^{B} \sum_{ij\in L}(f_{ij}^{p} + 0.5f_{ij}^{d})\, C_{ij}^{b}\, I_{ij}^{n}(1 + \tfrac{P_s}{2}) + 0.5\sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L}(f_{ij}^{p} + 0.5f_{ij}^{d})\, t_{kl}\, I_{ij}^{n}\, W_{ijkl}^{b} -$$

$$0.5\sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L} \sum_{m=1}^{T} \sum_{e=2}^{V}\left(f_{ij}^{p} + 0.5f_{ij}^{d}\right) t_{kl}\, I_{ij}^{n}(\tfrac{1}{e-1} - \tfrac{1}{e})\; U_{ijklme}^{b}] \qquad (51)$$

The constraints are the same as before and only the constraint for the service time needs to be updated based on the non-patrolling detection response time. Please note this formulation is based on the assumption that in the case of a reported incident, the incidents will be responded by trucks on the same beat. In general, in the model, there are two sets of variables. First stage variables are *X* and *V* which are main variables while the rest of the variables such as *R, S, C, W, U* are second stage variables. Second stage variables are calculated based on scenarios and values for the first stage variables. This study presents a comprehensive model that covers important aspects of patrol programs and addresses issues as much as possible to optimize the performance of the FSP programs. Part of the advantages of the current model compared to previous models in the literature is presented in Table 3.

Table 3 - Advantages of the Proposed Model

Proposed Model	Previous Models
Linear	Non-Linear
Convexity of Linear Relaxation	Non-Convex
Find Optimal Number of Beats	Pre-specified Number of Beats
Find Optimal Fleet Size	Pre-specified Number of Total Trucks
Clearance Time Considered	Only Response Time
Multi Depot	Single Depot
Individual Cost for Each Truck	Only One Cost
Trucks being Busy at the Time of Incident	Not Considered
Importance Factor	Not Considered

Chapter 4: Numerical Example

Study Area

To verify the model’s capability, confirm the formulation accuracy, and evaluate the impact of different features of the model in the solution, the proposed model is applied to part of the Tarrant County Courtesy Patrol (CP) program in Dallas-Fort Worth metropolitan area, as a numerical example. As a general rule, the study assumes that the probability of incident occurrence is uniform along each link because another freeway does not cross the link, and as a result, the traffic characteristics do not change significantly, though geometric conditions may change. Importance factors are assumed to be identical for all links. The network for the numerical example includes eight nodes and 11 links as illustrated in Figure 5.

Tarrant County CP maintains a log during each shift for each truck. The crew records the incident location and type, as well as the time that assistance was provided. In this study, we investigate their logs for October 2010 since October represents a typical month regarding traffic volume (i.e., there are no significant holidays). For this case, travel times are calculated based on the standard patrolling speed of 55 MPH for the Tarrant County CP.

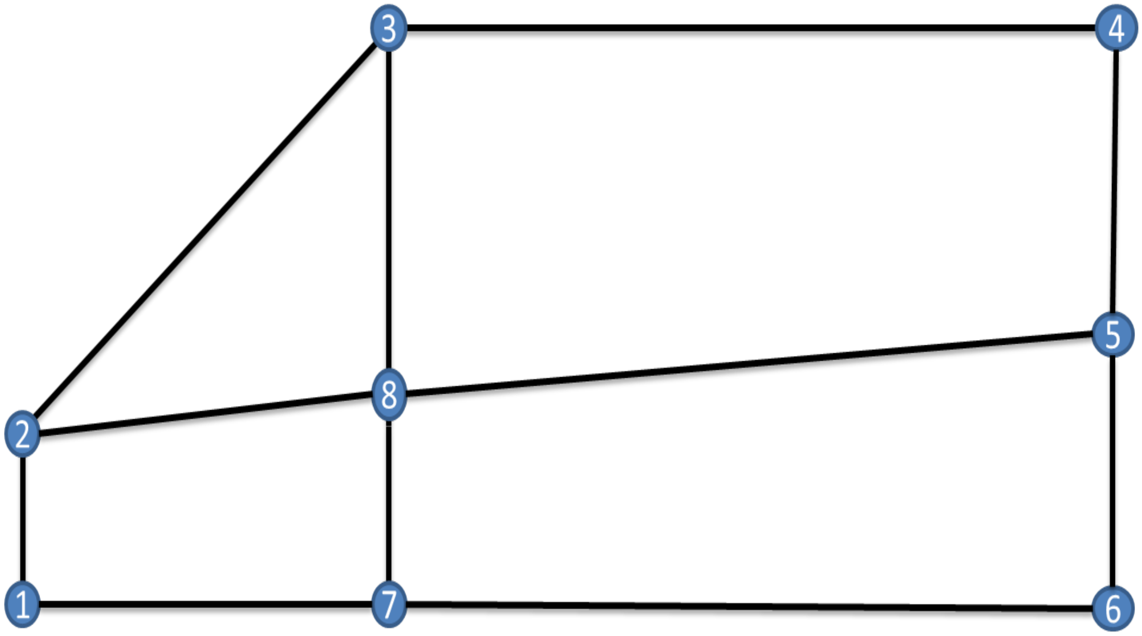


Figure 5 - Schematic Diagram of the Numerical Example’s Network

Another issue to deal with in traffic incident management programs is to find the ideal location for the depot to minimize travel for response units between the depot and potential incident locations. In patrol program, trucks keep patrolling on the network and only need to travel between the depot and their assigned beat twice per each shift: once from the depot to the beat to start the shift and once from their beat to the depot at the end of the shift. Patrol programs are not that much dependent on the location of depots like dispatch case (where, upon incident detection, trucks are sent to the incident location directly from depots, for each incident). However, the performance of the patrol programs could be improved (decrease in operation cost) by optimally assigning beats to available depots. Therefore, in the case that there are multiple choices available for the depot, it needs to be determined how depots should cover beats. Figure 6 shows two locations of Texas Department of Transportation from which patrol trucks could be sent off.

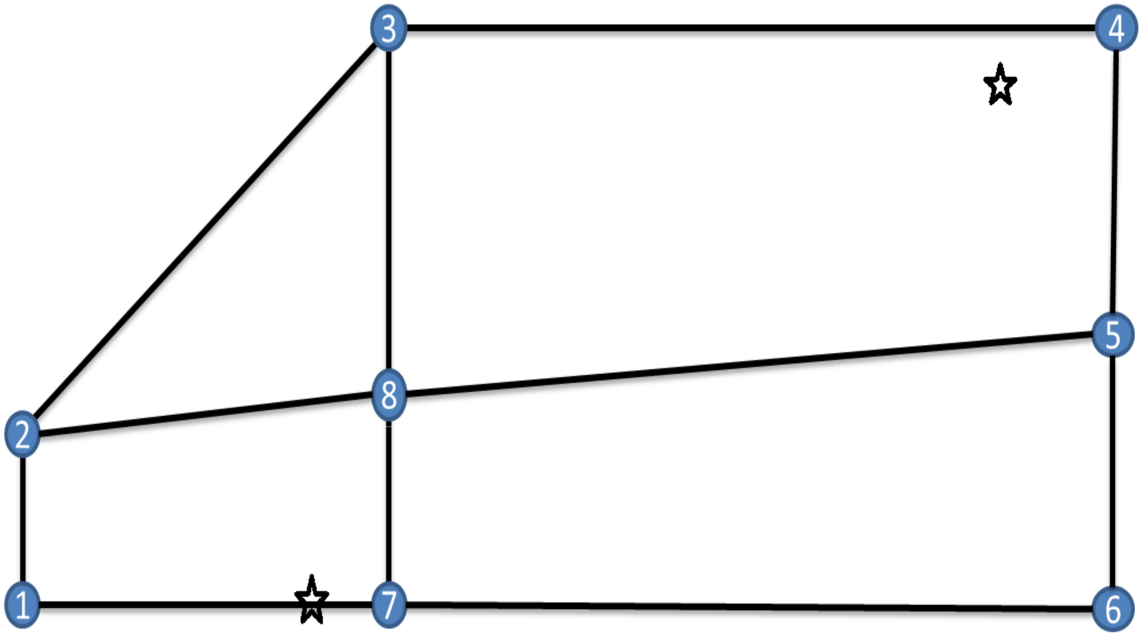


Figure 6 - Tarrant County's Courtesy Patrol Depots

Parameters Calculation

Parameter α was calculated based on findings of an earlier evaluation study [41] on H.E.L.P. (Highway Emergency Local Patrol) program, and details are presented below in Table 4. Five scenarios of response time reduction (RTR) are investigated. Each scenario is based on three different types of incident (shoulder blocked, one lane blocked, two lanes blocked) and four categories of hourly traffic volumes. Thus, each scenario is based on 12 categories of incident type and traffic volume. As discussed before, α is highly dependent on traffic volume and incident type. Parameter α is calculated based on each scenario and listed in Table 4. Parameter α approximately ranges between 10 to 15, and these values are used as the upper and lower bounds in this case.

For the H.EL.P network, there were 693 incidents assisted by the program. In Table 4, VEH-HR refers to the vehicle-hour unit, and RTR refers to the average response time reduction caused by the patrol program. For the numerical example, the value of time is assumed to be 15 dollars per hour.

Table 4 - Calculation of Parameter α

Scenario	RTR (min)	VEH-HR Saving	VEH-HR Saving Per 1-min RTR	VEH-HR Saving Per Incident Per 1-min RTR	Avg. Cost Saving Per 1-min RTR (α)
1	5	2558	512	0.738	11.1
2	10	5429	543	0.783	11.8
3	15	8633	576	0.83	12.5
4	20	12182	609	0.879	13.2
5	25	16804	672	0.97	14.5
Value of Time = 15 & Number of Incidents = 693					

Moreover, another parameter, β, is defined to convert non-serving time spent by patrol trucks, to/from depots from/to their assigned beats to monetary value, as below:

β = (number of shifts per day)*(number of trips per each shift)*(number of working days during the planning horizon)*(hourly cost per each truck) / (travel speed) *(52)*

This parameter is introduced to assign each beat to a depot, in case that multiple depots are available, by minimizing the non-serving travel times between beats and depots at the start and end of each shift. In other words, this parameter is added up to assign each beat to the closest depot. For our network parameter β is estimated to be about 75. This estimate is based on two working shifts per day and two trips per each shift for one single truck, and assuming truck's hourly cost of $50, 21 working days per planning horizon (October 2010), and travel speed of 55 MPH.

Analysis

In this section, the proposed model is applied to a set of different scenarios to evaluate the impact of different features of the model in the solution. First, the proposed model is applied to a base case scenario given the following assumptions:

- Number of beats: Two
- Only response time is considered

- Fleet size: 10 Trucks
- Single Depot

As mentioned, there are 11 links in this numerical study. The number of incidents, f, and the average travel time, t, for each of these links are listed in Table 5.

Table 5 - Base Case Inputs

NO	Links	f	t
1	1--2	23	3
2	2--3	133	12
3	3--4	81	17
4	4--5	81	5
5	5--6	79	5
6	6--7	306	16
7	7--1	127	9
8	8--2	174	9
9	8--3	196	6
10	8--5	342	14
11	8--7	136	5

Given the above assumptions and the input data in Table 5, the optimal beat configuration is determined and shown in Figure 7, and the truck allocation is presented in Table 6. The commercial optimization package FICO Xpress is used to solve the problem.

Table 6 - Truck Allocation for the Base Case

Total Response Time = 271 hours	Number of Vehicles (V)
Beat 1 (Blue)	7
Beat 2 (Red)	3

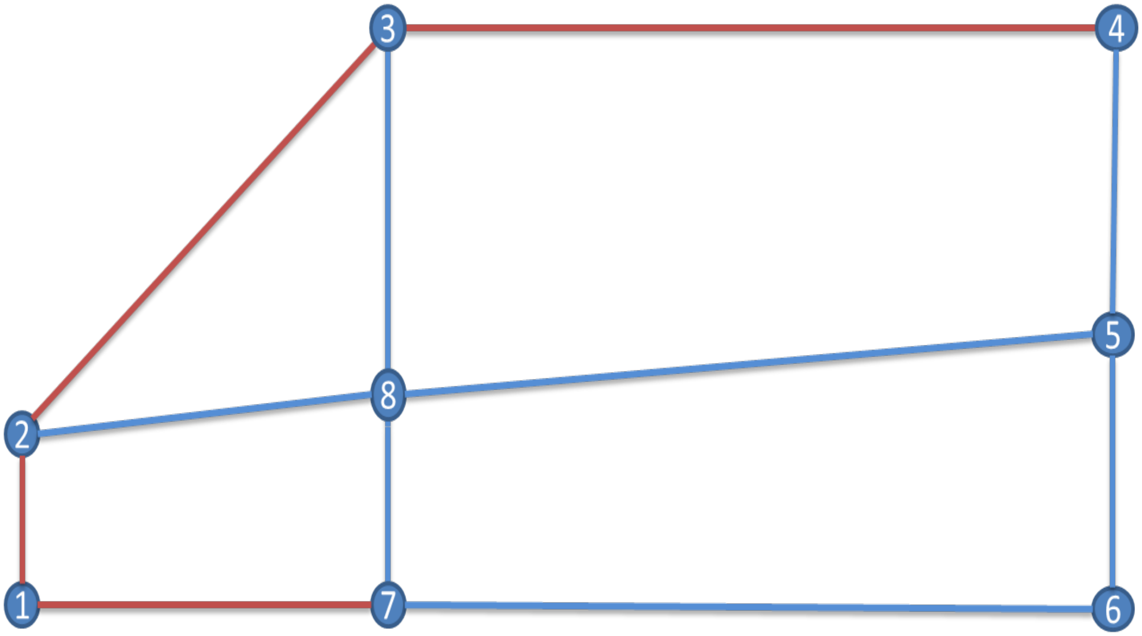


Figure 7- Beat Configuration for the Base Case

As shown, to minimize the total response time during the time horizon, October 2010, seven trucks should be allocated to the first beat while three trucks need to patrol on the other beat. The total response time (responding to 1678 incidents) experienced during the time horizon, in this case, is estimated to be 271 hours.

The problem is solved for another scenario which is similar to the base scenario with the difference that hypothetical service times are added to the objective function, as well, to find out the impact of this term on the solution. In this scenario, for all links, service times are assumed to be equal to 20 minutes (in case that only one truck removes each incident). This is to demonstrate that even in such a case that incident severity is similar for all links; clearance times could still have an impact on the result. The optimal beat configuration for this case is shown in Figure 8, and the truck allocation is presented in Table 7.

Table 7 - Truck Allocation (Service Time Added)

Total Response and Service Time = 938 (hrs.)	Number of Vehicles (V)
Beat 1 (Blue)	8
Beat 2 (Red)	2

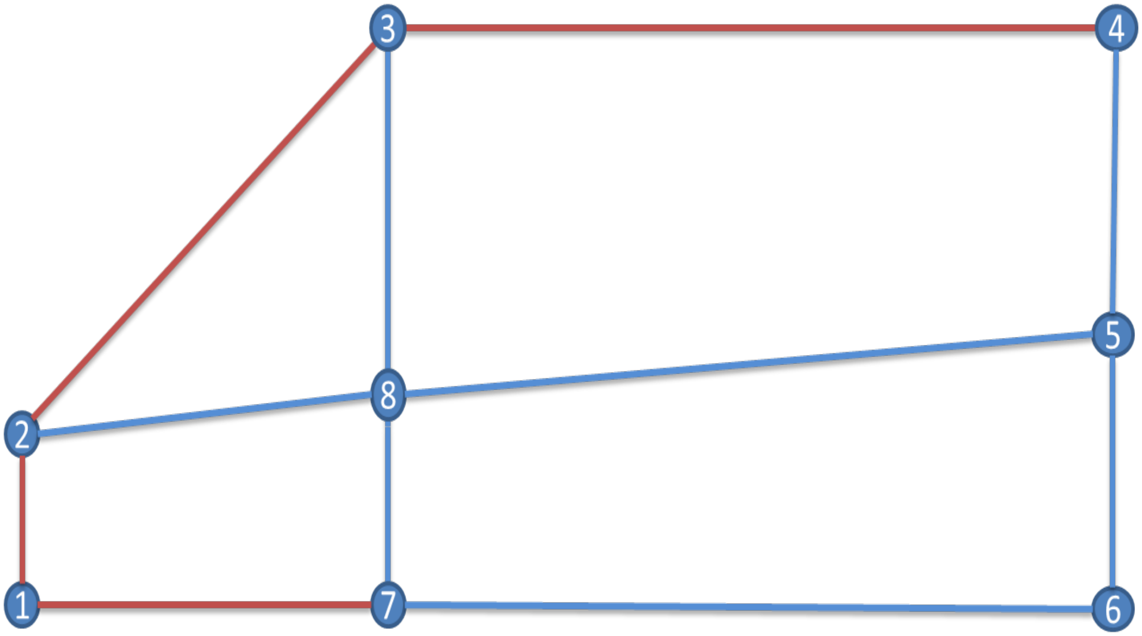


Figure 8 - Beat Configuration (Service Time Added)

As shown, the optimal beat configuration is similar, but the truck allocation has changed. The optimal solution indicates that eight patrol trucks must be allocated to the first beat, and only two trucks need to patrol on the second beat, now. Compared to the base case, one more truck needs to be allocated to the first beat reducing one truck from the second beat. Again, this assumes that all links have the same type of incidents regarding the average severity. Although the service times are assumed equal, the truck allocation is different than the base case which emphasizes the impact of clearance time on determining the optimal network. Apparently, this impact would be even larger because roads are likely different regarding average incident severity. Assuming the beat configuration and truck allocation in the base case solution, total response and service time would be 946 hours which is decreased to 938 hours in the solution which considers the service time in the objective function.

Now, the proposed model (not including the service time) is applied to the network without assuming pre-determined values as the number of beats and fleet size. All inputs and assumptions are presented in the Tables 8 and 9. The network has eight nodes and 11 links with two available depots. It is assumed that the maximum fleet size is 30 and the maximum number of trucks allowed to be allocated to each beat is 25. The number of incidents and travel times for each link plus distances from both depots to each link are provided in Table 8. The hourly cost of each truck is assumed to be \$50 per hour. Assuming 21 working days in a month, and 16 operation hours per day, the total cost during the time horizon could be calculated. Finally, as discussed in the previous section, parameter α (based on an earlier FSP evaluation study) and parameter β were estimated. Based on the input and the above assumptions for this scenario, the optimal beat configuration is determined and shown in Figure 9.

Table 8 - Case Study Inputs

NO	Links	f	t	r_1	r_2
1	1--2	23	3	7	30
2	2--3	133	12	11	17
3	3--4	81	17	17	4
4	4--5	81	5	24	7
5	5--6	79	5	18	13
6	6--7	306	16	4	20
7	7--1	127	9	1	25
8	8--2	174	9	10	20
9	8--3	196	6	10	17
10	8--5	342	14	10	11
11	8--7	136	5	4	20

Table 9 - Parameters

Parameters	Value
B	8
C_m	50
α	10-15
β	75
T	30
V	25
D	2
h	16
day	21

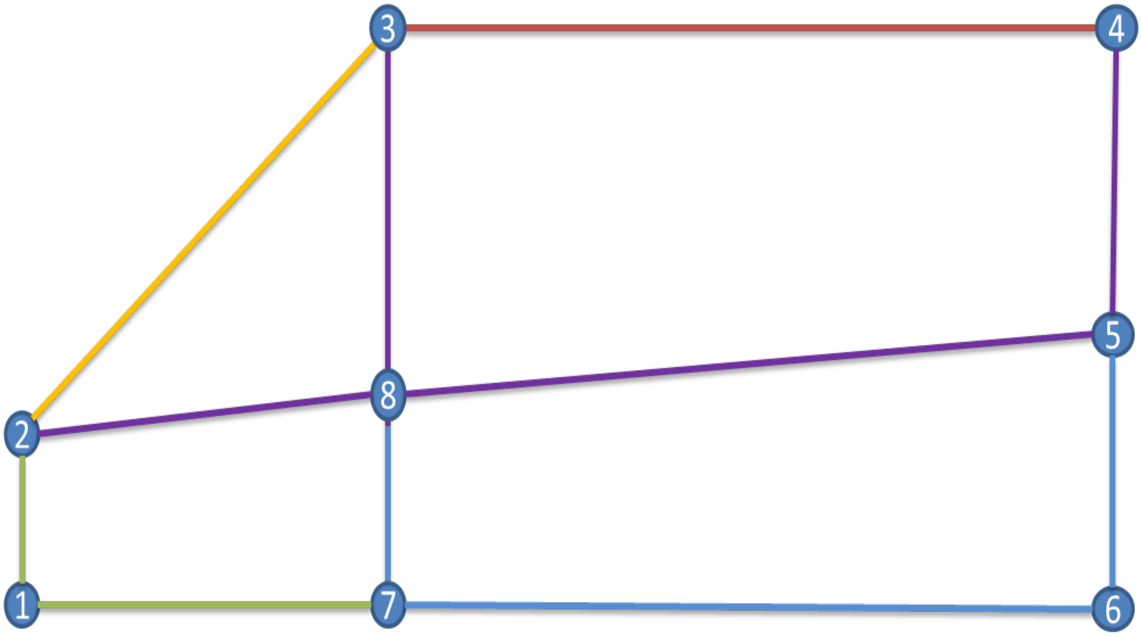


Figure 9 - Optimal Beat Configuration

The optimal fleet allocation based on α = 10 and α = 15 are presented in Tables 10 and 11, respectively. As listed in these tables, the total cost, including program's operation costs plus the cost associated with the incident delay (monetized loss caused by incident delay) is estimated to be around $332,300 to $409,200 for the subject network.

Table 10 - Truck Allocation Based on α = 10

Total Cost = $332300	**Number of Vehicles (V)**
Beat 1 (Green)	1
Beat 2 (Purple)	4
Beat 3 (Red)	1
Beat 4 (Orange)	1
Beat 5 (Blue)	3
Beat 5+	NA
Total	10

Table 11 - Truck Allocation Based on α = 15

Total Cost = $409200	**Number of Vehicles (V)**
Beat 1 (Green)	1
Beat 2 (Purple)	5
Beat 3 (Red)	1
Beat 4 (Orange)	1
Beat 5 (Blue)	3
Beat 5+	NA
Total	11

Average response times for all beats are presented in Tables 12 and 13 for both cases of α=10 and α=15, respectively. Also, total estimated response times during October 2010 are presented. Allocation of beats to depots is determined as well.

Table 12 - Average Response Times for α = 10

Beat	Depot	Number of Trucks	Avg. Response Time (min)
1	1	1	12
2	2	4	8.5
3	2	1	17
4	1	1	12
5	1	3	8.7
Total Response Time	266 hours		

Table 13 - Average Response Times for α = 15

Beat	Depot	Number of Trucks	Avg. Response Time (min)
1	1	1	12
2	2	5	6.8
3	2	1	17
4	1	1	12
5	1	3	8.7
Total Response Time	244 hours		

As mentioned, the total cost for the subject network is estimated to be \$332,300 assuming $\alpha = 10$ and \$409,200 assuming $\alpha = 15$. Please note that the total cost for the solution in the base case, for the same period, based on $\alpha = 10$ and $\alpha = 15$, would have been \$334,400 and \$415,600, respectively.

As shown, the optimal beat configuration includes five beats. For this beat configuration, given ten available trucks (similar to the base case), the optimized total response time, responding to 1678 incidents, found to be 266 hours during one month of operation. Therefore, the total response time during the time horizon is less compared to the optimal base case (271 hours).

Based on the comparisons above, we can claim that instead of assuming a predetermined number of beats, the optimal number of beats needs to be determined to improve the performance of the patrol programs. Furthermore, all other factors mentioned in the contribution need to be considered, and this example indicates their impact on designing the optimal network. Thoughtful consideration of all factors reduces the incident-incurred delay and yet decrease the cost associated with the patrol programs.

Chapter 5: Heuristic Algorithms

A heuristic algorithm is required to solve the problem for large size networks. This section presents a few different approaches to solve the problem. These approaches could be used individually or in combination with each other to form a heuristic algorithm which can generate close to optimal solutions.

Network Decomposition

For the first strategy, if applicable, we categorize the network based on dense parts and connection areas. For the connection areas, there is only one link entering and leaving at each node, and the main question is where to break the road to separate beats. If a network contains no specific connection area, the network still could be decomposed into a few sub-networks to continue the process. This is discussed further in the next section.

For now, to illustrate the network decomposition strategy, part of the Maryland's freeway network is presented in Figure 10 (this network will be used in our case study). The network consists of three major dense parts and three connection roads as shown in Figure 10. These dense parts are connected to each other through connection roads. The only way that, for example, one link in part 1 is in the same beat as a link in part 2 is that the whole connection road in between is in the same beat which may not be justified depending on the fleet size and incident distribution. Here, the strategy is to solve the model for each dense part separately and afterward, given the output from step 1, solve it for the whole network to determine the beat structure for the connection areas, and subsequently for the whole network. This approach is perfect for the networks with long roads and separate dense areas, such as the one here, but this also works for grid networks as explained in the following section. We do not count on this approach as a single heuristic algorithm, and as will be described in next sections, this approach is mainly used to generate a solid initial solution for another heuristic algorithm.

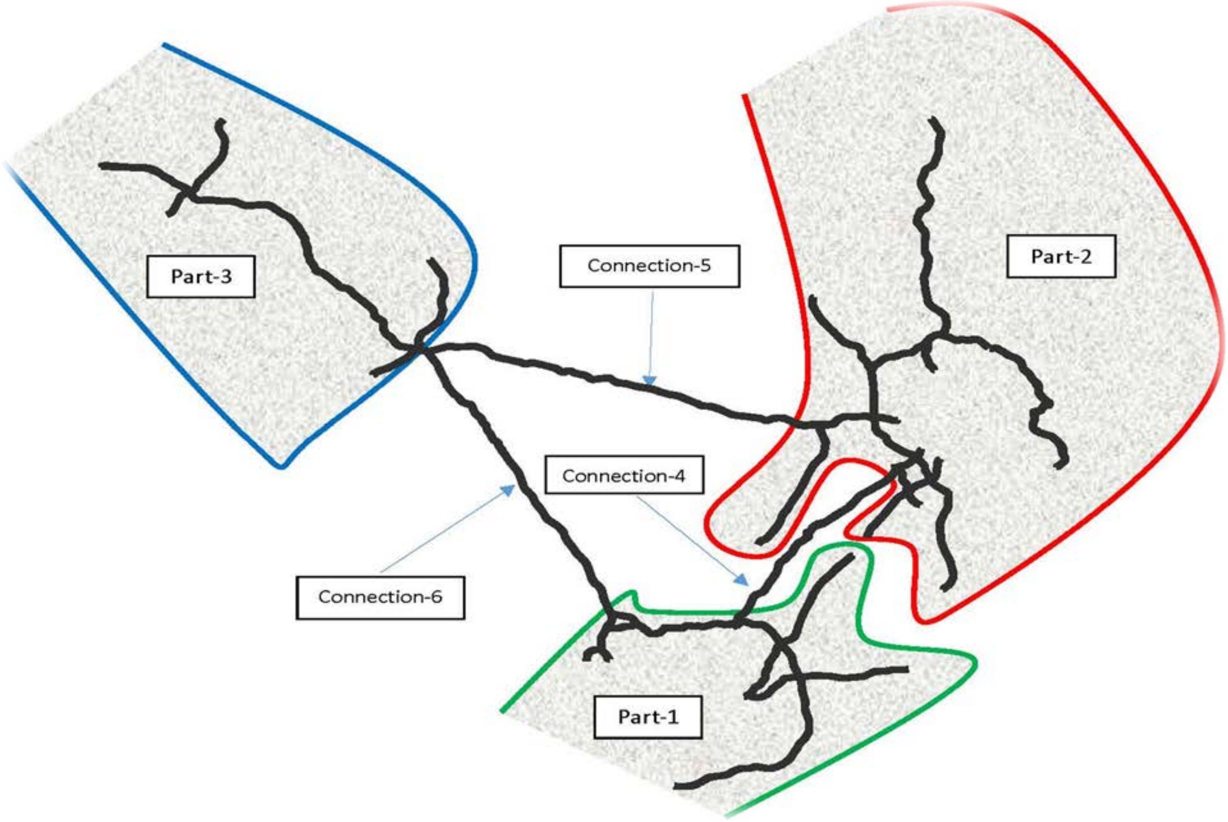


Figure 10 – Sub-networks

General Network Decomposition

In general, for any network, first, we need to decompose the network into a few sub-networks that are small enough so that the optimization problem can be solved easily. Please note that we do not need to assign every link to a sub-network. Those un-assigned links will be dealt with once the problem is solved for the whole network. However, if all links are assigned to sub-networks, then, we do not need to solve the problem for all sub-networks.

To generate sub-networks, if the network includes separate dense parts and connection areas, each of those dense parts will be a sub-network. Otherwise, if dealing with a grid network, we divide the network to a few relatively similar size sub-networks. For grid networks, sub-networks could be selected by clustering based on the number of incidents. Even sub-networks with different size and incident densities could be selected. An algorithm to generate sub-networks is presented at the end of this section.

Now, we solve the problem for sub-networks. Possibly, solving only for a few dense sub-networks should suffice. Then, given the results in the first step, we solve it for the whole network. We determine the result for connection areas or links that were not initially assigned to a sub-network in this step.

Please note that the number of beats and fleet size for each separate sub-network is determined individually by the model depending on the operation cost and incident density for that part. That's why the approach can offer a solid solution regardless of the size of each sub-network. This approach generates a decent solution that depending on the shape of the network may generate a very solid initial solution (close to the final solution) for another algorithm such as a neighbor search algorithm which is described in the next section.

Generating Sub-Networks

The steps below could be followed to generate sub-networks:

Step 1: Determine the maximum size or a limit for the size of sub-networks (number of links that are assigned to each sub-network). This limit should be selected such that each subnetwork is small enough to solve the optimization problem.

Step 2: Determine the total number of links that we would like to assign to sub-networks.

As mentioned before, we do not need to assign each link to a sub-network since un-assigned links will be assigned to a beat once solving the problem for the whole network. Therefore, assuming the maximum size of each sub-network to be n and the total number of links in the network to be $mn + d$ $(1 \leq d \leq n)$, then at least m sub-networks is needed and d links do not need to be assigned to any subnetwork.

Step 3: Assign a degree to each node such that the degree of each node represents the number of links that meet the node.

Step 4: Assign each node with degree 1 (endpoints) to a different subnetwork.

Step 5: For each sub-network, start to add links to it, one by one, until we get to a node with a degree more than one or once the size of the sub-network reaches the limit.

At this point, we have identified all branches of the network by assigning them in different sub-networks. Now, we need to check if any of these sub-networks are terminated at a common node such that they can be merged.

Step 6: For any pair of sub-networks that meet at the same node:

- If the sum of their sizes does not exceed the limit, merge them, and continue extending the merged sub-network until we get to a node with a degree more than one or once the size of the merged sub-network reaches the limit.
- If the sum of their sizes exceeds the limit, we assume the sub-network with the largest size is a final sub-network and will remove it from the network and continue with the other sub-network until it reaches a node with a degree more than one or its size reaches the limit.

If a sub-network is finalized (when its size reaches the limit or further extension or merge is not possible) and removed, the degree of nodes will be updated based on the updated network. We continue this process until no further changes in sub-networks could be made, meaning that, sub-networks cannot be merged or extended and no other sub-network can be generated as there are no more un-assigned nodes with a degree of one.

Step 7: For each sub-network, extend it by adding all neighbor links (which are not already assigned) to the sub-network. If the sub-network has no un-assigned neighbor links, check to see if it could be merged with its neighbor sub-network and continue this process for all sub-networks until the size of each sub-network reaches the limit, or the total number of links assigned to all sub-networks reaches to the target number (in step 2).

Once a subnetwork is finalized, we remove it from the network and continue the process with the rest of the network. If at any point, all the generated sub-networks are finalized and removed from the network, and the network has no more nodes with a degree of one (for example, all sub-networks are removed, and we are left with a total grid network), then assuming we have already extracted *k* sub-networks we can select *m*-*k* random nodes and extend them to generate sub-networks by repeating step 7.

Neighbor Search

As a complement to the network decomposition approach, given an initial solution from the above algorithm, for each beat, we evaluate all neighbor links to see if removing them from their current beat and adding them to the subject beat will result in a better solution. After re-assigning the link, we may let the model re-calculate the fleet allocation based on the updated configuration. Now, if a better solution is obtained, the current solution will be the new best solution. If removing a link from its current beat results in a disconnected beat, we allow the model to break that beat into two separate beats, in case that the new configuration generates better results. In neighbor search method, after each step, we may let the model update the fleet allocation for involving beats (beat that the link is added to and beat that the link is eliminated from). Obviously, this may change the fleet size, too.

Heuristic Algorithm: General Network Decomposition plus Neighbor Search

The combination of general network decomposition and neighbor search algorithms generates a decent heuristic algorithm which could be summarized in following steps. Please see above sections for further details on each step.

Step 1: Divide the network into a few sub-networks, which are small enough to solve. The process on how to generate sub-networks is explained in general network decomposition section.

Step 2: Solve the problem for sub-networks.

Step 3: Given the results from each sub-network, solve the problem for the whole network.

Now we have a very solid initial solution. Choose this solution as the current best solution and continue to step 4. Please note that step 1 through step 3 only aims to generate a solid initial solution.

Step 4: Select each beat one by one, and for each beat, evaluate all neighbor links to see if removing them from their current beat and adding them to the subject beat will improve the solution. If a better solution is obtained, update the best solution. Continue the process for all neighbor links for every beat.

Step 5: Stop if, in step 4, after checking all neighbor links for every beat in the best current beat configuration, no better solution is found.

Step 6: Save the latest result including beat configuration, fleet size, and fleet allocation as the final solution.

The heuristic algorithm described above is summarized and illustrated in a flowchart shown in Figure 11. The circle part briefly explains the process in neighbor search approach. Two other algorithms, Model Decomposition, and Beat Merge are also presented in the following sections.

Model Decomposition

Another algorithm is to decompose the problem into two sub-problems:

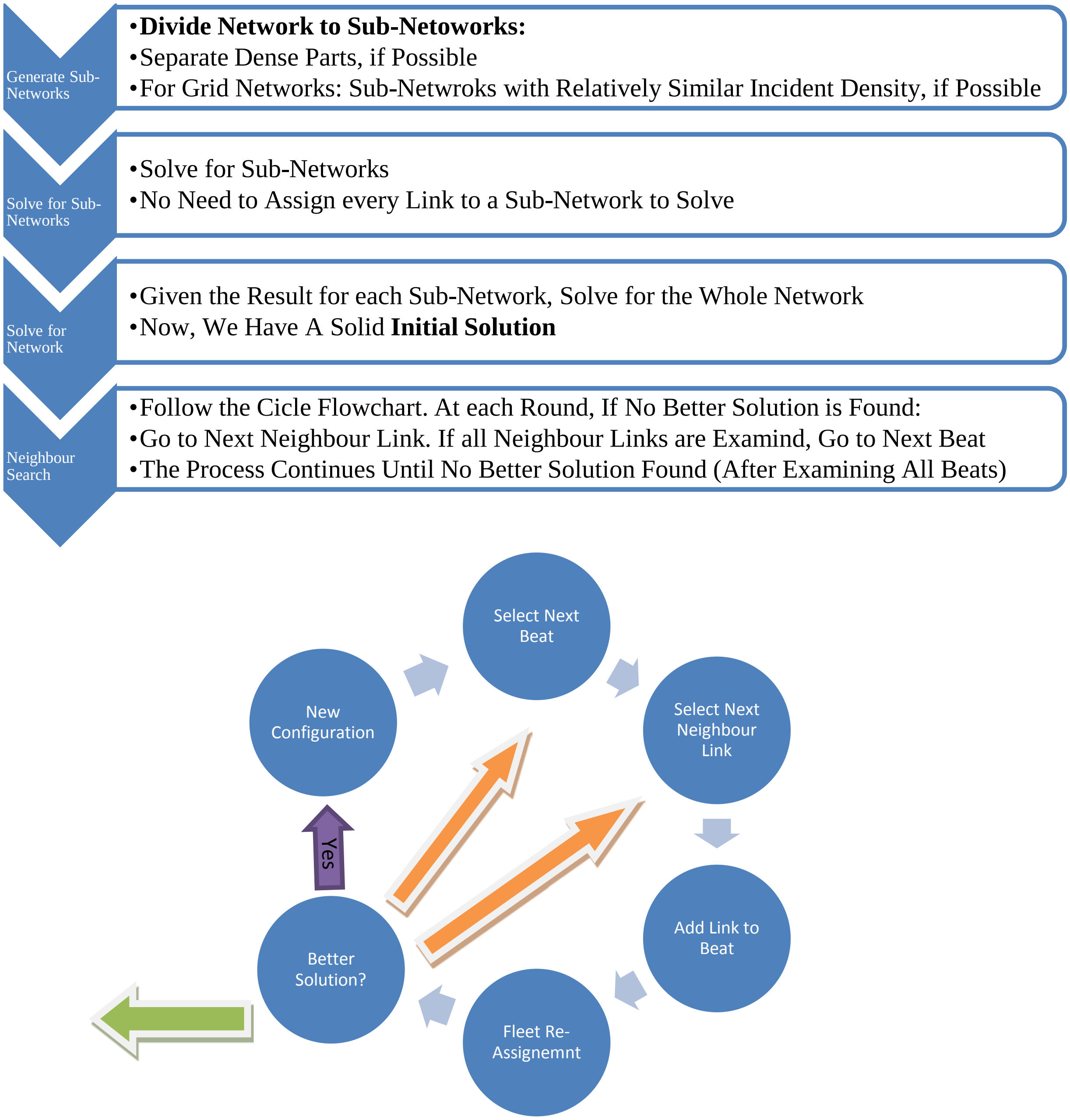
1. Determine the beat structure given the fleet size and fleet allocation
2. Determine the fleet size and fleet allocation given the beat structure

This heuristic algorithm could be summarized in following steps:

Step 1: Set $k = 0$

Step 2: Choose a sensible number as the maximum possible number of beats.

Step 3: Set $V_b = 1$ for all beats as the current fleet allocation (assign only one truck to each beat)



- **Divide Network to Sub-Netoworks:**
- Separate Dense Parts, if Possible
- For Grid Networks: Sub-Netwroks with Relatively Similar Incident Density, if Possible

- Solve for Sub-Networks
- No Need to Assign every Link to a Sub-Network to Solve

- Given the Result for each Sub-Network, Solve for the Whole Network
- Now, We Have A Solid **Initial Solution**

- Follow the Cicle Flowchart. At each Round, If No Better Solution is Found:
- Go to Next Neighbour Link. If all Neighbour Links are Examind, Go to Next Beat
- The Process Continues Until No Better Solution Found (After Examining All Beats)

Figure 11 - Heuristic Algorithm

Step 4: Solve the problem to determine the beat configuration based on the current fleet allocation. Save the solution as the current beat configuration and update the objective function.

Please note that, in the first sub-problem, we let the model revise the number of beats by assigning no link to a hypothetical beat number and removing the cost associated with assigned trucks to that beat. This way the number of beats may reduce if a better solution found with a smaller number of beats. Please note that it still may be difficult to solve the first sub-problem for very large networks optimally. Therefore, general network decomposition strategy, again, may be applied for this algorithm to tackle the problem, if necessary.

Step 5: Given the beat configuration from the previous step, solve the problem to determine the optimal fleet size and fleet allocation. Save the solution as the current fleet allocation and update the objective function

Please note that the second sub-problem is a simple assignment problem and could be solved using available commercial solvers.

Step 6: Set $k = k + 1$

Step 7: Stop if the solution in step 4 is close enough to the solution in step 5 **OR** $k >= M$ (the maximum number of runs*);* Otherwise go back to step 4

Step 8: Save the latest result including beat configuration, fleet size, and fleet allocation as the final solution

Beat Merging

For this algorithm, first, we determine the beat structure based on the assumption of one truck per beat. Then, we need to see if merging neighbor beats and having two trucks for the combined beat will improve the solution. This algorithm could be summarized in following steps:

Step 1: Set $V_b = 1$ for all beats as the current fleet allocation (assign only one truck to each beat)

Step 2: Solve the problem to determine the beat configuration based on the current fleet allocation. Save the solution as the current beat configuration and update the objective function

Step 3: For the current solution, for each beat i (V_i trucks assigned to beat i), see if merging the beat to the neighbor beat j (V_j trucks assigned to beat j) to create a combined beat with V_i+V_j trucks in the beat will improve the solution. If a better solution is obtained change the current beat solution to the new solution.

Step 4: Stop if checking all beats (to merge with their neighbor beats) in step 3 does not generate a better solution anymore

Step 5: Save the latest result including beat configuration, fleet size, and fleet allocation as the final best solution

Comparison

The problem to determine the beat configuration, fleet size and fleet assignment for the numerical example network is solved applying each of these three algorithms described above.

To solve the problem using the network decomposition plus neighbor search algorithm, first, the algorithm for generating sub-networks is applied to determine sub-networks. For this purpose, assume we would like to have up to 5 links per each sub-network. Therefore, we need two sub-networks for the subject network. Since no node with degree one exists, we start at two random nodes 1 and 2 to generate two sub-networks. Then, two sub-networks are generated labeled as sub-network 1 including links 1-2, 1-7, 5-6, 6-7, and 7-8, and sub-network 2 including links 2-3, 2-8, 3-4, 3-8, and 5-8, while link 4-5 is not assigned to any sub-network. The problem is solved for both of these sub-networks, and then the problem is solved for the whole network to determine the beat for un-assigned link 4-5 as well as the fleet size and fleet allocation for the whole network. Afterward, the neighbor search algorithm is applied to find the solution. Also, the model decomposition approach is applied by starting with six beats and one vehicle per beat. The problem is solved using the Beat Merge algorithm, too.

The result based on each algorithm is listed in Table 14. Also, beat configurations based on the algorithms are presented in Figure 12 through Figure 14. According to the testing of different algorithms, it appears that the network decomposition plus neighbor search algorithm provides a more promising solution. Also, although the other two algorithms can improve the solution process, in general, they are based on the assumption that solving the problem for the beat structure, given the fleet size and fleet allocation, is achievable. However, for large networks, even determining the beat structure alone becomes pretty difficult and requires an algorithm. Therefore, the network decomposition plus neighbor search heuristic is the main heuristic that is used to solve the problem for the case study and, as will be presented, works pretty well in creating good solutions for the problem.

Table 14 - Algorithms Comparison

Beat	**Network Decomposition plus Neighbor Search**	**Model Decomposition**	**Beat Merge**
Beat 1 (Green)	1	2	3
Beat 2 (Purple)	4	2	3
Beat 3 (Red)	1	1	1
Beat 4 (Orange)	1	2	1
Beat 5 (Blue)	3	2	1
No. of Beats	5	5	5
Fleet Size	10	9	9
Objective Value	$332300	$334000	$334700

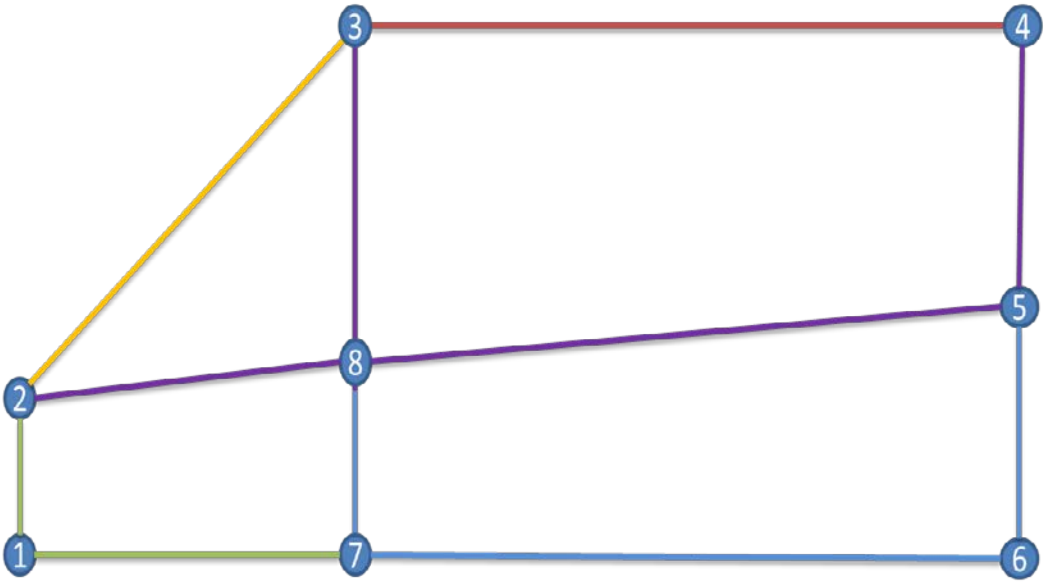


Figure 12 - Beat Configuration Based on Network Decomposition plus Neighbor Search Algorithm

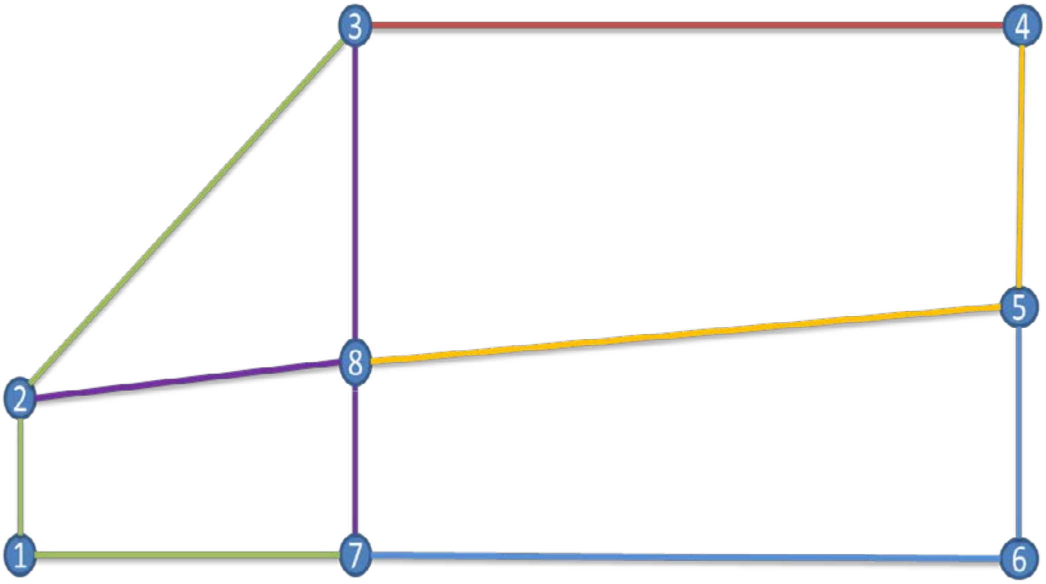


Figure 13 - Beat Configuration Based on Model Decomposition Algorithm

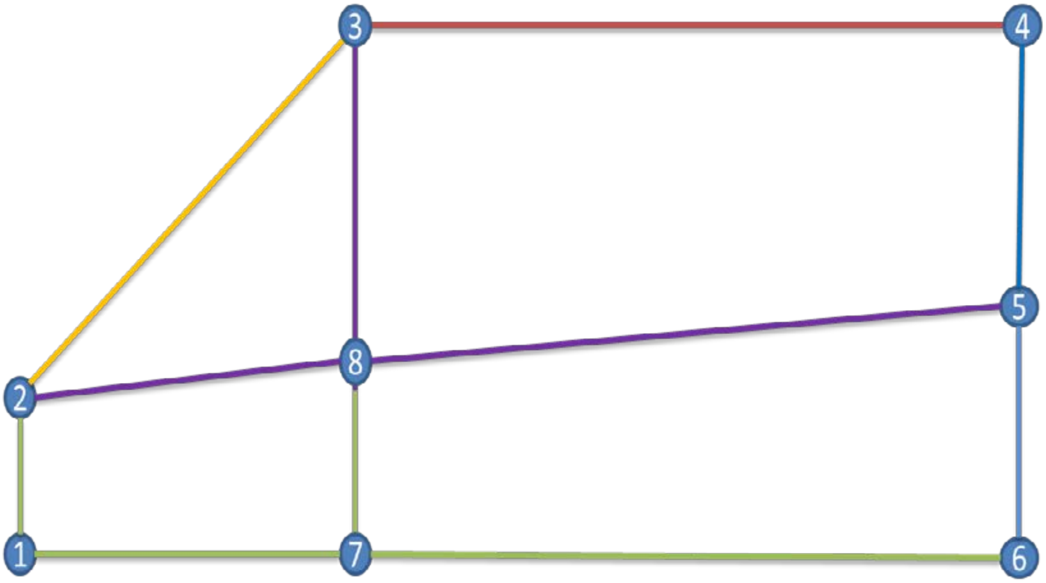


Figure 14 - Beat Configuration Based on Beat Merge Algorithm

Chapter 6: Coordinated Highways Action Response Team

Overview

State of Maryland operates a patrol program which is implemented by the Coordinated Highways Action Response Team (CHART). CHART works in partnership with the Maryland State Highway Administration (SHA), Maryland Department of Transportation (MDOT), Maryland Transportation Authority (MDTA), and the Maryland State Police (MSP) [42].

Figure 15 - Coordinated Highways Action Response Team (CHART)

CHART uses Emergency Traffic Patrols (ETP) to provide emergency motorist assistance and to relocate disabled vehicles out of travel lanes. CHART Emergency Traffic Patrols uses three different types of response vehicles to deal with the incidents:

- CHART Custom Response Vehicle – CRV
- CHART Heavy-Duty Utility Truck
- CHART Tow Truck

These response units are shown in Figures 16 through 18, respectively. These units are equipped with tools and devices to remove incidents from the roadway, provide assistance for motorists, and warn the traffic of incidents and possible actions they need to make.

Figure 16 - CHART Custom Response Vehicle – CRV

Figure 17 - CHART Heavy-Duty Utility Truck

Figure 18 - CHART Tow Trucks

CHART operates with five depots and seven Traffic Operation Centers (TOC). Three of these TOCs are permanent while the others are seasonal. The network permanently covered by CHART is shown in Figure 19 including Western, Baltimore, and National Capital region patrols.

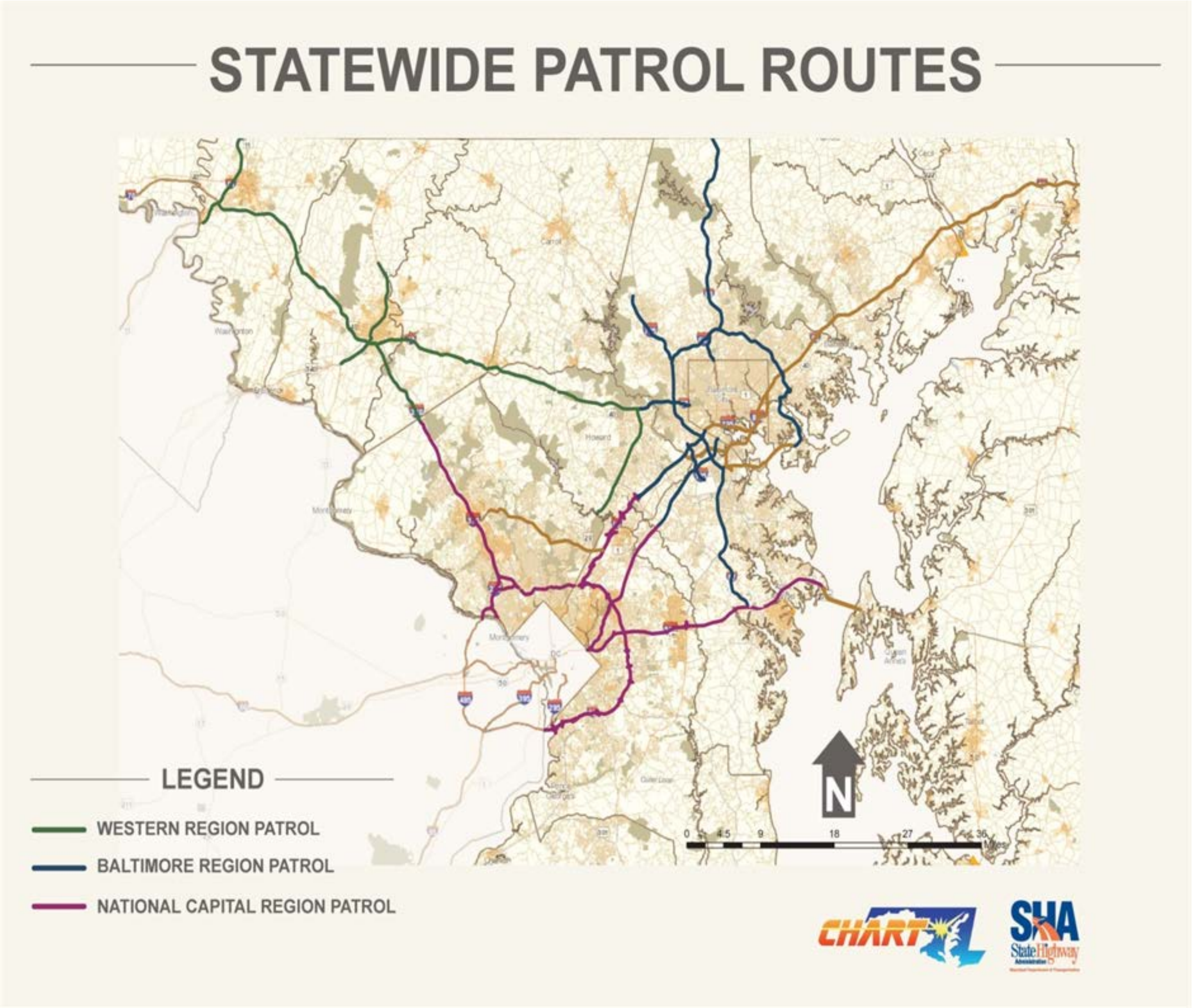


Figure 19 - Statewide Patrol Routes

CHART field patrol routes operate based on the following regions [43]:

National Capital Region (NCR):

The following routes within Prince George's, Montgomery, and Southeastern Howard Counties:

I-95 from Woodrow Wilson Bridge to MD 32 (Exit 38), I-270, I-495, US 50, MD 5, and MD 295

Baltimore:

The following routes within Baltimore, Anne Arundel Counties and Northeastern Howard Counties:

I-70 from US 29 to Security Blvd, I-83, I-95 from MD 32 to Caton Ave (Exit 50), I-97, I-795, US 50, MD 100, and MD 295

Western:

The following routes within Carroll, Frederick, Washington and Western Howard Counties:

I-70 from US 29 to the area of Hancock, I-81, I-270, US 15, US 340, and MD 140 from Baltimore/Carroll County line to MD 31

The proposed model is applied to part of the Maryland's freeway network which is covered by CHART. CHART patrol units operate 24/7 in Baltimore and National Capital regions while the Western region is covered each day from 5 AM to 9 PM [44].

Study Area

As indicated, the proposed model is applied to part of the Maryland's freeway network and data. Incident data during the year of 2015 is investigated to determine the optimal design. Based on the historic log data, the number of incidents that are detected and responded by CHART (not necessarily CHART units) in the above network is estimated to be more than 11,000 incidents during the year of 2015. Please note that this dataset includes incidents that occurred on CHART patrol coverage routes or in the vicinity of 10 miles from patrol routes and does not include incidents that are responded by CHART units outside this limit. Incidents that did not occur on the patrol routes (still in 10 miles vicinity) are assigned to the closest patrol route to the incident location. Obviously, that may increase the number of incidents assigned to the patrol boundary routes. It is assumed that CHART patrol units detected all of these incidents.

For the analysis, the CHART network is divided into 119 two-way segments, as partially shown in Figure 20. Each number in Figure 20 represents one segment. These segments, which are called links in this study, are separated by 116 nodes. Details about the exact location of these 116 nodes and 119 links are summarized in Appendix A and Appendix B, respectively. Nodes are typically chosen at the major interchanges where re-routing for patrol units is possible. Also, some nodes are designated to specify the boundaries of CHART current coverage area on different routes. A few other nodes are also designated just to separate different paths.

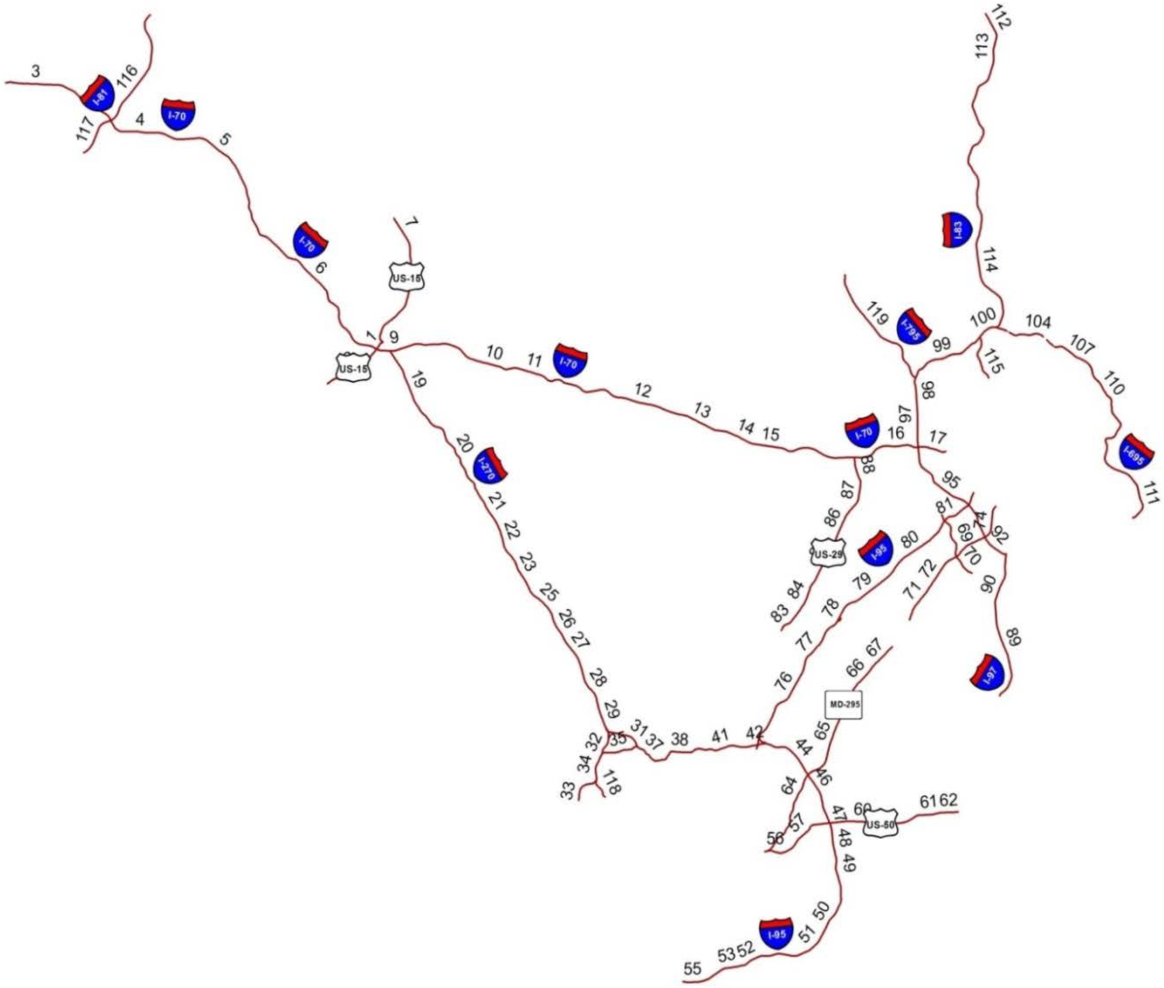


Figure 20 - Network Links

For this case, importance factors are assumed to be identical for all roads. Also, service time is not included in the analysis, and we aim to minimize the total patrolling response time (including detection and verification times) considering the operation cost. For this purpose, it is assumed that the maximum number of trucks which could be assigned to a single beat is two trucks. Furthermore, the hourly cost of each truck including the driver's wage and vehicle costs are estimated to be about 50 dollars per hour. The vehicle cost includes items such as fuel, maintenance, and supplies plus other costs associated with the patrol trucks. Also, the CHART network is assumed to have one depot only (no beat to depot assignment is needed) and total costs in results do not include the minor costs associated with deadhead times spent by patrol trucks between depots and beats. In general, this deadhead cost is trivial for networks where depot locations are not far from the network and may be ignored.

CHART patrol trucks run under three different shifts during weekdays including the morning shift, afternoon shift, and night shifts. CHART patrol trucks also operate during weekends. Night and weekend shifts typically have lower traffic volume and less number of incidents compared to the morning and afternoon shifts during weekdays. Because of the lower traffic volume, patrol units can travel faster in their assigned beats during the night and weekend shifts. Therefore, different patrolling speeds could be assumed for different shifts.

As revealed, CHART patrol trucks cover the network permanently throughout the year by operating in a number of shifts during different times of the day and the week. Night and weekends are similarly low regarding traffic volume and incident density and could be treated in the same way. Therefore, the problem is solved for three separate cases as below:

1. Weekday Mornings (5 AM- 1 PM)
2. Weekday Afternoons (1 PM – 9 PM)
3. Weekday Nights (9 PM – 5 AM) and Weekends

Now, assuming 52 weeks per year, the number of working hours for the morning and afternoon shifts during weekdays is estimated to be 2080 hours for one year of operation. Furthermore, the number of working hours during the night and weekend shifts is estimated to be 4576 hours per year. Travel times are calculated based on the average patrolling speed of 40 MPH for the morning and afternoon shifts during weekdays, while for the night and weekend shifts travel time is estimated based on the standard patrolling speed of 55 MPH.

The input for the model, including the travel time and the number of incidents for each link, during the weekday morning shift, weekday afternoon shift, and the night and weekend shifts are listed in Tables 15 through 17, respectively. Also, the sub-network to which each link belongs is listed.

Table 15 - Input: Weekday Morning

Link	Travel Time (min)	No. of Incidents	Sub-network	Link	Travel Time (min)	No. of Incidents	Sub-network
1	1.8	21	3	**31**	4.8	6	2
2	12.9	41	3	**32**	5.9	10	2
3	24.2	25	3	**33**	6.9	32	2
4	17.7	20	3	**34**	4.3	16	2
5	30.8	33	3	**35**	5.7	11	2
6	30.6	26	3	**36**	2.9	21	2
7	28.2	64	3	**37**	5.6	41	2
8	2.6	8	3	**38**	6.6	35	2
9	2.6	15	5	**39**	4.2	68	2
10	25.9	39	5	**40**	2.1	57	2
11	15.2	11	5	**41**	4.7	13	2
12	16.4	45	5	**42**	5.9	58	2
13	9.5	8	5	**43**	2.2	2	2
14	11	20	5	**44**	6.5	60	2
15	21.1	36	5	**45**	3.7	28	2
16	13.9	9	1	**46**	7.9	71	2
17	5.9	21	1	**47**	3	27	2
18	3.9	15	6	**48**	5	21	2
19	15.3	34	6	**49**	5.2	37	2
20	10.4	13	6	**50**	12	40	2
21	12.3	8	6	**51**	10.4	60	2
22	8.4	4	6	**52**	8.9	49	2
23	4	6	6	**53**	4.6	15	2
24	1.5	4	6	**54**	4.2	26	2
25	7.4	14	6	**55**	4.2	6	2
26	6	21	6	**56**	8.3	17	2
27	9	74	6	**57**	4	7	2
28	3.6	25	6	**58**	3.6	13	2
29	7.9	25	6	**59**	2.2	3	2
30	2.4	14	2	**60**	16.8	45	2

Link	Travel Time (min)	Number of Incidents	Sub-network
61	4.2	22	2
62	3.8	42	2
63	4.4	14	2
64	14	27	2
65	16.8	35	2
66	10.3	26	2
67	5.4	23	2
68	1.2	5	1
69	8	6	1
70	4.9	7	1
71	7.7	78	1
72	8.7	12	1
73	7.1	32	1
74	6.8	61	1
75	11.2	35	4
76	9.2	26	4
77	11	36	4
78	8.6	21	4
79	8	7	4
80	17.6	59	4
81	6	17	1
82	2.6	13	1
83	2.1	0	1
84	8.8	2	1
85	10.2	2	1
86	3.4	1	1
87	8.8	11	1
88	3.9	1	1
89	14.6	273	1
90	15.4	188	1
91	1.9	9	1
92	3.9	30	1
93	3.3	49	1
94	4.1	51	1
95	12.6	64	1
96	4.1	12	1
97	9	42	1
98	5	11	1
99	16.3	79	1
100	4.2	8	1
101	2.5	19	1
102	2.8	9	1
103	1.5	3	1
104	3.4	6	1
105	1.5	0	1
106	3.2	16	1
107	2.9	13	1
108	1.9	15	1
109	3.4	6	1
110	9.2	36	1
111	27.1	35	1
112	3.7	1	1
113	26.7	21	1
114	39	61	1
115	9	23	1
116	24.5	40	3
117	9	14	3
118	4.9	0	2
119	26.7	77	1

Table 16 - Input: Weekday Afternoon

Link	Travel Time (min)	No. of Incidents	Sub-network	Link	Travel Time (min)	No. of Incidents	Sub-network
1	1.8	23	3	**31**	4.8	23	2
2	12.9	31	3	**32**	5.9	38	2
3	24.2	33	3	**33**	6.9	37	2
4	17.7	50	3	**34**	4.3	21	2
5	30.8	63	3	**35**	5.7	22	2
6	30.6	47	3	**36**	2.9	51	2
7	28.2	88	3	**37**	5.6	48	2
8	2.6	5	3	**38**	6.6	56	2
9	2.6	18	5	**39**	4.2	37	2
10	25.9	62	5	**40**	2.1	22	2
11	15.2	20	5	**41**	4.7	53	2
12	16.4	43	5	**42**	5.9	3	2
13	9.5	9	5	**43**	2.2	90	2
14	11	27	5	**44**	6.5	37	2
15	21.1	52	5	**45**	3.7	79	2
16	13.9	8	1	**46**	7.9	50	2
17	5.9	19	1	**47**	3	25	2
18	3.9	19	6	**48**	5	55	2
19	15.3	45	6	**49**	5.2	62	2
20	10.4	6	6	**50**	12	61	2
21	12.3	13	6	**51**	10.4	42	2
22	8.4	11	6	**52**	8.9	6	2
23	4	7	6	**53**	4.6	11	2
24	1.5	1	6	**54**	4.2	11	2
25	7.4	15	6	**55**	4.2	16	2
26	6	35	6	**56**	8.3	8	2
27	9	53	6	**57**	4	21	2
28	3.6	24	6	**58**	3.6	18	2
29	7.9	37	6	**59**	2.2	42	2
30	2.4	21	2	**60**	16.8	23	2

Link	Travel Time (min)	Number of Incidents	Sub-network	Link	Travel Time (min)	Number of Incidents	Sub-network
61	4.2	18	2	**91**	1.9	2	1
62	3.8	47	2	**92**	3.9	21	1
63	4.4	9	2	**93**	3.3	34	1
64	14	30	2	**94**	4.1	82	1
65	16.8	55	2	**95**	12.6	94	1
66	10.3	12	2	**96**	4.1	13	1
67	5.4	28	2	**97**	9	51	1
68	1.2	2	1	**98**	5	24	1
69	8	4	1	**99**	16.3	101	1
70	4.9	1	1	**100**	4.2	11	1
71	7.7	75	1	**101**	2.5	48	1
72	8.7	15	1	**102**	2.8	12	1
73	7.1	38	1	**103**	1.5	11	1
74	6.8	95	1	**104**	3.4	23	1
75	11.2	38	4	**105**	1.5	3	1
76	9.2	49	4	**106**	3.2	23	1
77	11	37	4	**107**	2.9	13	1
78	8.6	16	4	**108**	1.9	14	1
79	8	12	4	**109**	3.4	11	1
80	17.6	56	4	**110**	9.2	68	1
81	6	28	1	**111**	27.1	41	1
82	2.6	12	1	**112**	3.7	1	1
83	2.1	1	1	**113**	26.7	13	1
84	8.8	6	1	**114**	39	63	1
85	10.2	3	1	**115**	9	12	1
86	3.4	3	1	**116**	24.5	50	3
87	8.8	12	1	**117**	9	24	3
88	3.9	5	1	**118**	4.9	2	2
89	14.6	337	1	**119**	26.7	110	1
90	15.4	149	1				

Table 17 – Input: Night and Weekend

Link	Travel Time (min)	No. of Incidents	Sub-network	Link	Travel Time (min)	No. of Incidents	Sub-network
1	1.3	17	3	**31**	3.5	3	2
2	9.4	49	3	**32**	4.3	10	2
3	17.6	5	3	**33**	5.0	19	2
4	12.8	5	3	**34**	3.1	26	2
5	22.4	40	3	**35**	4.1	9	2
6	22.2	56	3	**36**	2.1	21	2
7	20.5	122	3	**37**	4.0	72	2
8	1.9	11	3	**38**	4.8	61	2
9	1.9	13	5	**39**	3.1	74	2
10	18.9	80	5	**40**	1.5	55	2
11	11.0	39	5	**41**	3.4	18	2
12	11.9	50	5	**42**	4.3	65	2
13	6.9	9	5	**43**	1.6	3	2
14	8.0	23	5	**44**	4.8	81	2
15	15.4	45	5	**45**	2.7	30	2
16	10.1	18	1	**46**	5.7	73	2
17	4.3	19	1	**47**	2.1	29	2
18	2.8	23	6	**48**	3.7	26	2
19	11.1	74	6	**49**	3.8	65	2
20	7.6	27	6	**50**	8.7	61	2
21	8.9	22	6	**51**	7.6	77	2
22	6.1	8	6	**52**	6.5	35	2
23	2.9	11	6	**53**	3.4	10	2
24	1.1	0	6	**54**	3.0	22	2
25	5.4	14	6	**55**	3.1	8	2
26	4.4	19	6	**56**	6.0	21	2
27	6.6	40	6	**57**	2.9	10	2
28	2.6	11	6	**58**	2.6	9	2
29	5.7	10	6	**59**	1.6	9	2
30	1.8	14	2	**60**	12.2	39	2

Link	Travel Time (min)	Number of Incidents	Sub-network	Link	Travel Time (min)	Number of Incidents	Sub-network
61	3.1	17	2	**91**	1.4	6	1
62	2.7	17	2	**92**	2.8	17	1
63	3.2	11	2	**93**	2.4	26	1
64	10.2	33	2	**94**	3.0	33	1
65	12.2	37	2	**95**	9.2	104	1
66	7.5	14	2	**96**	3.0	34	1
67	3.9	28	2	**97**	6.5	59	1
68	0.9	2	1	**98**	3.6	20	1
69	5.8	4	1	**99**	11.9	110	1
70	3.5	2	1	**100**	3.1	11	1
71	5.6	70	1	**101**	1.8	33	1
72	6.3	12	1	**102**	2.0	9	1
73	5.2	29	1	**103**	1.1	7	1
74	5.0	82	1	**104**	2.5	18	1
75	8.2	60	4	**105**	1.1	1	1
76	6.7	46	4	**106**	2.3	25	1
77	8.0	29	4	**107**	2.1	18	1
78	6.3	7	4	**108**	1.4	21	1
79	5.9	8	4	**109**	2.5	9	1
80	12.8	56	4	**110**	6.7	42	1
81	4.3	17	1	**111**	19.7	47	1
82	1.9	14	1	**112**	2.7	0	1
83	1.5	0	1	**113**	19.4	27	1
84	6.4	3	1	**114**	28.4	50	1
85	7.4	0	1	**115**	6.5	29	1
86	2.4	2	1	**116**	17.8	4	3
87	6.4	1	1	**117**	6.6	2	3
88	2.8	3	1	**118**	3.6	3	2
89	10.6	112	1	**119**	19.4	68	1
90	11.2	86	1				

Incident Duration Reduction Savings

As presented before, to monetize the savings that result from incident duration reduction, the parameter α for the numerical example was estimated assuming the value of time of 15 dollars per hour based on different scenarios of average response time reduction. Now, to re-calculate the parameter for the CHART network, we need to determine the value of time and estimate the average response time reduction caused by the CHART patrol program.

As for the value of time, there are different values recommended from different sources. Department of Transportation (DOT) has provided recommended values of travel time (VOTT) for 2009 [45] and 2012 [46] based on two types of intercity and local trips for surface modes. The values for the intercity trip are listed in Table 18, and the values for the local trip are listed in Table 19. According, to these recommended values for 2009 and 2012, values of travel times for 2015 are extrapolated and added up to the tables, too.

Table 18 - Recommended Hourly Values of Travel Time Savings for Intercity Trips

Category	**2009**	**2012**	**2015**
Personal	\$16.7	\$17.2	\$17.7
All Purposes	\$18.0	\$18.7	\$19.4

Table 19 - Recommended Hourly Values of Travel Time Savings for Local Trips

Category	**2009**	**2012**	**2015**
Personal	$12	$12.3	$12.6
All Purposes	$12.5	$12.8	$13.1

According to the US DOT report, the value of travel time for “All Purpose” category is estimated based on the weighted averages, using distributions of travel by trip purpose in various modes. The distribution for the intercity travel by conventional surface modes is reported to be 78.6% personal and 21.4% business. Also, the distribution for the local travel by surface modes is reported to be 95.4% personal and 4.6% business [46].

Another study [47] by Center for Advanced Transportation Technology (CATT), at the University of Maryland, recommends a more specific value of travel time for Maryland freeway users by particularly analyzing major high-volume freeways in Maryland around areas of Baltimore and National Capital. This study exclusively investigates on sections of I-95, I-495, I-270, MD 295, and US 29 corridors in Maryland, as shown in Figure 21. They recommend a value of time of 29.82 dollars per hour for passengers while values of 45.4 and 20.21 dollars per hours are suggested for cargo and truck drivers, respectively.

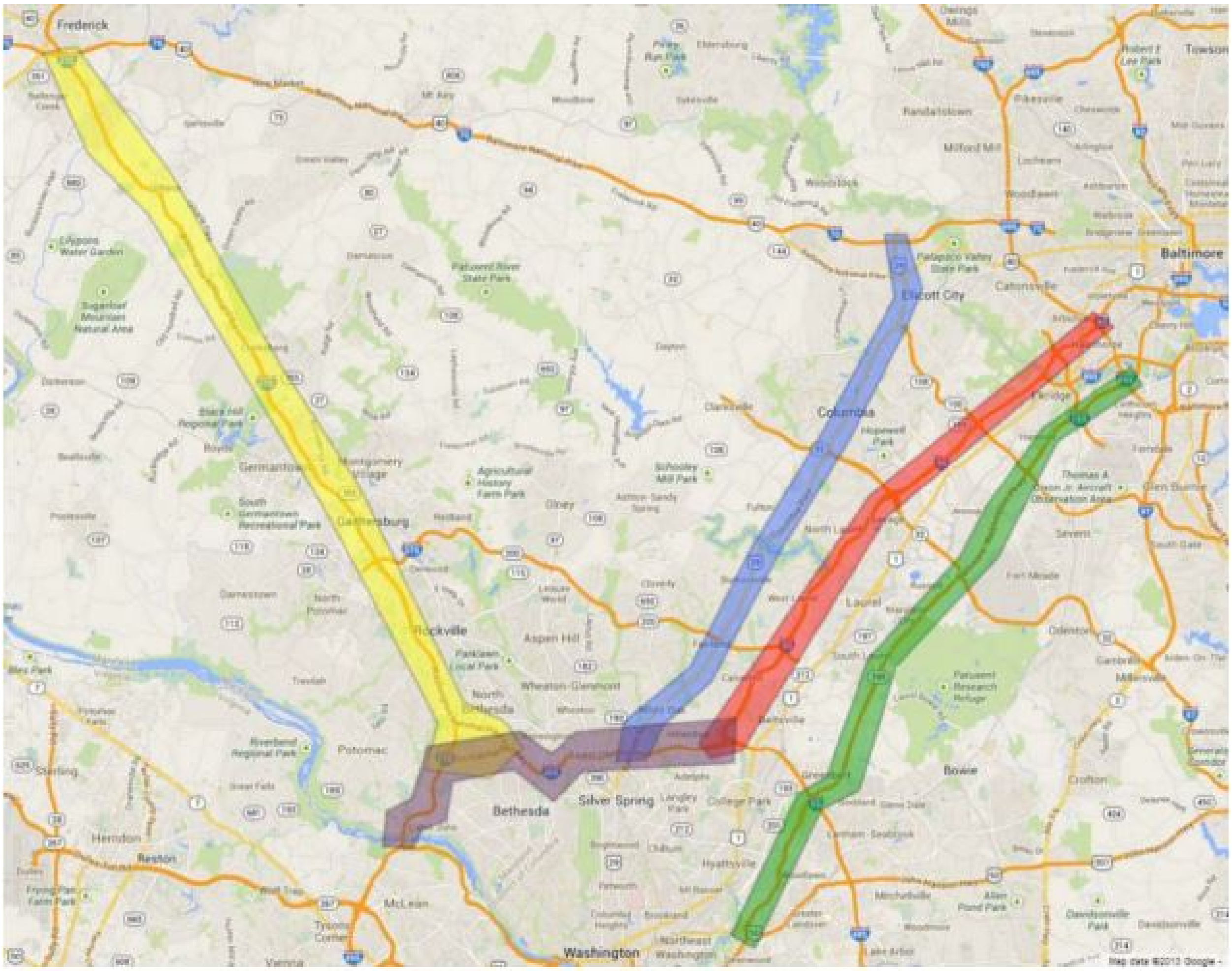


Figure 21 - Corridors Analyzed [47]

As it appears, different values are recommended depending on the trip purpose, trip mode, type of vehicle, type of trip, and other relevant factors. However, as provided by CHART officials, the average value of time used in this study is 20 dollars per hour for the subject network.

Now, we need to estimate the average response time reduction caused by the CHART patrol program. For this purpose, we may refer to the existing results reported by the CHART evaluation studies. According to the CHART evaluation reports [48-50], the average incident duration with CHART response is about 10 minutes less compared to incidents without an assist from CHART. Therefore, we may assume that the average response time is reduced about 5 minutes to less than 10 minutes by the CHART patrol program. Therefore, similar to the calculation for the numerical example, the parameter is estimated based on possible scenarios of response time reduction and results are listed in Table 20. Based on this, parameter α is estimated to be about 15 for the subject network.

Table 20 - Parameter α Estimated for the CHART Network

Scenario	RTR (min)	VEH-HR Saving	VEH-HR Saving Per one min RTR	VEH-HR Saving Per Incident Per 1 min RTR	Avg. Cost Saving Per 1 min RTR (α)
1	5	2558	512	0.738	14.76
2	10	5429	543	0.783	15.66
Value of Time = 20 & Number of Incidents = 693					

Results

For the subject network here, the combination of network decomposition and neighbor search algorithms presented in the preceding section is applied to solve the problem. Therefore, first, based on the network decomposition algorithm, the model is solved for three individual sub-networks (dense parts), and given these results, the problem is solved to determine a decent solution for the full network. Afterward, this result is improved through the neighbor search algorithm which means for each beat, all of its neighbor links are examined individually to explore if adding them to the subject beat and removing them from their current beat may introduce a better solution. This process continues until no better solution is found.

The problem is solved for three cases and beat configuration for the weekday morning, weekday afternoon, and night and weekend shifts are displayed in Figure 22 through Figure 24, respectively. Also, the result of the fleet size and fleet allocations for each case are listed in Tables 21 through 23. According to the results, 15 patrol trucks are needed to patrol on 13 designed beats for the weekday morning shift. Two beats are assigned double trucks while the other beats are assigned one truck each. The beat configuration for the weekday afternoon shift has 13 beats, similar to the weekday morning shift, but requires 17 patrol trucks. For the weekday afternoon shift, four beats are assigned double trucks, and the other beats are assigned one truck each. As anticipated, the night and weekend shifts require less number of patrol trucks compared to the weekday morning and afternoon shifts. Eight patrol trucks need to patrol on ten designed beats for the night and weekend shifts. For these shifts, two beats are assigned double trucks, and six beats are assigned single truck.

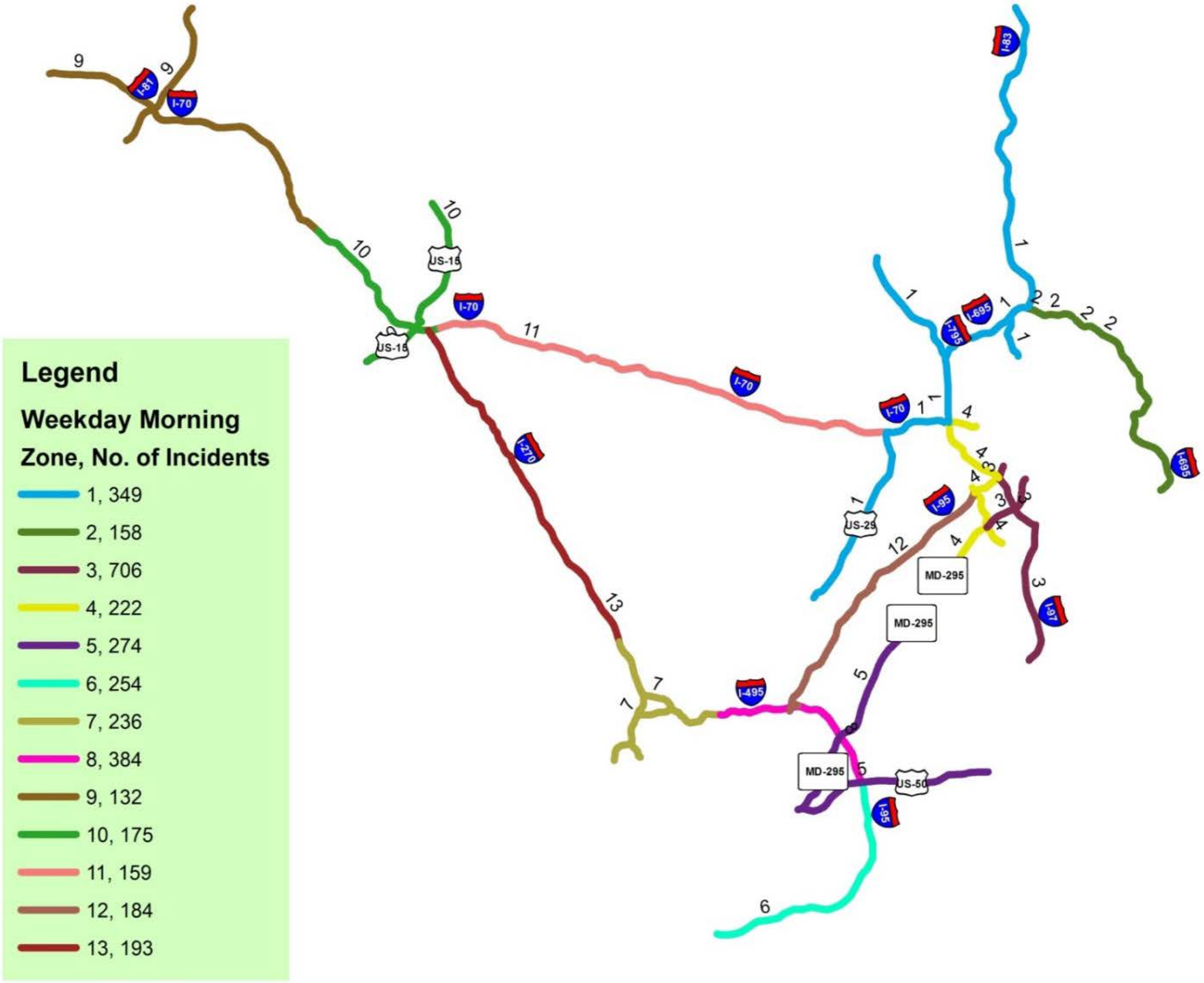


Figure 22 – Beat Configuration for the Weekday Morning Shift

Table 21 – Fleet Size and Allocation for the Weekday Morning Shift

Beat	Number of Trucks
1	2
2	1
3	2
4	1
5	1
6	1
7	1
8	1
9	1
10	1
11	1
12	1
13	1
Fleet Size	**15**

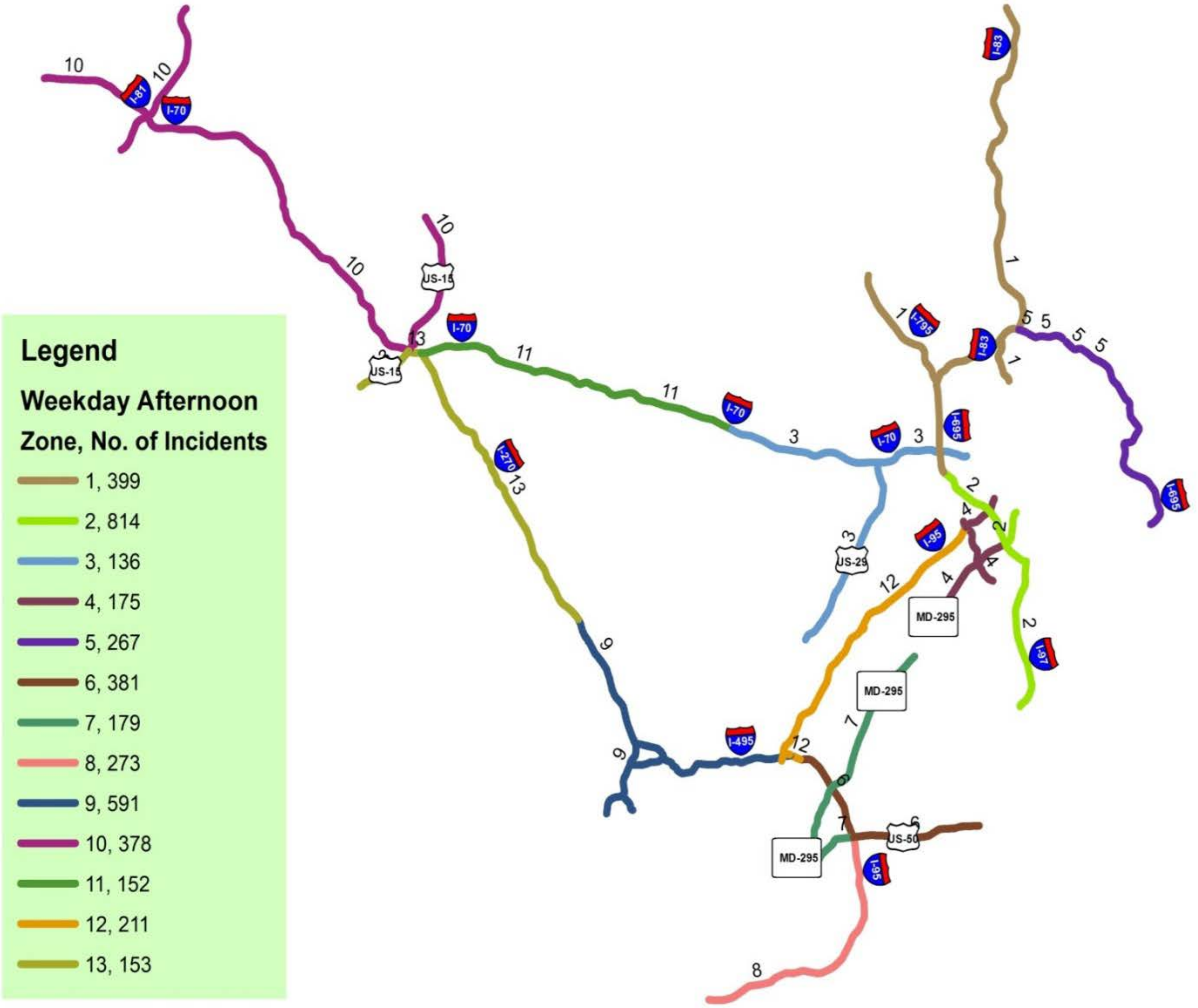


Figure 23 - Beat Configuration for the Weekday Afternoon Shift

Table 22 – Fleet Size and Allocation for the Weekday Afternoon Shift

Beat	Number of Trucks
1	2
2	2
3	1
4	1
5	1
6	1
7	1
8	1
9	1
10	2
11	2
12	1
13	1
Fleet Size	**17**

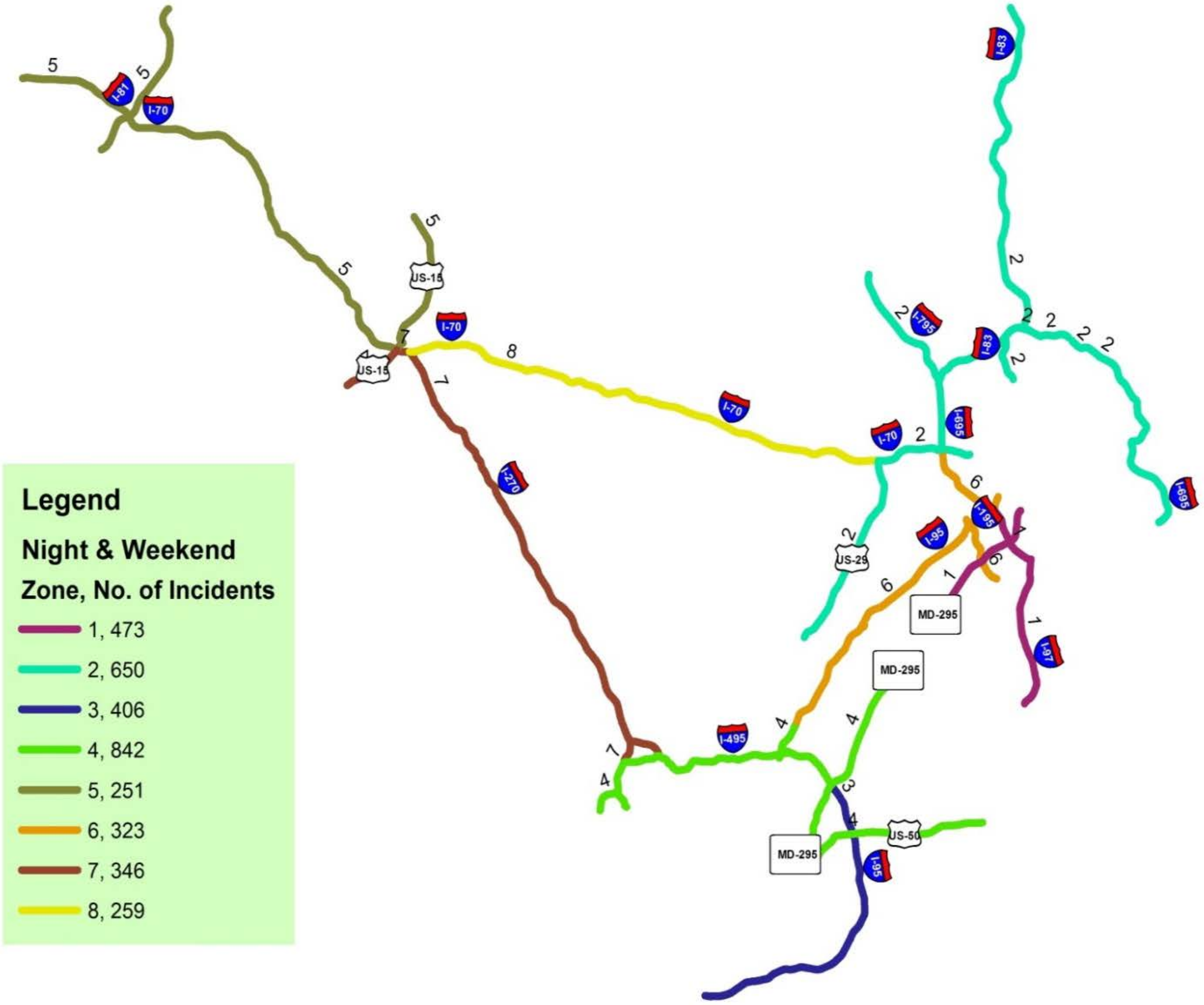


Figure 24 – Beat Configuration for the Night and Weekend Shift

Table 23 – Fleet Size and Allocation for the Night and Weekend Shift

Beat	**Number of Trucks**
1	1
2	2
3	1
4	2
5	1
6	1
7	1
8	1
Fleet Size	**10**

Major characteristics and performance measures of the designed program are summarized in Table 24. The result of each shift and total results are all provided. According to the outcomes, the total operating cost is estimated to be $5,616,000 for one year of full-time operation. Also, the total patrolling response time, including the detection and verification times, for the designed network is estimated to be 5898 hours for responding to 11,805 incidents during one year of operation. Therefore, the average patrolling response time is estimated to be less than 32 minutes. Please note that this time includes detection and verification time, as well. As a result, on average, incidents are responded in about half an hour from the time they actually occur on the network.

As presented, the optimal beat configuration, fleet size, and fleet allocation could significantly change based on the time of the day. This happens as incident densities and possibly travel times are different during the day. Therefore, to optimize the performance of the program, while the operating cost is minimized, it is beneficial to design different configurations for each part of the day. The same reasoning applies to justify designing separate networks for weekdays and weekends. Furthermore, since incidents density and traffic volume may vary during the year, a seasonal or monthly based design could generate a more specific solution for each part of the year.

Once again, results confirm the importance of determining the fleet size and number of beats instead of simply assuming predetermined numbers. Furthermore, it is determined that efficiency of the patrol program is significantly dependent on the beat configuration and fleet allocation. Finally, for the optimal performance of the program, it is necessary to design the network with all major issues taken into account in a combined model, which considers all relevant factors together, instead of dealing with each issue separately.

Table 24 - Performance Measures

Description	Weekday Morning	Weekday Afternoon	Night and Weekend	Total
Shift Duration (hours per year)	2080	2080	4576	8736
Average Patrolling Response Time [including detection and verification	31.7	28.1	36.4	31.9
Number of Incidents	3426	4109	3550	11085
Total Patrolling Response Time [including detection and verification times] (hours)	1810	1929	2159	5898
Operation Cost ($1000)	1,560	1,768	2,288	5,616
Objective Value ($1000)	3,189	3,505	4,231	10,925

Sensitivity Analysis

To design the network for patrol programs, first, we need to determine the input and possibly make some assumptions about the program. However, sometimes we are not sure about the exact value of some of the inputs because of the varying nature of the input or simply because the data is not available. Therefore, in this section, sensitivity analysis is performed to determine the impact of these varying parameters on the beat configuration, fleet size, and fleet allocation. In the following sections, a few influential parameters are investigated, and their impact on the optimal design is determined.

Value of Time Parameter

For the main results, we used the value of time of $20 per hour. However, different values of time are recommended by different sources. These values are different depending on the trip purpose, trip mode, type of vehicle, type of trip, and other relevant factors. As mentioned, one study [47] by Center for Advanced Transportation Technology (CATT), at the University of Maryland, recommends a more specific value of travel time for Maryland freeway users by particularly analyzing major high-volume freeways in Maryland. The recommended value of time by CATT is about $30 per hour for traveling on some of the major freeways in Maryland. Therefore, below a few additional scenarios are solved assuming the value of time of $30 per hour. The beat configuration for the weekday morning and weekday afternoon shifts, based on the value of time of 30 dollars per hour, are shown in Figure 25 and Figure 26, respectively. Also, fleet size and fleet allocation results, based on the value of time of 30 dollars per hour, for the weekday morning and weekday afternoon shifts are listed in Table 25 and Table 26, respectively.

Results indicate that increasing the value of time from $20 per hour to $30 per hour causes the fleet size to increase. Fleet size for the weekday morning shift increases from 15 to 18 patrol units and for the weekday afternoon increases from 17 to 22 patrol units. This is reasonable because the higher value of time requires reduced incident duration and as a result, additional patrol units are needed.

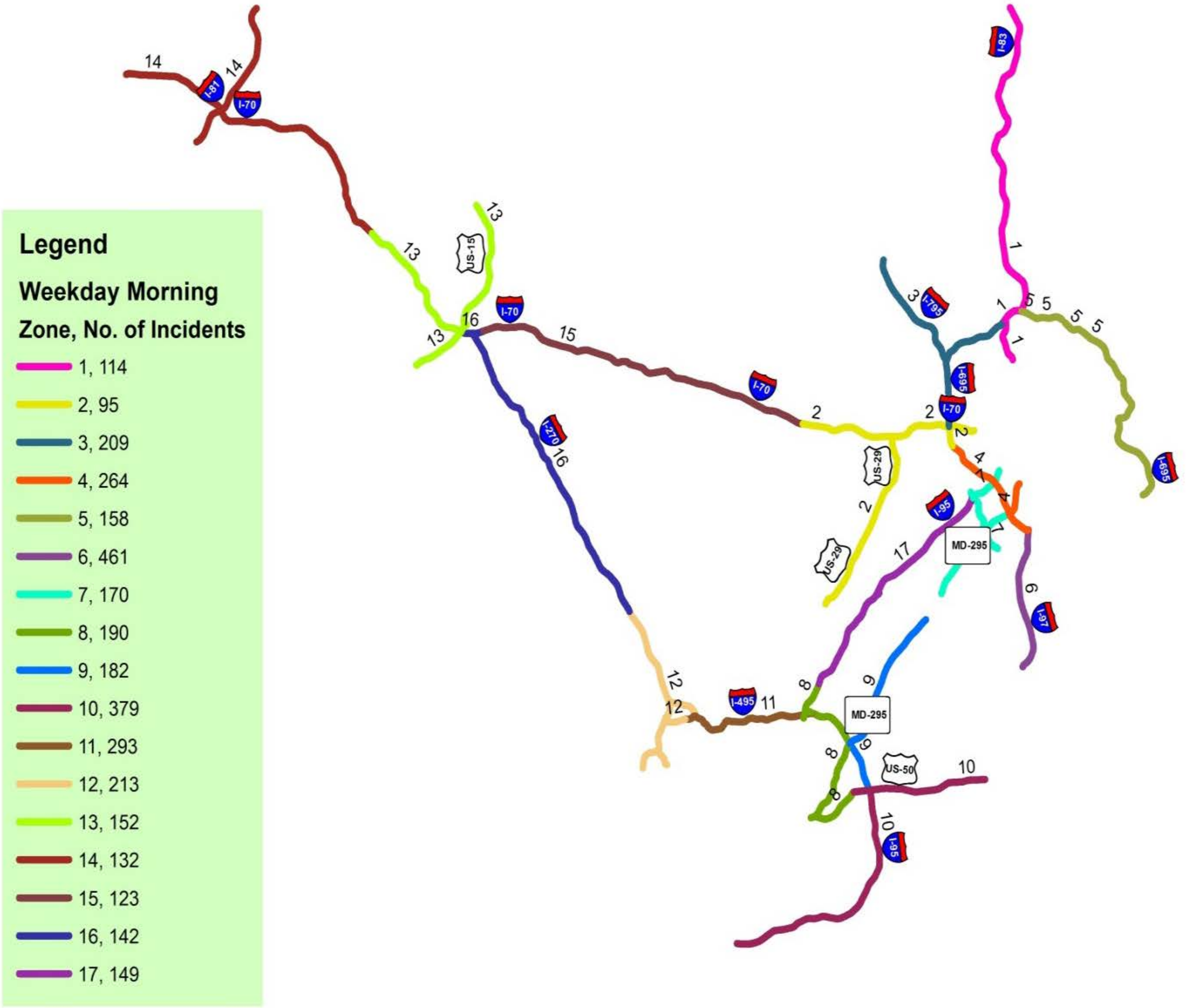


Figure 25 - Beat Configuration for the Weekday Morning Shift - VOT=30$/hr

Table 25 – Fleet Size and Allocation for the Weekday Morning Shift - VOT=30$/hr

Beat	Number of Trucks
1	1
2	1
3	1
4	1
5	1
6	1
7	1
8	1
9	1
10	2
11	1
12	1
13	1
14	1
15	1
16	1
17	1
Fleet Size	**18**

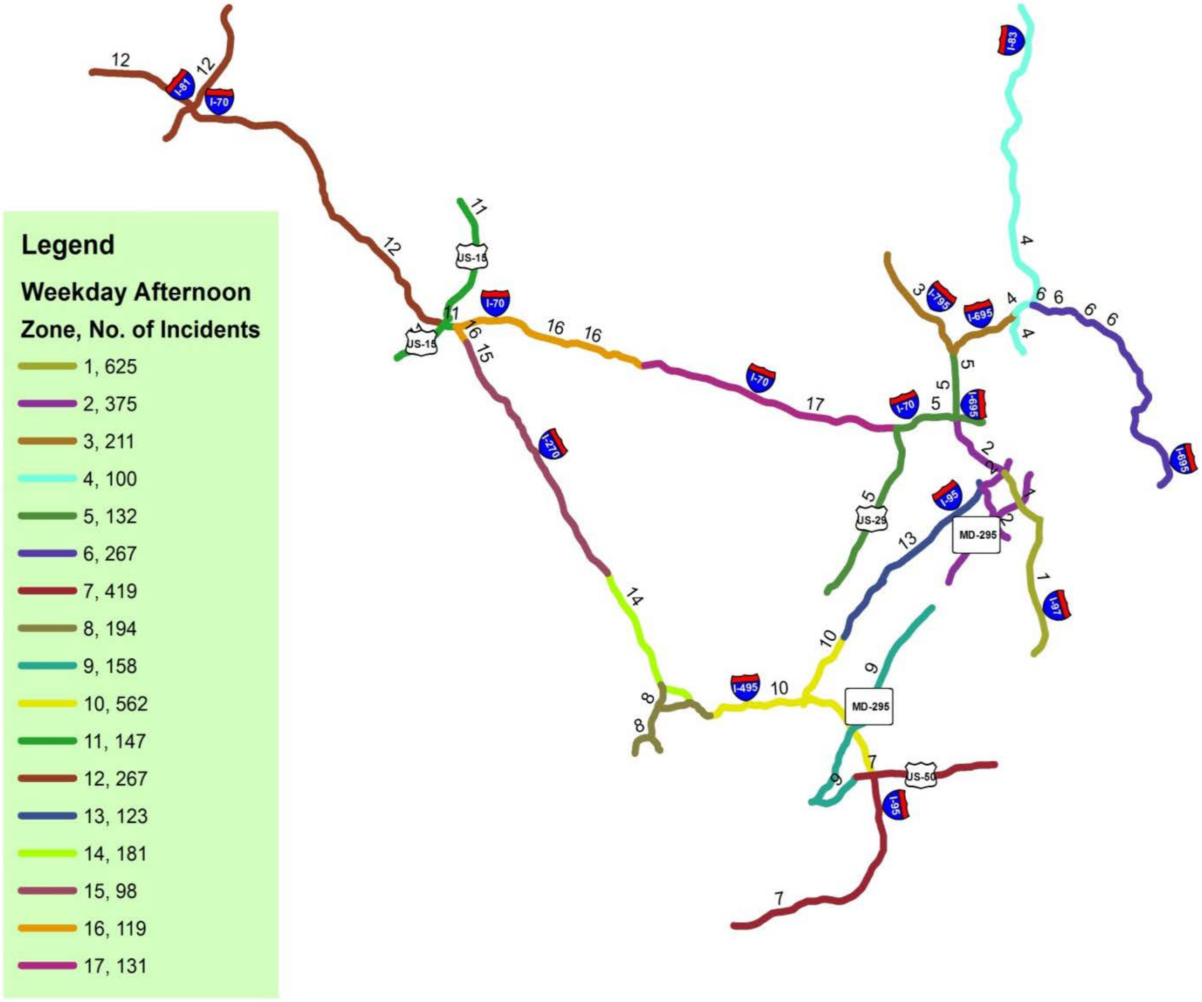


Figure 26 - Beat Configuration for the Weekday Afternoon Shift - VOT=30$/hr

Table 26 - Fleet Size and Allocation for the Weekday Afternoon Shift - VOT=30$/hr

Beat	**Number of Trucks**
1	2
2	2
3	1
4	1
5	1
6	1
7	2
8	1
9	1
10	2
11	1
12	2
13	1
14	1
15	1
16	1
17	1
Fleet Size	**22**

Maximum Number of Trucks per Beat

In the main analysis, the maximum number of patrol units per beat is assumed to be two. In general, assigning a large number of patrol units to one beat may not be practical as keeping a relatively constant headway between all trucks may not be easy (please note that constant headway between trucks is assumed to calculate the average response time). However, in this section, two different scenarios of maximum possible number of patrol units per beat are assumed to determine the network design. Here, two additional scenarios of one truck per beat and three trucks per beat are considered.

The beat configuration for the weekday morning and weekday afternoon shifts, based on one truck per beat, are presented in Figure 27 and Figure 28, respectively. Also, the beat configuration for the weekday afternoon shift based on the maximum number of three trucks per beat is shown in Figure 29. Furthermore, fleet size and fleet allocation result for the weekday afternoon shift, based on the maximum number of three trucks per beat, is provided in Table 27. The beat configuration, fleet size, and fleet allocation, based on the maximum number of three trucks per beat, did not change for the weekday morning shift compared to the main results. Objective values for three different scenarios of the maximum number of trucks per beat are presented in Table 28. Obviously, increasing the maximum number of trucks per beat allows the model to choose a higher fleet size for a specific beat if it produces a better solution. However, as observed in Table 28, although there is a considerable improvement, the difference in objective values is not significantly high. This happens as the model can create extra beats with a smaller number of units per each beat instead of one large beat with more number of patrol units. However, the breakdown of the network to links that are sufficiently small is needed.

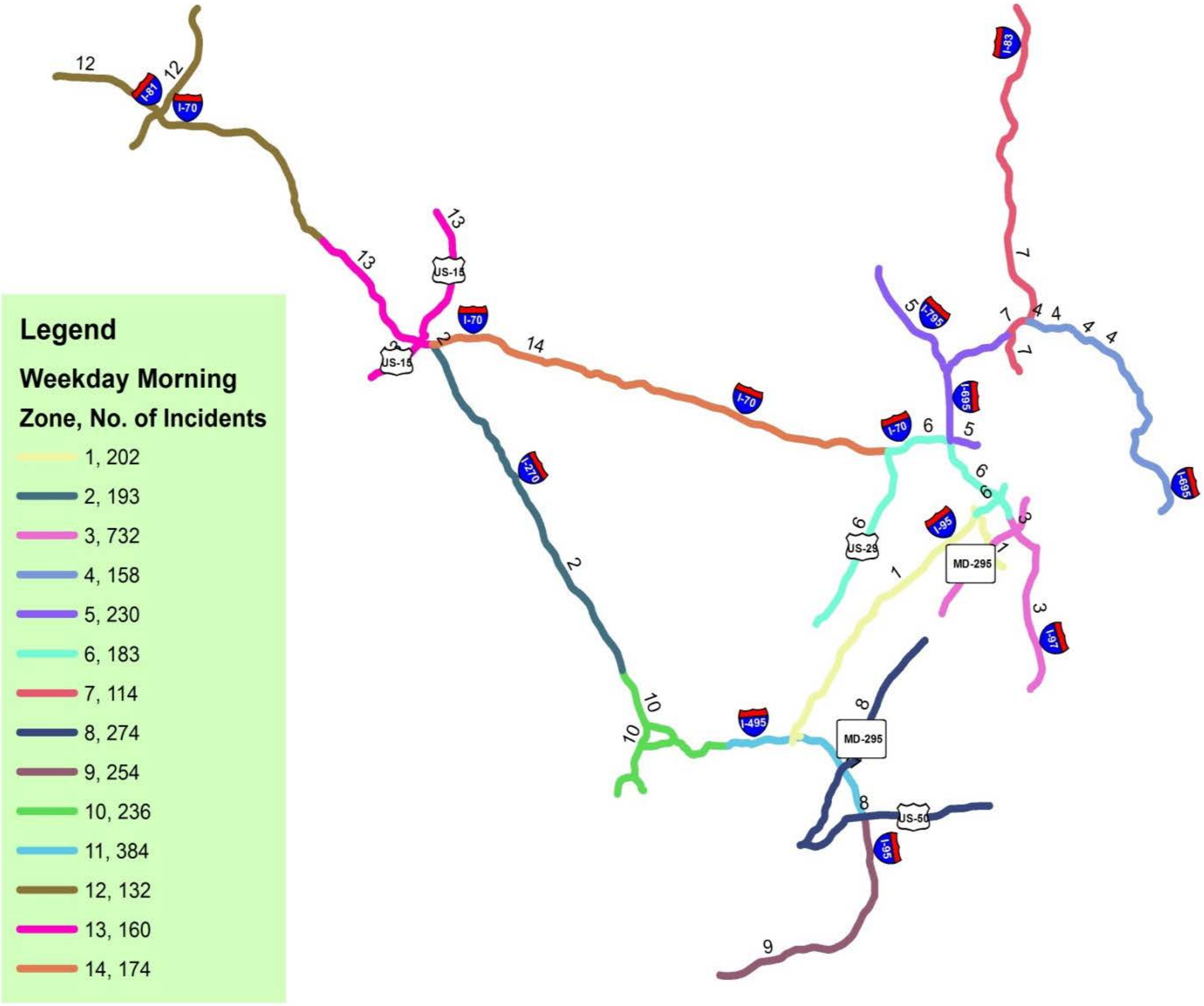


Figure 27 - Beat Configuration for the Weekday Morning Shift – One Truck per Beat

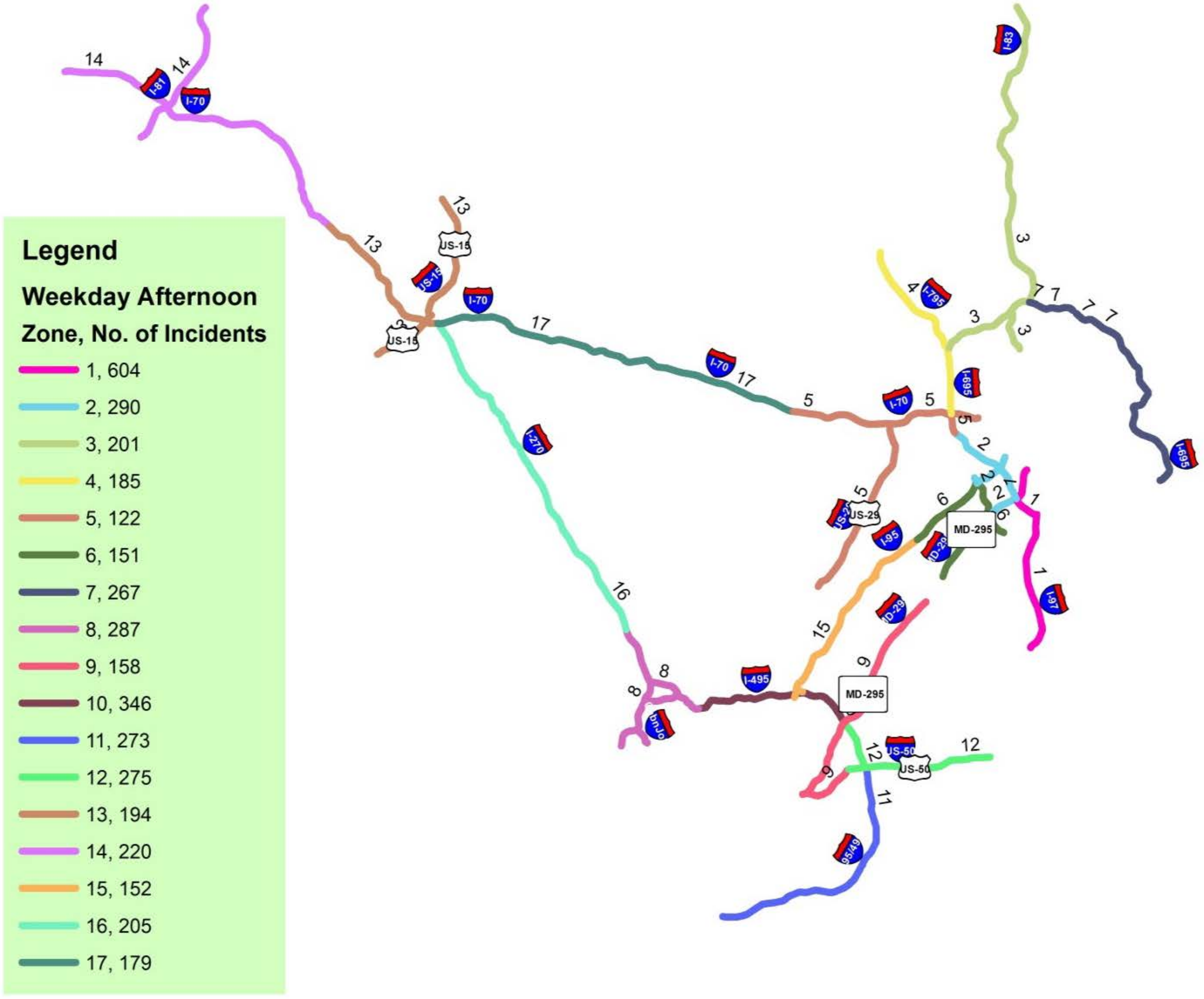


Figure 28 - Beat Configuration for the Weekday Afternoon Shift – One Truck per Beat

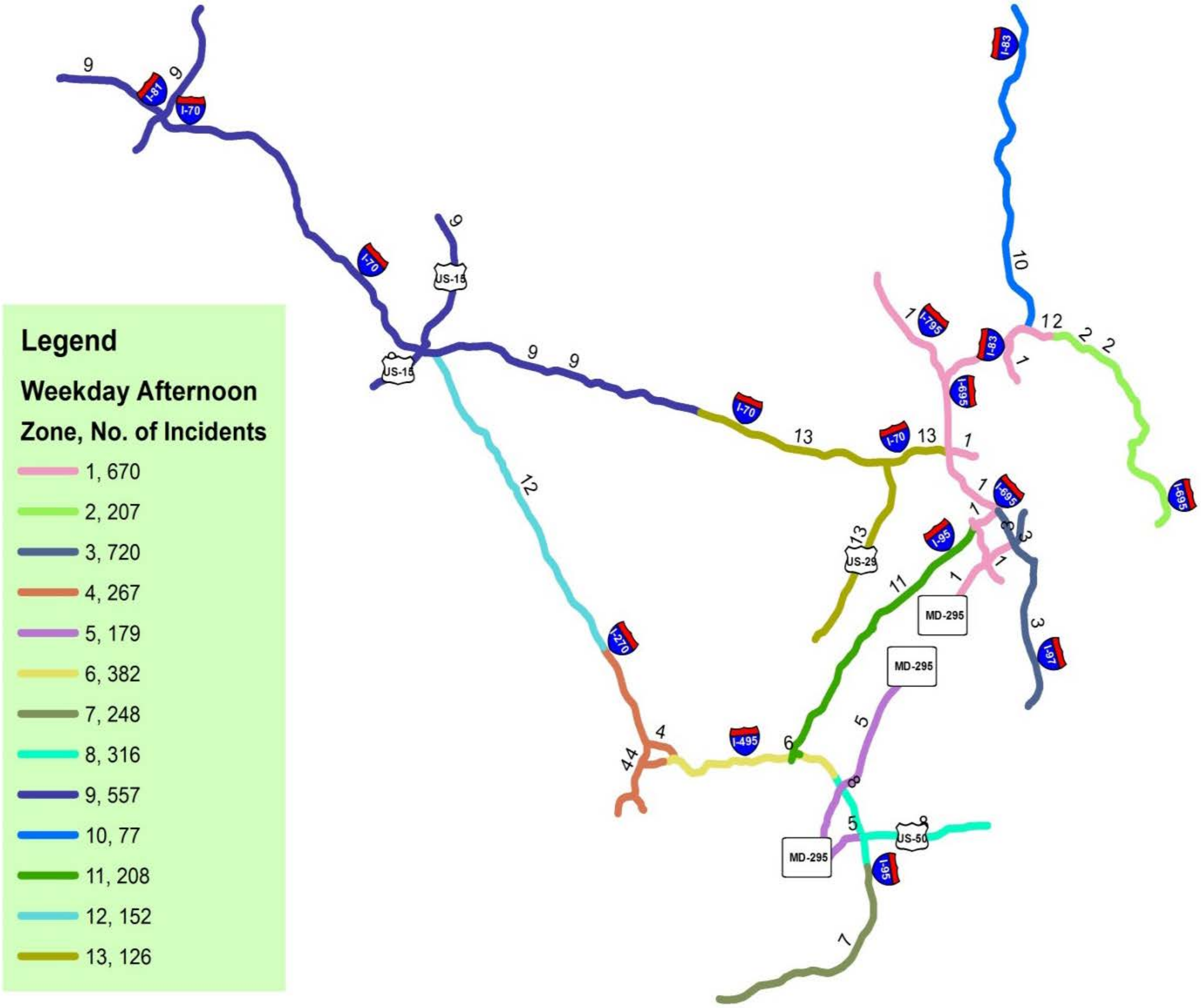


Figure 29 - Beat Configuration for the Weekday Afternoon Shift – Maximum Three Trucks per Beat

Table 27 - Fleet Size and Allocation for the Weekday Afternoon Shift – Maximum Three Trucks per Beat

Beat	Number of Trucks
1	3
2	1
3	2
4	1
5	1
6	1
7	1
8	1
9	3
10	1
11	1
12	1
13	1
Fleet Size	**18**

Table 28 - Maximum Number of Trucks per Beat

	Weekday Morning	Weekday Afternoon
Max. 1 truck/beat - Objective Value	3282	3547
Max. 2 truck/beat - Objective Value	3189	3505
Max. 3 truck/beat - Objective Value	3189	3500

Standard Patrolling Speed

One of the most influential parameters in designing the network for freeway service patrol programs is the standard patrolling speed of patrol units. Therefore, one additional scenario of the standard patrolling speed of 55 MPH is considered for the weekday morning and weekday afternoon shifts. The beat configuration for the weekday morning and weekday afternoon shifts, based on 55 MPH standard patrolling speed, are shown in Figure 30 and Figure 31, respectively. Also, the fleet size and fleet allocation for the weekday morning and weekday afternoon shifts are listed in Table 29 and Table 30, respectively.

According to the result, for weekday morning shift, increasing the standard patrolling speed from 40 MPH to 55 MPH reduces the number of required patrol units from 15 to 14. Similarly, for the weekday afternoon shift, increasing the standard patrolling speed from 40 MPH to 55 MPH causes the fleet size to decrease from 17 to 15 patrol units. Therefore, smaller fleet size is required if emergency response units can patrol faster on their assigned beats.

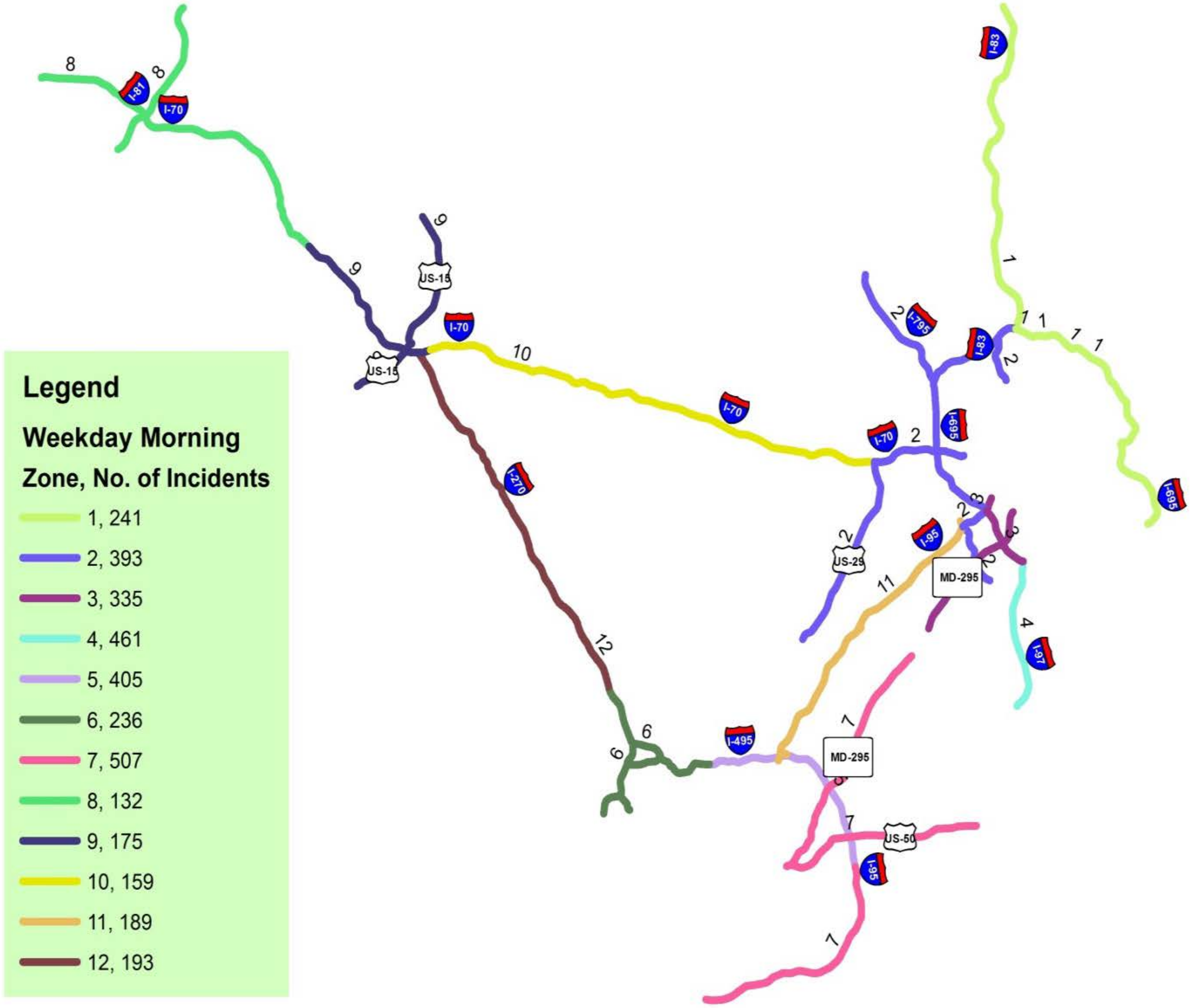


Figure 30 - Beat Configuration for the Weekday Morning Shift - 55 MPH

Table 29 - Beat Configuration for the Weekday Morning Shift - 55 MPH

Beat	**Number of Trucks**
1	1
2	2
3	2
4	1
5	1
6	1
7	2
8	1
9	1
10	1
11	1
12	1
Fleet Size	**14**

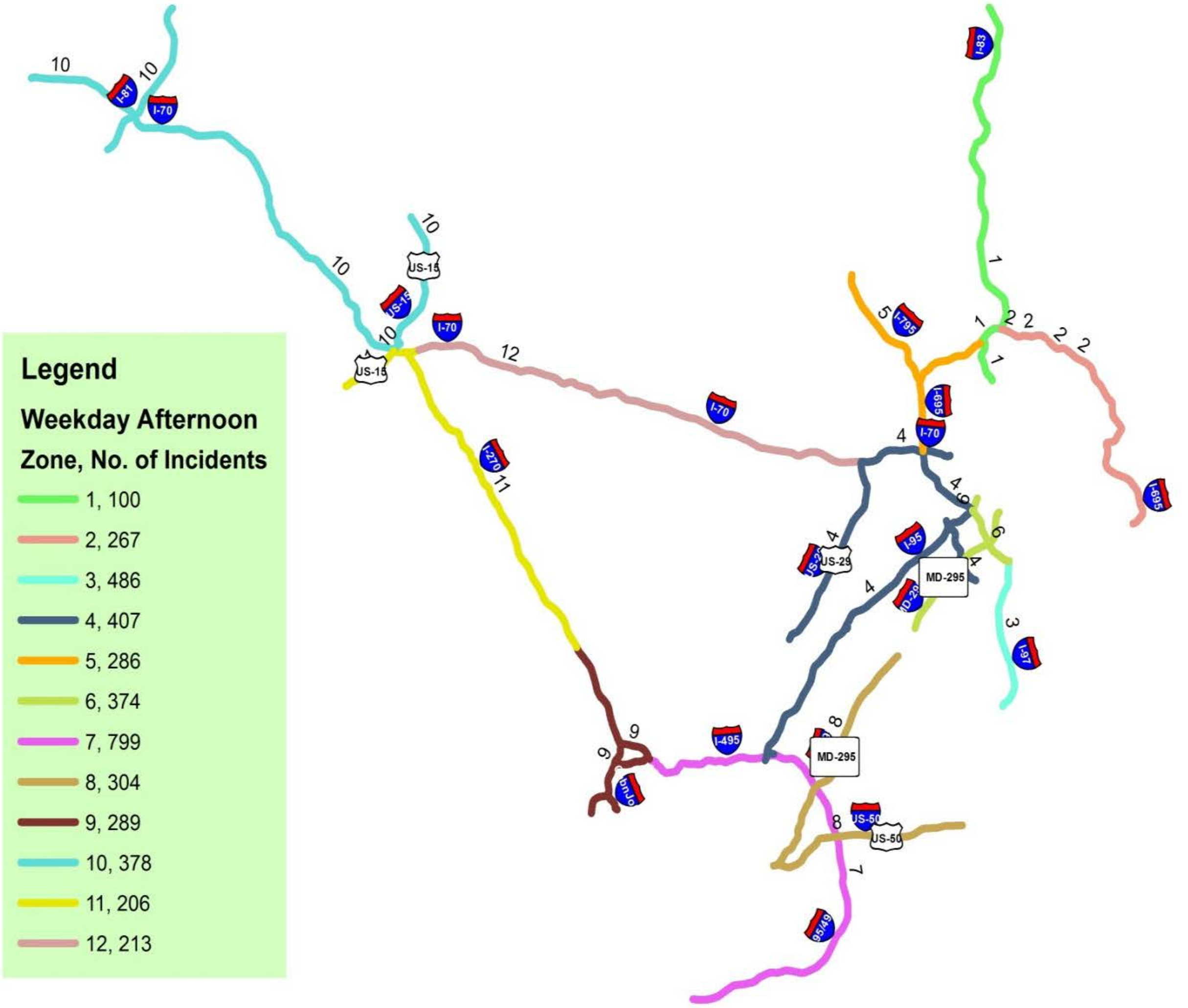


Figure 31 - Beat Configuration for the Weekday Afternoon Shift - 55 MPH

Table 30 - Beat Configuration for the Weekday Afternoon Shift - 55 MPH

Beat	**Number of Trucks**
1	1
2	1
3	1
4	2
5	1
6	1
7	2
8	1
9	1
10	2
11	1
12	1
Fleet Size	**15**

Non-Patrolling Detection: Result

As already discussed, based on the historic log data, the number of incidents that are both detected and responded by CHART (not necessarily CHART patrol units) in the network is estimated to be more than 11,000 incidents during the year of 2015. We assumed that CHART patrol units detected all of these incidents. However, in addition to the above dataset, we are provided with a larger set of incident data, too. This larger dataset includes all incidents that CHART units responded to but did not necessarily detect. According to this dataset, there are more than 30,000 incidents, during the year of 2015, which occurred on CHART patrol coverage routes or in the vicinity of 10 miles from patrol routes. For this larger incident dataset, since a significant majority of the incidents are not detected by CHART and also details on incident detection by CHART patrol units is not available, we assume incidents are detected by other sources rather than patrol units and, as a result, non-patrolling detection response time method is applied. Also, for this dataset, as advised by CHART officials, we assume that only one response unit is assigned to each beat. Other assumptions are similar to the assumptions made for the previous dataset.

Based on the non-patrolling detection dataset, again, the problem is solved for three cases and beat configurations for the weekday morning, weekday afternoon, and night and weekend shifts are presented in Figure 32 through Figure 34, respectively. Also, for each shift, the details regarding links covered by each beat are presented in Tables 31 through 33. Please see Appendix B for the exact location of the links. According to the results, 17 patrol units are needed to patrol during the weekday morning shift, and 19 units are needed to patrol during the weekend afternoon shift. As expected, the night and weekend shift require less number of patrol units, compared to the weekday morning and weekday afternoon shifts, because of lower incident frequencies. Eleven patrol units are needed to patrol during the night and weekend shift. Please note that, for each shift, the number of incidents per each beat is provided in Tables 31 through 33. Details regarding the number of incidents per each link, during each shift, are also presented in Appendix C. This information could be useful to determine where to assign additional units during each shift.

Major characteristics and performance measures of the designed program are summarized in Table 34. The result for each shift including fleet size, shift duration and number of incidents during one year, average response time, total response time, and operations costs are provided in Table 34. According to the result, the total operating cost is estimated to be $6,261,000 for one year of full-time operation. Also, the total response time for the designed network is estimated to be about 6930 hours for responding to 30,162 incidents during one year of operation. The average response time for each shift is estimated and presented in the table. Please note the average and total response times are based on the assumed average response speeds (40 MPH for the weekday morning and weekday afternoon shifts, and 55 MPH for the night and weekend shifts) and obviously will decrease if patrol units can drive faster.

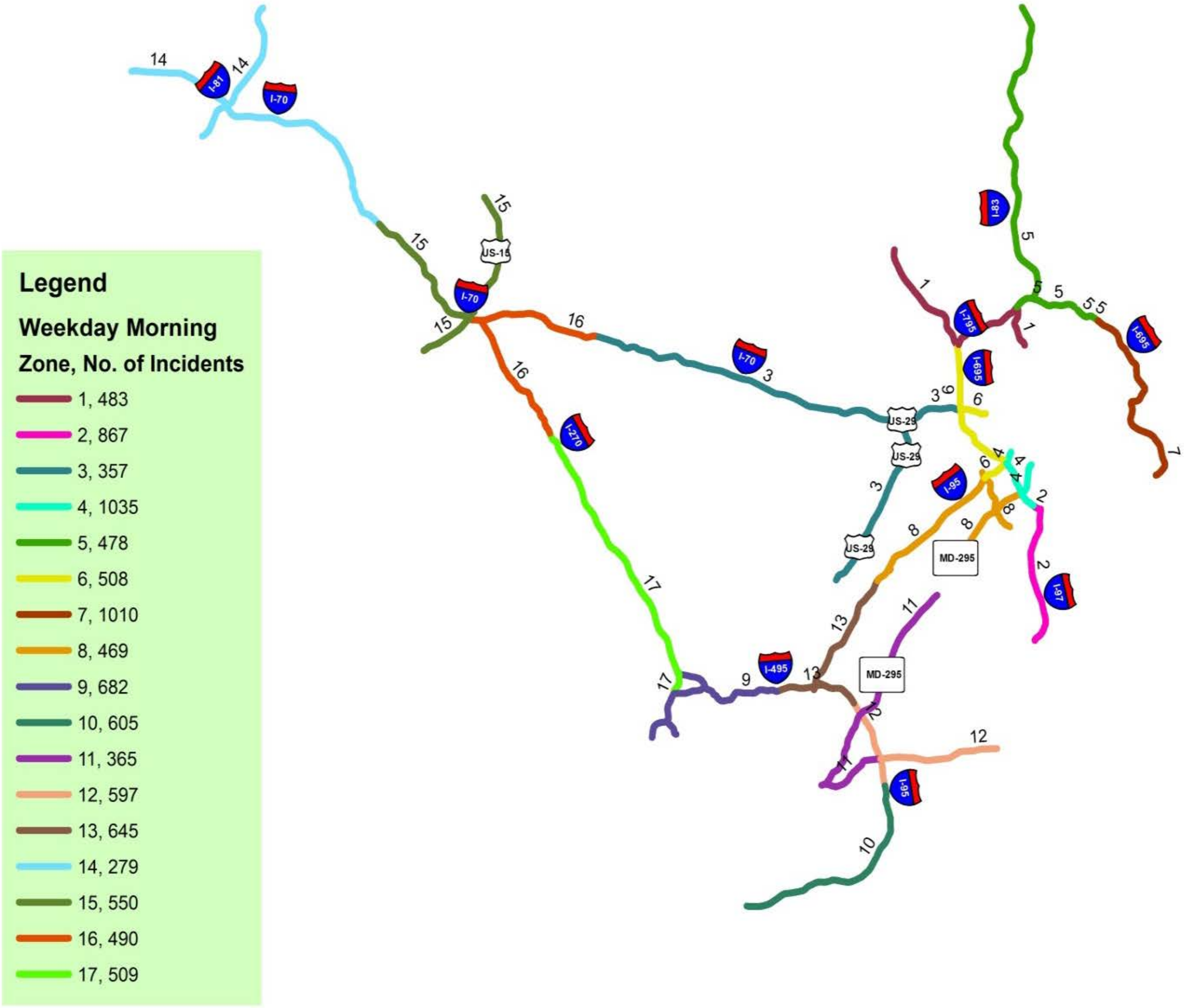


Figure 32 - Non-Patrolling Detection: Beat Configuration for the Weekday Morning Shift

Table 31 - Non-Patrolling Detection: Beat Configuration for the Weekday Morning Shift

Beat	Covered Links	Number of Incidents
1	99, 115, 119	483
2	89, 90, 91	867
3	11, 12, 13, 14, 15, 16, 83, 84, 85, 86, 87, 88	357
4	74, 82, 92, 93, 94	1035
5	100, 101, 102, 103, 104, 105, 106, 112, 113, 114	478
6	17, 81, 95, 96, 97, 98	508
7	107, 108, 109, 110, 111	1010
8	68, 69, 70, 71, 72, 73, 78, 79, 80	469
9	30, 31, 33, 34, 35, 36, 37, 38, 39, 40, 118	682
10	49, 50, 51, 52, 53, 54, 55	605
11	56, 57, 58, 63, 64, 65, 66, 67	365
12	45, 46, 47, 48, 59, 60, 61, 62	597
13	41, 42, 43, 44, 75, 76, 77	645
14	3, 4, 5, 116, 117	279
15	1, 2, 6, 7	550
16	8, 9, 10, 18, 19, 20	490
17	21, 22, 23, 24, 25, 26, 27, 28, 29, 32	509

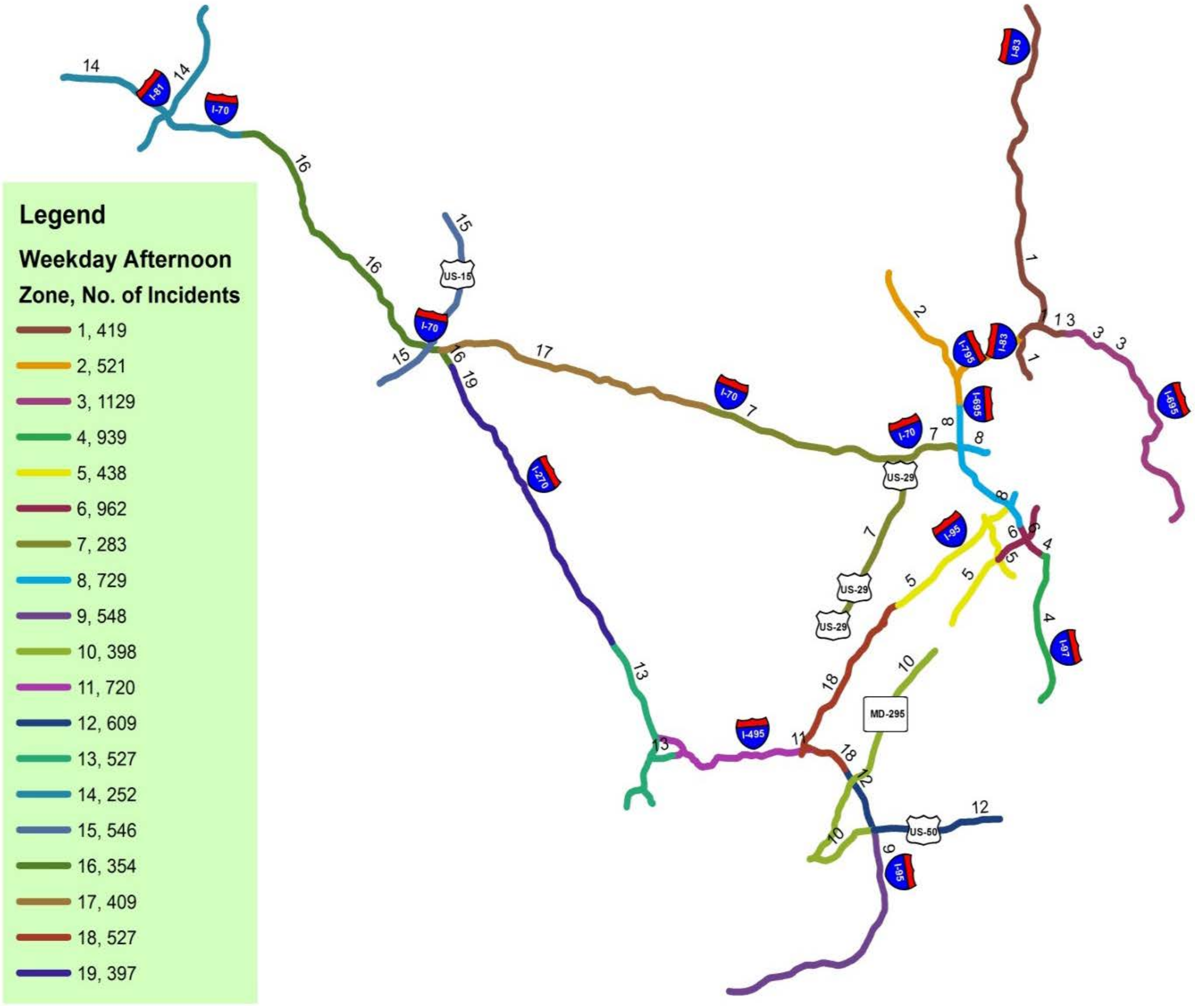


Figure 33 - Non-Patrolling Detection: Beat Configuration for the Weekday Afternoon Shift

Table 32 - Non-Patrolling Detection: Beat Configuration for the Weekday Afternoon Shift

Beat	Covered Links	Number of Incidents
1	100, 101, 102, 112, 113, 114, 115	419
2	98, 99, 119	521
3	103, 104, 105, 106, 107, 108, 109, 110, 111	1129
4	89, 90, 91	939
5	68, 69, 70, 71, 72, 79, 80, 81	438
6	73, 74, 92, 93	962
7	13, 14, 15, 16, 83, 84, 85, 86, 87, 88	283
8	17, 82, 94, 95, 96, 97	729
9	48, 49, 50, 51, 52, 53, 54, 55	548
10	56, 57, 58, 63, 64, 65, 66, 67	398
11	30, 31, 36, 37, 38, 39, 40, 41, 42	720
12	45, 46, 47, 59, 60, 61, 62	609
13	27, 28, 29, 32, 33, 34, 35, 118	527
14	3, 4, 116, 117	252
15	1, 2, 7	546
16	5, 6, 8, 18	354
17	9, 10, 11, 12	409
18	43, 44, 75, 76, 77, 78	527
19	19, 20, 21, 22, 23, 24, 25, 26	397

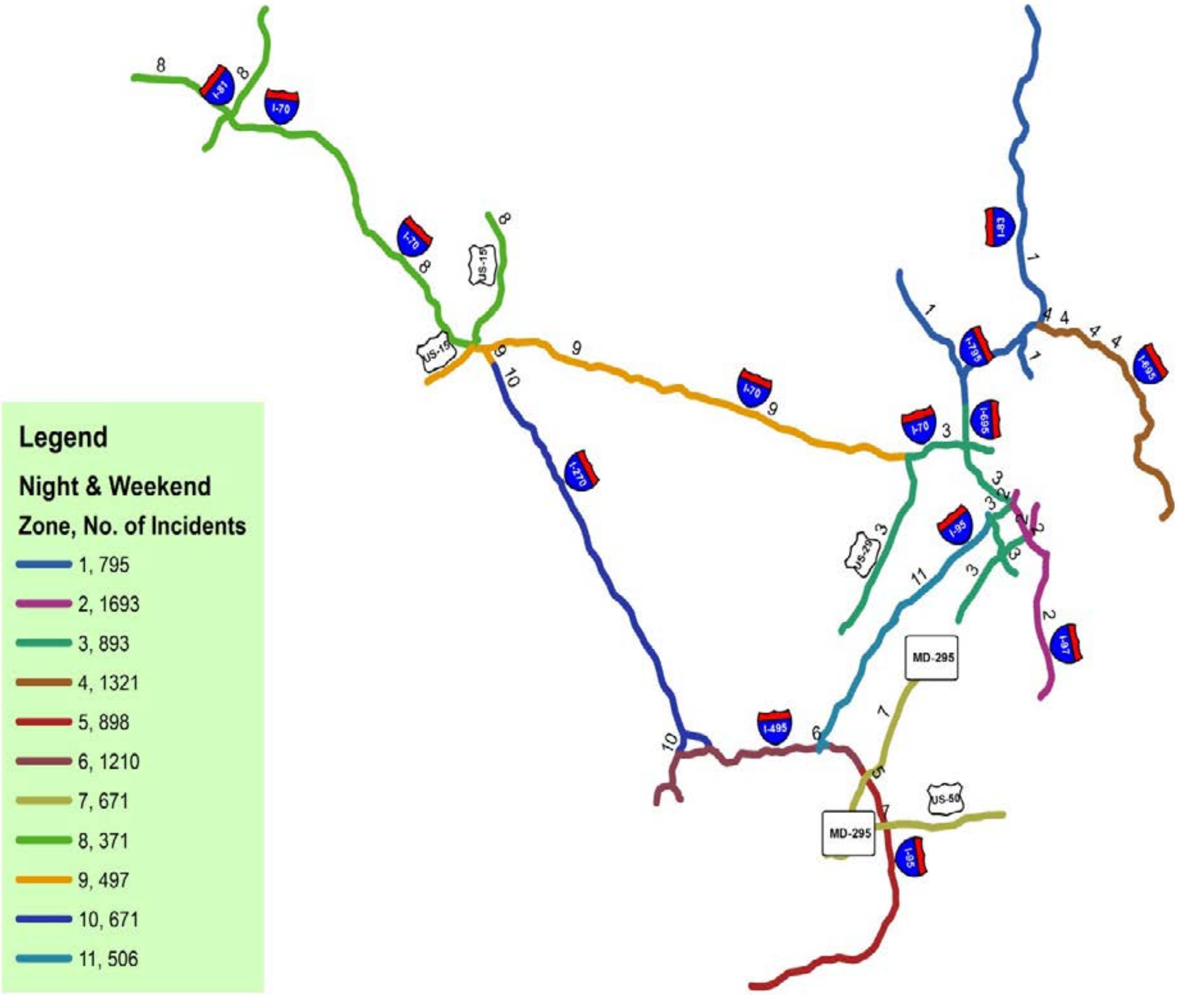


Figure 34 - Non-Patrolling Detection: Beat Configuration for the Night and Weekend Shift

Table 33 - Non-Patrolling Detection: Beat Configuration for the Night and Weekend Shift

Beat	Covered Links	Number of
1	98, 99, 100, 112, 113, 114, 115, 119	795
2	74, 82, 89, 90, 91, 92, 93, 94	1693
3	16, 17, 69, 70, 71, 72, 73, 81, 83, 84, 85, 86, 87, 88, 95,	893
4	101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111	1321
5	45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55	898
6	33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 118	1210
7	56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67	671
8	1, 3, 4, 5, 6, 7, 116, 117	371
9	2, 8, 9, 10, 11, 12, 13, 14, 15, 18	497
10	19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	671
11	68, 75, 76, 77, 78, 79, 80	506

Table 34 - Non-Patrolling Detection: Performance Measures

Description	Weekday Morning	Weekday Afternoon	Night & Weekend
Fleet Size	17	19	11
Shift Duration (hours/year)	2080	2080	4576
Avg. Response Time (min) - 40 MPH	13.7	12.4	-
Avg. Response Time (min) - 55 MPH	-	-	15.4
Number of Incidents	9929	10707	9526
Total Response Time (hours) - 40 MPH	2267	2220	-
Total Response Time (hours) - 55 MPH	-	-	2443
Operation Cost ($1000)	1,768	1,976	2,517

Non-Patrolling Detection: Sensitivity Analysis

Now, sensitivity analysis is performed for the non-patrolling detection dataset to determine the impact of varying parameters on the beat configuration and fleet size. One parameter that is investigated is the average response speed of emergency units to arrive at the incident location once they are informed of the incident occurrence. Please note that this speed could be different than standard patrolling speed (discussed for the previous dataset) because units are already informed of the incidents and may be able to drive faster.

Here, two additional scenarios of the average response speed of 55 MPH and 65 MPH are considered for the weekday morning and weekday afternoon shifts. Also, the problem is solved for one additional scenario for the night and weekend shifts assuming the average response speed of 65 MPH. The beat configuration for the weekday morning (based on 55 MPH average response speed), weekday afternoon (55 MPH), weekday morning (65 MPH), weekday afternoon (65 MPH), and night and weekend (65 MPH) shifts are illustrated in Figures 35 through 39, respectively.

Performance measures for the sensitivity analysis results, based on the mentioned average response speeds for each shift, are summarized in Table 35. Results include the fleet size, the average response time, and total response time based on each of the speed scenarios for each shift. According to the result, for both weekday morning and weekday afternoon shifts, increasing the speed from 40 MPH to 55 MPH, and from 55 MPH to 65 MPH, reduces the number of required patrol units while the average response time decreases, too. Then, as far as safety concerns are observed, the higher response speed is desired. However, it is obvious that increasing speed may not be possible as there are safety concerns. Also, traffic volumes, especially during peak hours, may force the patrol units to slow down.

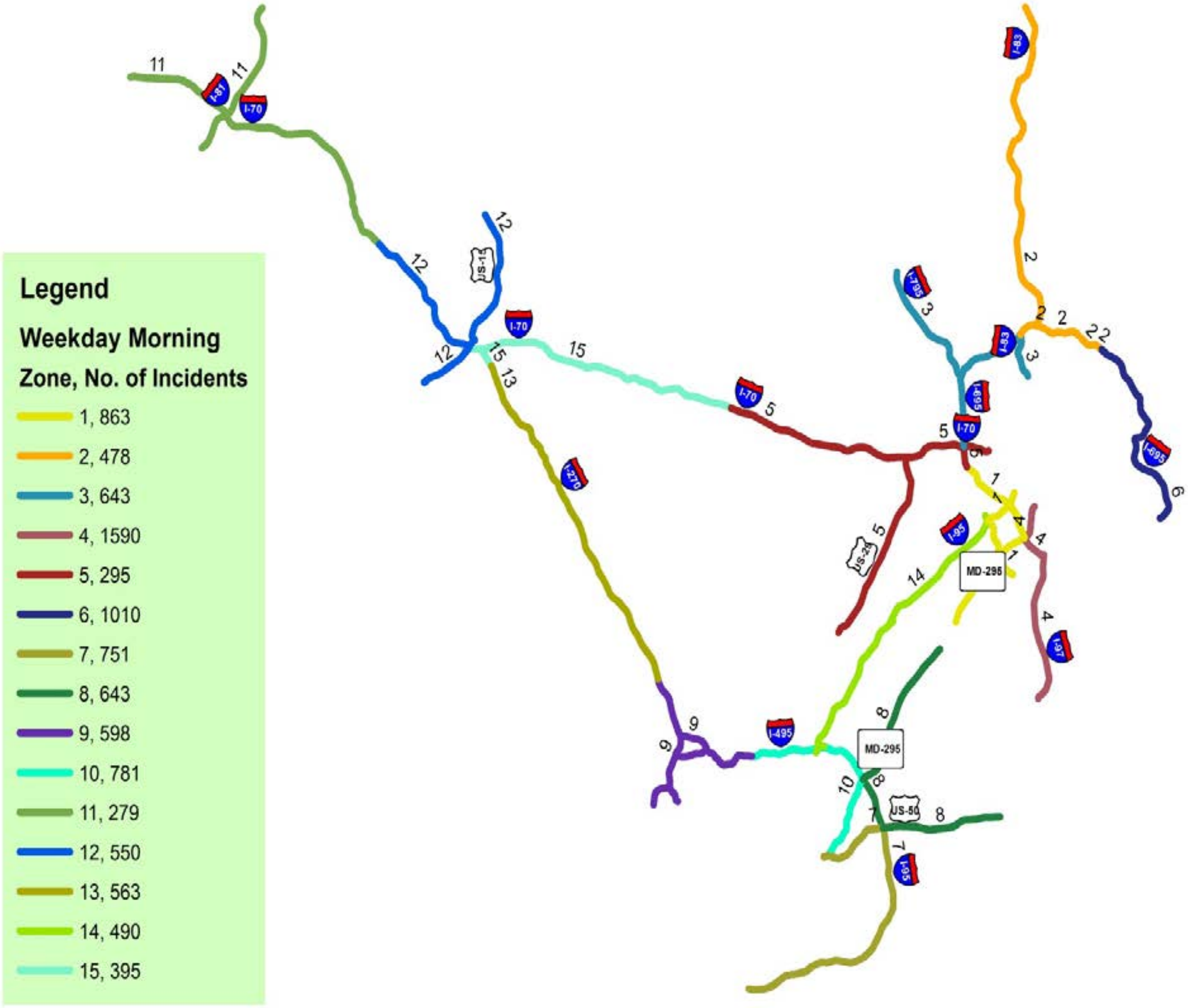


Figure 35 – Non-Patrolling Detection: Beat Configuration for the Weekday Morning Shift – 55 MPH

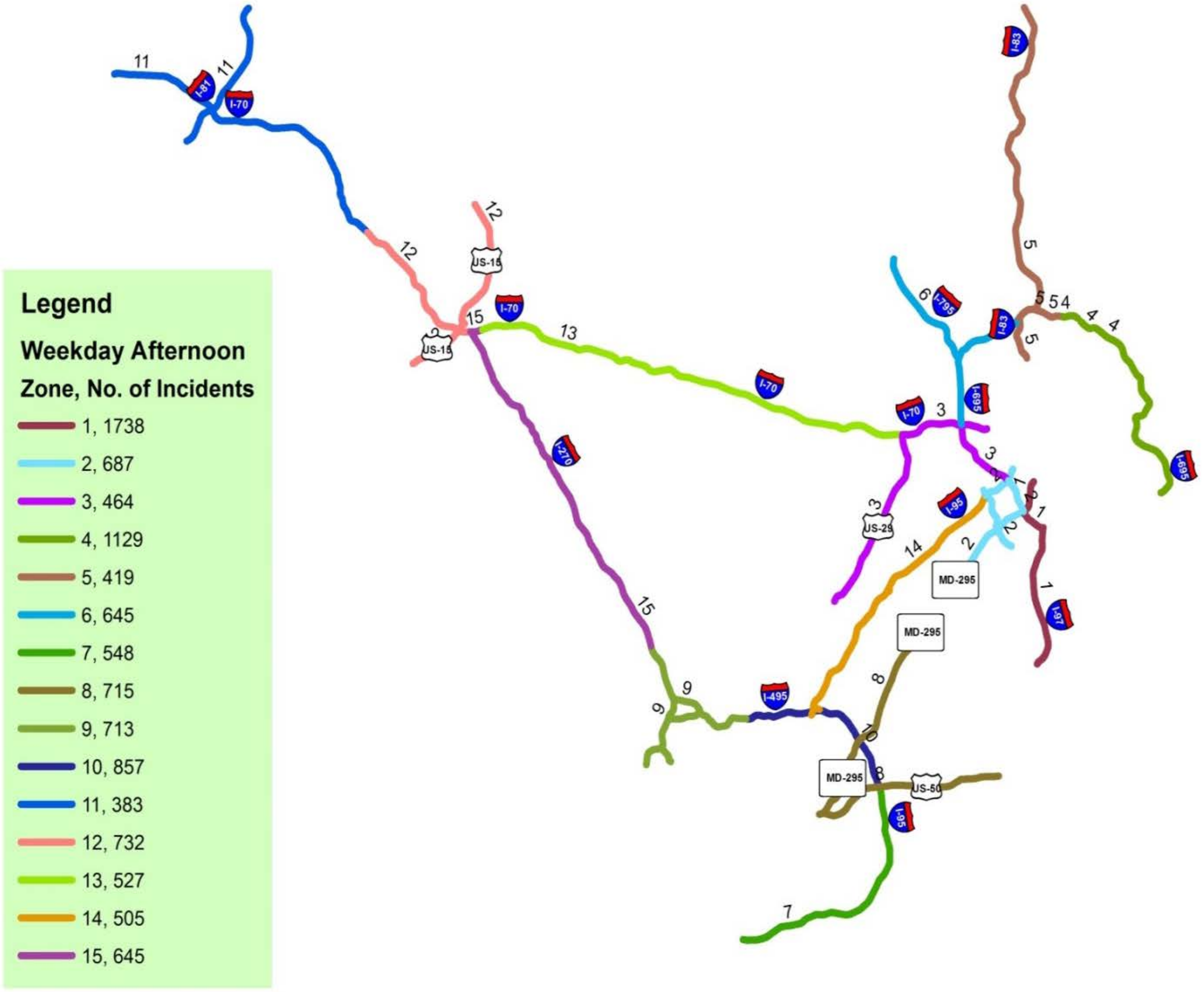


Figure 36 - Non-Patrolling Detection: Beat Configuration for the Weekday Afternoon Shift – 55 MPH

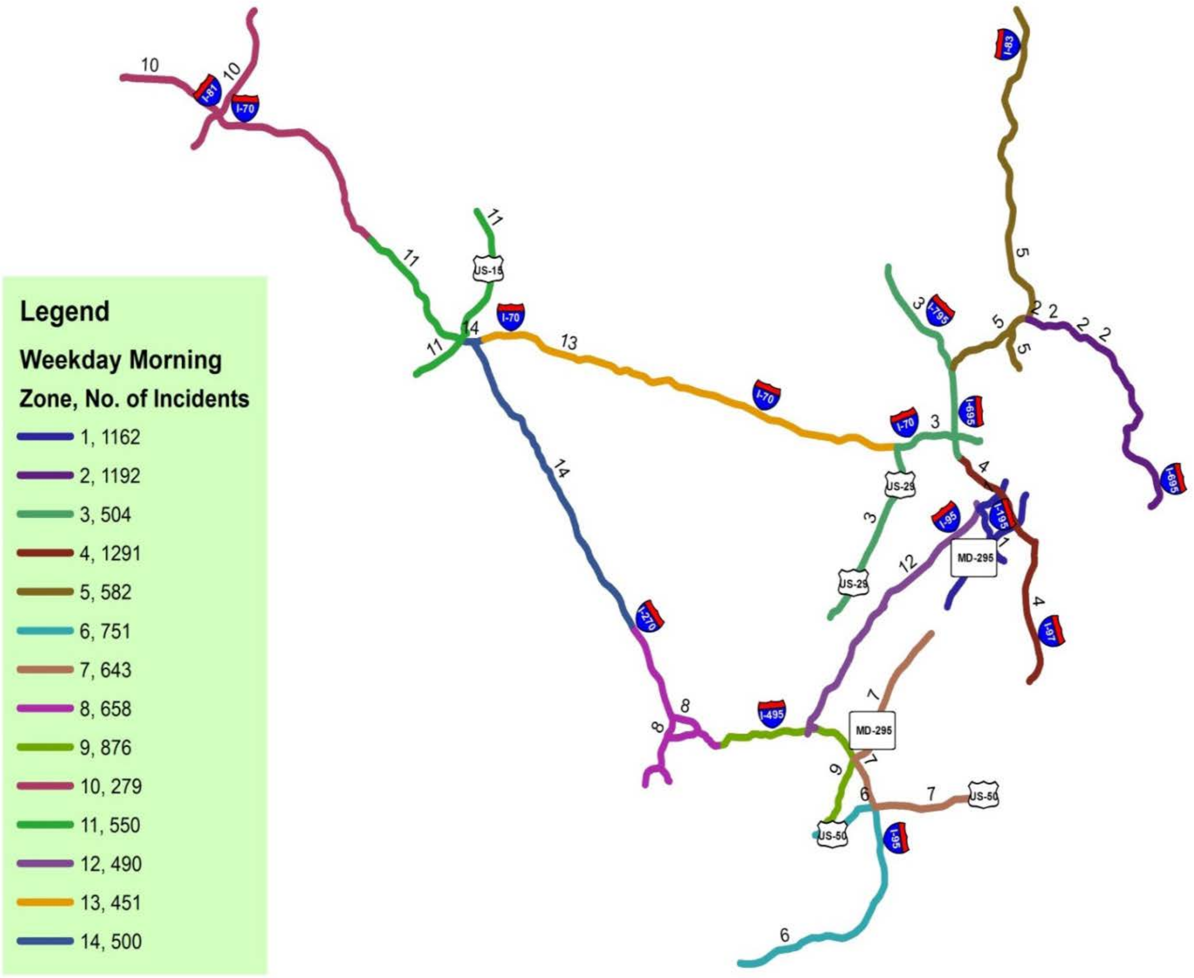


Figure 37 - Non-Patrolling Detection: Beat Configuration for the Weekday Morning Shift – 65 MPH

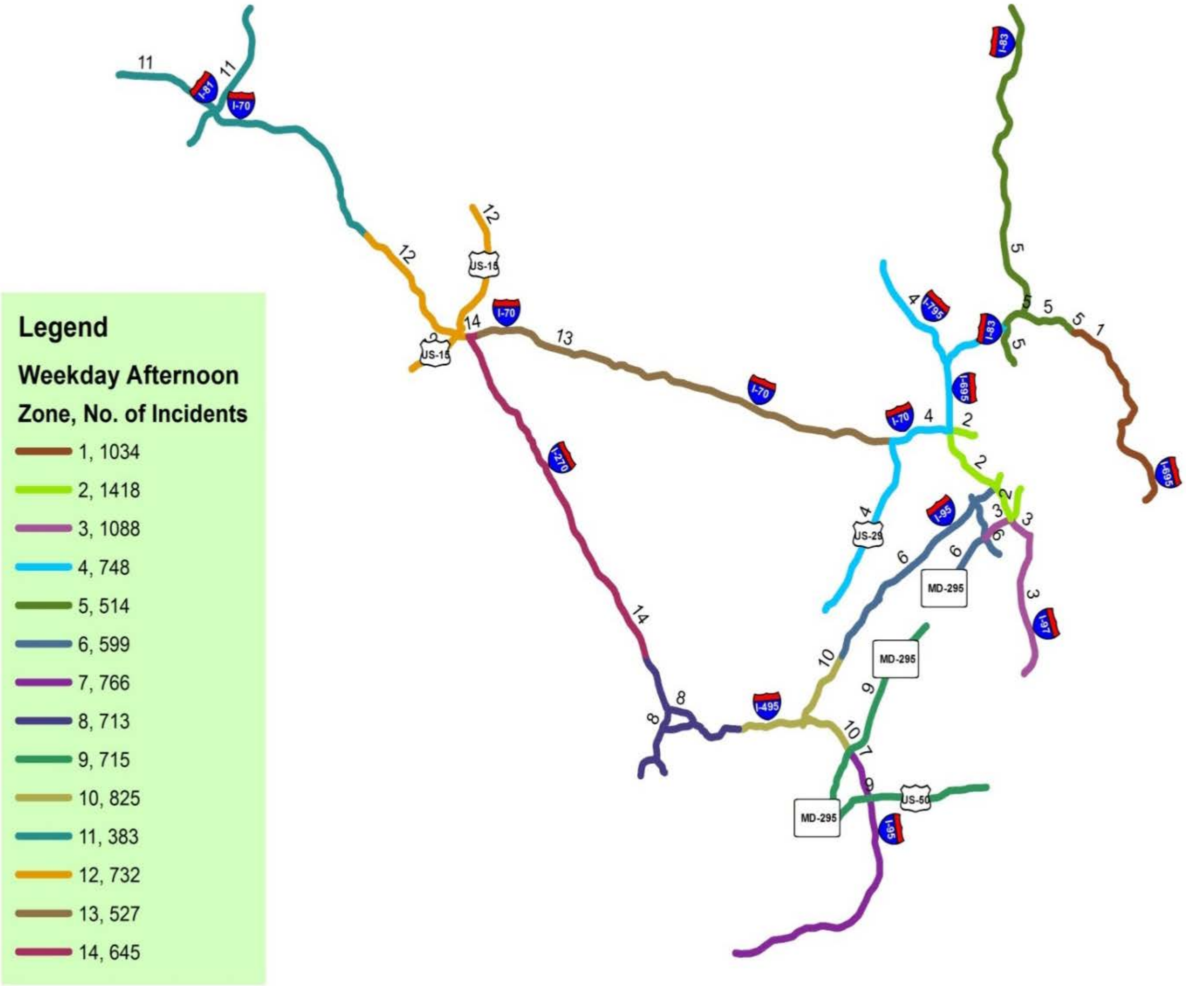


Figure 38 - Non-Patrolling Detection: Beat Configuration for the Weekday Afternoon Shift – 65 MPH

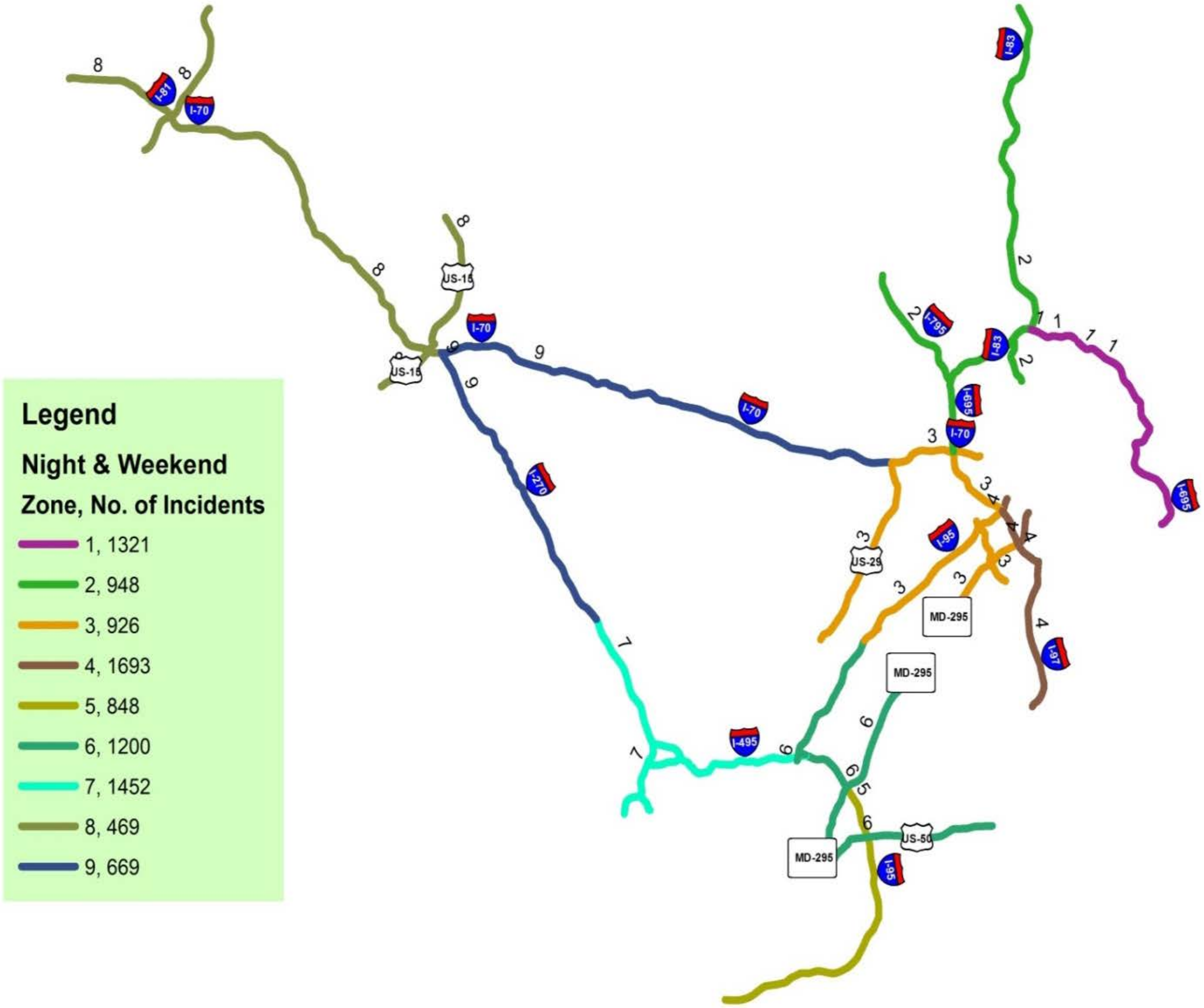


Figure 39 - Non-Patrolling Detection: Beat Configuration for the Night and Weekend Shift – 65 MPH

Table 35 - Non-Patrolling Detection Sensitivity Analysis: Performance Measures

Description	**Weekday Morning**	**Weekday Afternoon**	**Night & Weekend**
Fleet Size 55 MPH	15	15	11
Fleet Size 65 MPH	14	14	9
Shift Duration (hours/year)	2080	2080	4576
Avg. Response Time (min) - 55 MPH	11.5	11.7	-
Avg. Response Time (min) - 65 MPH	10.6	10.5	16.2
Number of Incidents	9929	10707	9526
Total Response Time (hours) - 55 MPH	1901	2088	-
Total Response Time (hours) - 65 MPH	1756	1874	2572

Although the proposed model can determine the optimal beat configuration and number of beats, it is also possible to design the beat configuration based on a pre-specified number of beats. This approach may be needed as sometimes enough resources are not available and we may prefer to design the network based on the maximum available number of patrol units. This means that we need to adjust the number of beats according to the available fleet size. For example, if there are a maximum ten patrol units available, the maximum possible number of beats is ten beats. This happens as we need to assign at least one patrol unit to each beat.

Therefore, as part of the sensitivity analysis for the non-patrolling detection dataset, we assume a fixed number of beats and design the network based on 11 beats. The beat configuration for the weekday morning and weekday afternoon shifts, based on 11 beats, are shown in Figure 40 and Figure 41, respectively.

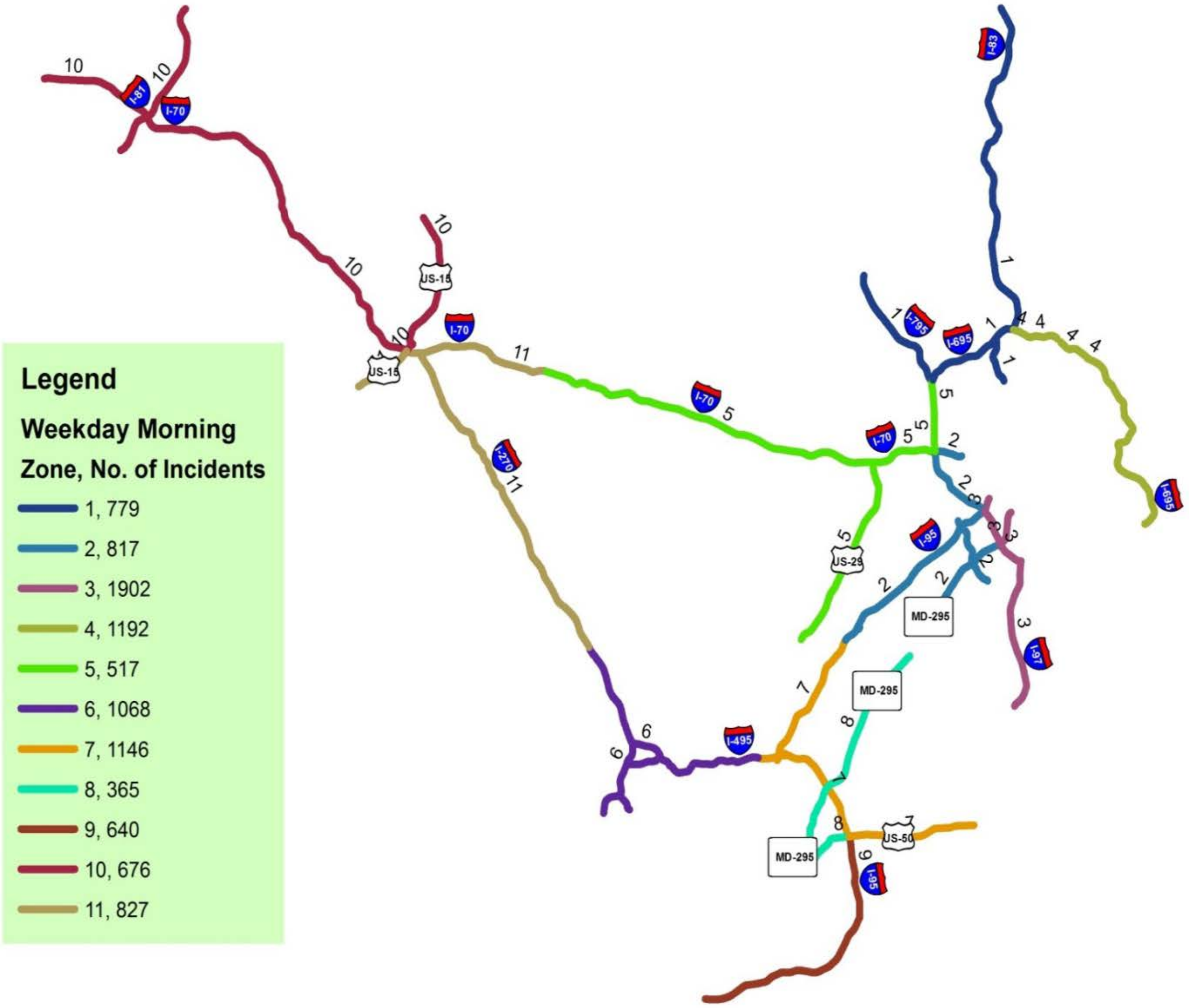


Figure 40 – Non-Patrolling Detection: Beat Configuration for the Weekday Morning Shift – Pre-Specified 11 Beats

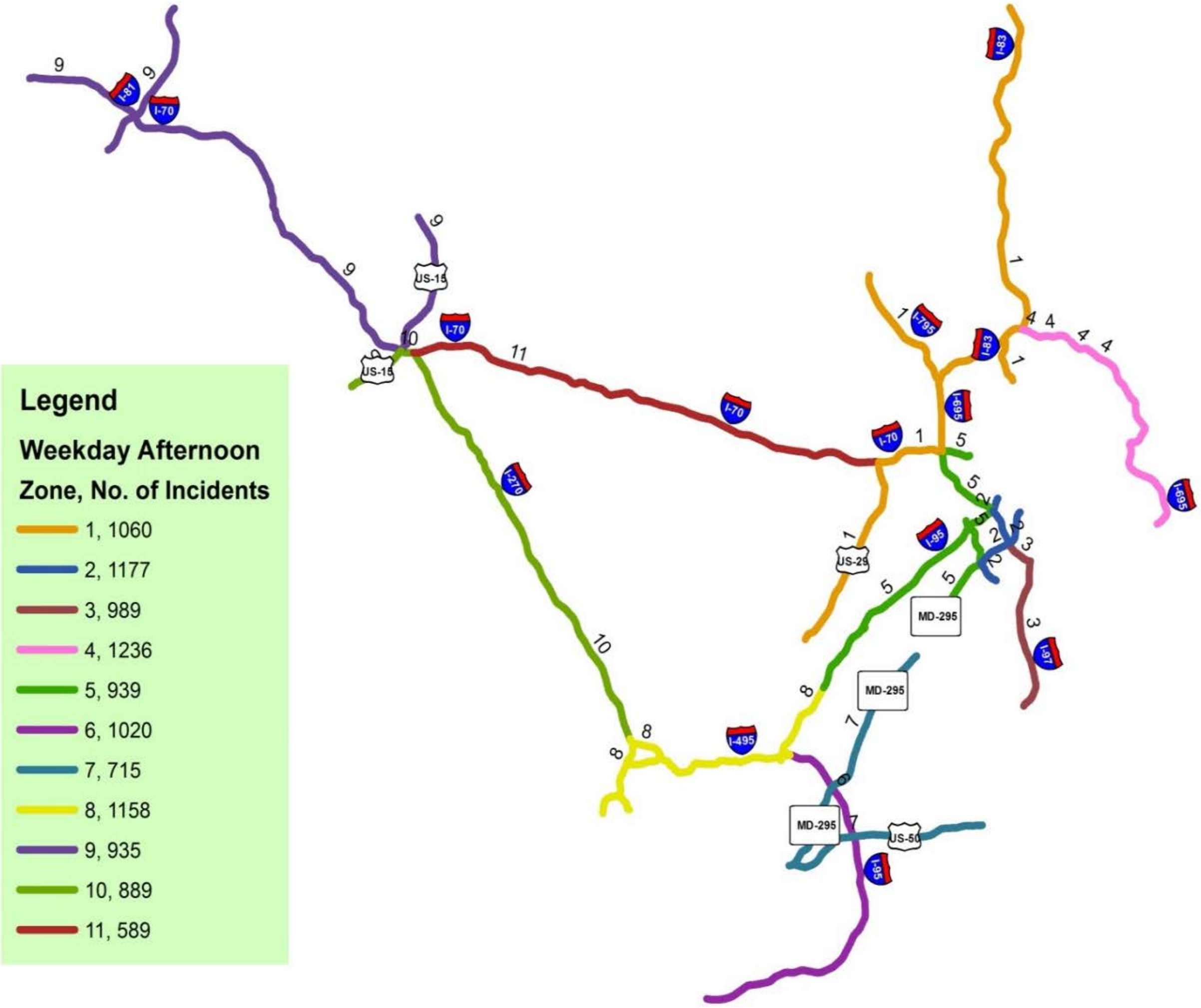


Figure 41 - Non-Patrolling Detection: Beat Configuration for the Weekday Afternoon Shift: Pre-Specified 11 Beats

As shown in the last result, assuming a given fleet size, optimal beat configurations for different shifts are determined. On the other hand, sometimes we may be interested in determining the fleet size and fleet allocation for a given beat configuration.

Therefore, the problem is solved based on the current CHART operating beat configuration which includes 11 beats, as shown in Figure 42, to determine the optimal fleet size and fleet allocation among these beats. Results on the fleet size and fleet allocations, based on each shift, are presented in Table 36. These results are based on assuming constant headway between patrol units on the same beat.

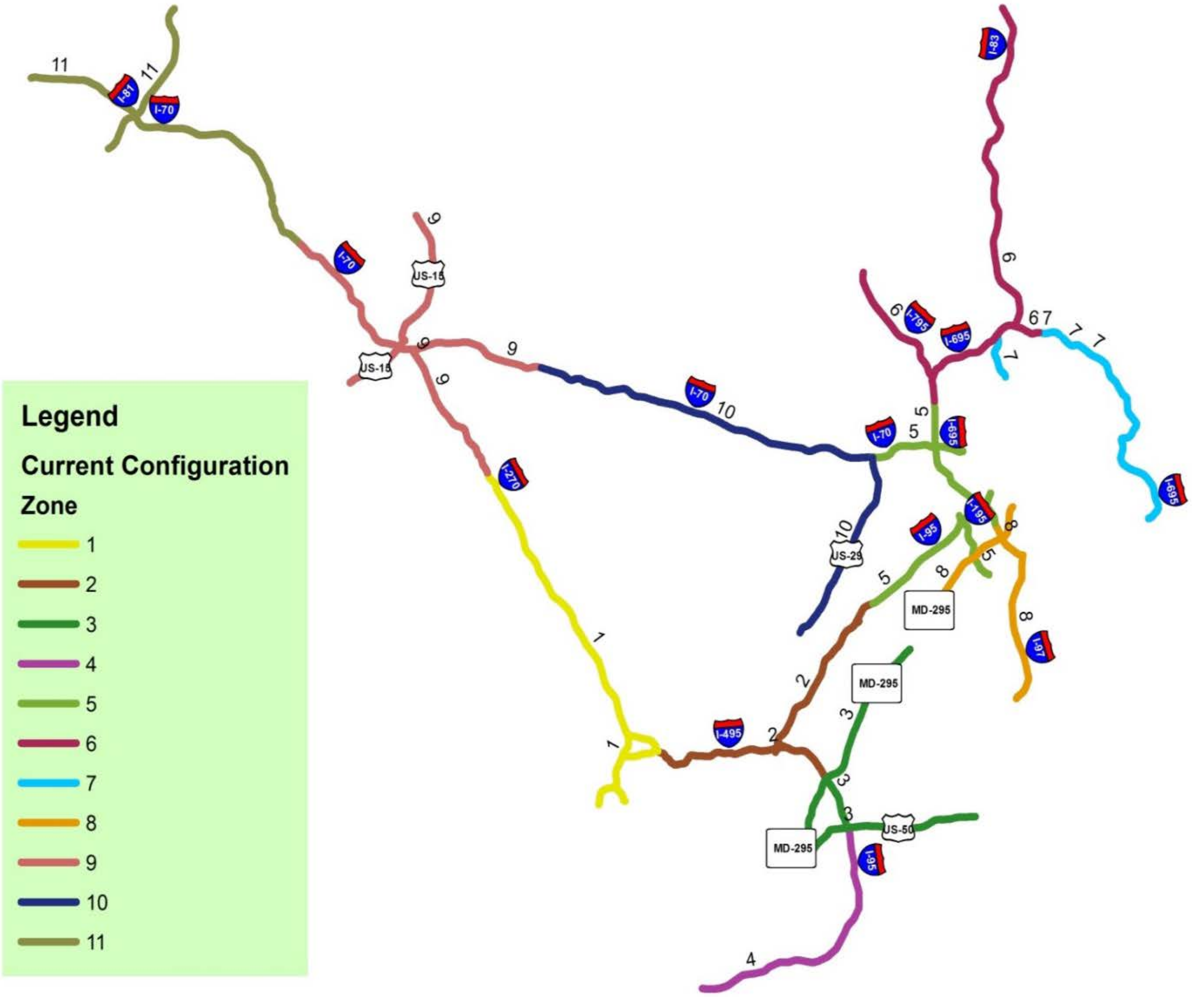


Figure 42 – CHART Current Beat Configuration

Table 36 – Fleet Size and Allocation Based on the Current Beat Configuration

Beat	Weekday Morning	Weekday Afternoon	Night and Weekend
1	2	2	1
2	2	2	1
3	2	2	1
4	1	1	1
5	2	2	1
6	2	2	1
7	2	2	1
8	2	2	1
9	2	3	1
10	1	1	1
11	1	1	1
Fleet Size	**19**	**20**	**11**

Chapter 7: Summary, Conclusion, and Direction for Future Research

Summary

Freeway service patrol programs are proven to be one of the most beneficial and economic incident management strategies. This system is being widely used in many major metropolitan areas. The main issues that need to be addressed, to plan the patrol program for a given network, are determining the fleet size, determining the beat structure, and determining the fleet allocation. These issues could be dealt with individually, but they are interrelated. Therefore, it is much more appealing to investigate all issues simultaneously in a joint model instead of dealing with each issue separately. So, this study presented a comprehensive mixed-integer programming model to design the network for patrol programs by dealing with these issues concurrently while all important factors such as operating costs are taken into account. The problem is solved using the combination of network decomposition and neighbor search algorithms. The proposed heuristic works well in generating close to optimal solutions promptly.

Conclusions

The result indicates that the approach to design the network based on the joint model can significantly improve the solution to optimize the efficiency of the freeway service patrol program. Furthermore, the result specifies that considering each of the involving factors in the model can elevate the performance of the patrol program, too. Especially, the number of beats, beat configuration, fleet size, and fleet allocation among other elements in the model need to be determined and should not be simply assumed.

As proven by the result, to optimize the performance of the program while operating costs are minimized, it is important to consider several configurations based on different times of the day, week, or year as there could be dissimilar incident densities for the same network during different periods. However, we do not require designing the network for every single period. Data processing and statistical analysis on incident data may reveal periods that may require individual design. In this study, the network is designed based on the weekday morning, weekday afternoon, and night and weekend shifts, as official CHART shifts. Additional scenarios could focus on designing for the peak and non-peak hours. Also, seasonal or monthly based designs could be helpful.

Sensitivity analysis shows that varying parameters such as the value of time and emergency trucks' average response speed or standard patrolling speed have a significant impact on the optimal beat configuration, fleet size, and fleet allocation. Then, these values need to be carefully chosen and inserted into the model. In the case of uncertainty, a range of values could be chosen to design the network based on, and the impact on the solution should be determined. Also, increasing the maximum number of patrol units per beat has an impact on the optimal solution. However, the difference in objective values is not significantly high as the model can create extra beats with a smaller number of units per each beat instead of one large beat with more patrol units. Though, for this purpose, the network should be broken down into sufficiently small links.

Results indicate that increasing the value of time from \$20 per hour to \$30 per hour causes the fleet size to increase significantly for each shift. This result is sensible because when the value of time is higher, the model tries to reduce the total incident duration further and, as a result, additional patrol units are assigned to accomplish that.

According to the result, as patrol units' average response speed or standard patrolling speed increases, less number of patrol units is needed to cover the network even though the average response time may reduce, too. However, it is obvious that increasing speed may not be possible as there are safety concerns. Also, typically traffic volumes, especially during peak the morning and afternoon hours, may force the patrol units to slow down.

Although the proposed model can determine the optimal beat configuration and number of beats, it is also possible to design the beat configuration based on a pre-specified number of beats. This approach is interesting especially when the available fleet size is limited. As an example, the beat configuration is determined based on assuming pre-specified 11 beats. Furthermore, fleet size and fleet allocation could be determined for any given beat configuration assuming constant headway between patrol units in the same beat.

Based on the results, for each shift, it is found that Baltimore and National Capital regions need more patrol units than the Western region. This outcome makes sense because the Western region has a lower number of incidents compared to Baltimore and National Capital regions. Moreover, the Baltimore region may need one or two more patrol units than the National Capital region during different shifts.

For the planning purpose, upon data availability, it is advantageous to classify incidents based on detection method and design the network considering both classes in the same model. This classification is needed because the average response time is different based on the patrolling and non-patrolling detection methods.

Agencies can follow a few basic guidelines for operating patrol programs without fully implementing models such as the one proposed in this dissertation. In general, frequency of coverage for different segments of the network should be approximately related to the number of incidents on those segments. Also, the overall fleet size can be roughly estimated based on total number of incidents and an acceptable average response time assuming one beat only configuration. Also, proper fleet size and beat configuration should be considered for different shifts based on their incident frequencies. Then, the overall fleet size could be split between shifts based on the number of incident in each shift. Also, for existing configurations, a few small sensitivity analyses could be applied by, for example, swapping links between beats or removing one link and adding it to the neighbor beat and evaluating the new configuration.

Similarly, for existing configurations, a simple fleet size increase or decrease for each beat could be evaluated to determine the benefit or loss of any change in fleet size.

As urban freeway networks continue to become more congested, well-planned patrol programs offer significant potential for reducing the network delay and thus require profound procedures to maximize their impacts. Our proposed model and developed algorithms can assist officials to plan and design patrol programs that are very efficient regarding reducing incident-incurred delay and operation cost.

Future Research

Future research may investigate to fully capture and directly reflect the impact of additional factors such as traffic volume, incident type and severity, and road characteristic into the model. Also, another study may try to address additional issues such as considering several types of trucks with different operating costs and different capabilities regarding incident response time and clearance time reduction.

Furthermore, future research may focus to minimize total incident duration including recovery time, clearance time, response time, detection time, and verification time. For this purpose, additional inputs such as incident types, traffic volumes, and geometry of the roads need to be considered and inserted into the analysis.

An important question for incident management officials is to determine where patrol units are required and where other strategies such as dispatch response are sufficient. Therefore, the future study may focus to determine the patrol coverage area, for a given transportation network, by taking into account elements such as incident frequency, operating costs, average patrolling and dispatch response times. Determining the patrol coverage area and the non-patrolling area can save operating costs by avoiding non-necessary patrolling in the areas with low incident density.

Although sometimes we are better off not patrolling low-incident rate areas, at some other times, it could be even beneficial to cover some routes by more than one beat. This could be due to high incident rates for those specific routes or just as a matter of geometric design. For this purpose, the future study will need to redefine the average response time for those specific routes as they will be covered by more than one beat, and those routes benefit from a reduced average response time.

Another possibility for future work is to develop a dynamic model framework to update the designed network immediately upon each incident occurrence to instantly change routing and assignment of patrol trucks. However, there could be implementation difficulties to adjust routes and relocate patrol units immediately. Then, to build a dynamic model, practical facts should be carefully considered.

Also, a stochastic planning model could be developed to take into account the uncertainty associated with inputs such as incident numbers or travel times. This is particularly important as the incident data is very uncertain and roads do not necessarily have similar incident rates as the previous year. Therefore, considering a range of incident frequencies for each road and developing a stochastic model based on that may provide a more reliable solution.

Finally, although the proposed model is developed to design the network for incident response patrol units, the model could be modified and customized to solve similar patrolling problems such as designing the patrol routes for police cars. For example, with a similar strategy for a different application, Shafahi and Haghani developed an integer model to determine the routing for police patrols to cover high-crime areas more often [51]. Meter reading and snow plowing problems are among other arc routing problems that could be similarly solved.

Appendix A:

Network Nodes

Node	**Patrol highway**	**Interchange with**	**Node**	**Patrol highway**	**Interchange with**
1	I-70	I-81	**31**	I-495	MD 5
2	I-70	US 40	**32**	I-495	MD 210
3	I-70	MD 17	**33**	I-495	MD 414
4	I-70	MD 85	**34**	I-495	I-295
5	I-70	MD 75	**35**	I-495	MD 97
6	I-70	MD 27	**36**	I-495	MD 193
7	I-70	MD 94	**37**	I-495	MD 650
8	I-70	MD 97	**38**	I-95	MD 212
9	I-70	MD 32	**39**	I-95	MD 200
10	I-70	US 29	**40**	I-95	MD 216
11	I-70	Endpoint	**41**	I-95	MD 175
12	I-270	MD 85	**42**	I-695	I-83
13	I-270	MD 80	**43**	I-695	MD 45
14	I-270	MD 109	**44**	I-695	MD 146
15	I-270	MD 121	**45**	I-695	MD 542
16	I-270	MD 118	**46**	I-695	MD 147
17	I-270	MD 119	**47**	I-695	MD 43
18	I-270	MD 124	**48**	I-695	US 1
19	I-270	I-370	**49**	I-695	US 40
20	I-270	MD 28	**50**	I-695	Endpoint
21	I-270	MD 189	**51**	I-695	I-97
22	I-270	MD 187	**52**	I-695	MD 648
23	I-495	US 29	**53**	I-695	MD 295
24	I-495	US 1	**54**	I-695	I-895 b
25	I-495	MD 201	**55**	I-83	MD 439
26	I-495	MD 295	**56**	I-83	MD 137
27	I-495	MD 202	**57**	US 50	Endpoint
28	I-495	MD 450	**58**	US 50	MD 202
29	I-495	MD 214	**59**	US 50	MD 410
30	I-495	MD 4	**60**	US 50	MD 704

Node	Patrol highway	Interchange with	Node	Patrol highway	Interchange with
61	US 50	MD 197	**91**	I-83	Endpoint
62	US 50	MD 3 (US 301)	**92**	I-695	Providence Road
63	MD 295	MD 450	**93**	I-695	MD 139
64	MD 295	Endpoint	**94**	I-695	Endpoint
65	MD 295	MD 32	**95**	I-695	Endpoint
66	MD 295	MD 175	**96**	Cabin John Pkwy	Endpoint
67	MD 295	MD 100	**97**	I-97	Endpoint
68	US 29	US 40	**98**	I-95	MD 32
69	US 29	MD 108	**99**	I-495	MD 185
70	US 29	MD 175	**100**	I-495	MD 187
71	US 29	MD 32	**101**	I-495	MD 190
72	US 29	MD 216	**102**	I-270	MD 27
73	I-97	MD 3	**103**	I-695	Perring Pkwy
74	I-95	Endpoint	**104**	I-495	Endpoint
75	MD 295	Endpoint	**105**	I-270	I-70
76	I-83	Endpoint	**106**	I-270	I-270 spur
77	US 29	Endpoint	**107**	I-495	I-270 spur
78	MD 295	Endpoint	**108**	I-695	I-795
79	US 50	Endpoint	**109**	I-695	I-83
80	I-795	Endpoint	**110**	I-95	I-195
81	I-83	Endpoint	**111**	I-70	I-695
82	I-70	Endpoint	**112**	I-195	MD 295
83	US 15	Endpoint	**113**	I-95	I-495
84	US 340	Endpoint	**114**	I-95	I-695
85	I-83	Endpoint	**115**	I-70	US 15
86	US 340	Endpoint	**116**	I-270	US 15
87	I-695	MD 26			
88	I-495	MD 355			
89	I-495	MD 704			
90	I-695	US 40			

Appendix B:

Network Links

Link	Between Nodes		On Road	Link	Between Nodes		On Road
1	116	115	US-15	**31**	22	88	I-270
2	115	84	US-15	**32**	107	106	I-270 spur
3	82	1	I-70	**33**	76	101	I-495
4	1	2	I-70	**34**	101	107	I-495
5	2	3	I-70	**35**	107	100	I-495
6	3	115	I-70	**36**	100	88	I-495
7	83	116	US-15	**37**	88	99	I-495
8	115	105	I-70	**38**	99	35	I-495
9	105	4	I-70	**39**	35	23	I-495
10	4	5	I-70	**40**	23	36	I-495
11	5	6	I-70	**41**	36	37	I-495
12	6	7	I-70	**42**	37	113	I-495
13	7	8	I-70	**43**	113	24	I-495
14	8	9	I-70	**44**	24	25	I-495
15	9	10	I-70	**45**	25	26	I-495
16	10	111	I-70	**46**	26	28	I-495
17	111	11	I-70	**47**	28	89	I-495
18	105	12	I-270	**48**	89	27	I-495
19	12	13	I-270	**49**	27	29	I-495
20	13	14	I-270	**50**	29	30	I-495
21	14	15	I-270	**51**	30	31	I-495
22	15	102	I-270	**52**	31	33	I-495
23	102	16	I-270	**53**	33	32	I-495
24	16	17	I-270	**54**	32	34	I-495
25	17	18	I-270	**55**	34	104	I-495
26	18	19	I-270	**56**	57	58	US-50
27	19	20	I-270	**57**	58	59	US-50
28	20	21	I-270	**58**	59	89	US-50
29	21	106	I-270	**59**	89	60	US-50
30	106	22	I-270	**60**	60	61	US-50

Link	Between Nodes		On Road
61	61	62	US-50
62	62	79	US-50
63	57	63	MD-295
64	63	26	MD-295
65	26	78	MD-295
66	78	64	MD-295
67	64	65	MD-295
68	95	110	I-195
69	110	112	I-195
70	112	94	I-195
71	66	67	MD-295
72	67	112	MD-295
73	112	53	MD-295
74	53	75	MD-295
75	113	38	I-95
76	38	39	I-95
77	39	40	I-95
78	40	98	I-95
79	98	41	I-95
80	41	110	I-95
81	110	114	I-95
82	114	74	I-95
83	77	72	US-29
84	72	71	US-29
85	71	70	US-29
86	70	69	US-29
87	69	68	US-29
88	68	10	US-29
89	97	73	I-97
90	73	51	I-97
91	51	52	I-695
92	52	53	I-695
93	53	54	I-695
94	54	114	I-695
95	114	90	I-695
96	90	111	I-695
97	111	87	I-695
98	87	108	I-695
99	108	42	I-695
100	42	109	I-695
101	109	93	I-695
102	93	43	I-695
103	43	44	I-695
104	44	92	I-695
105	92	45	I-695
106	45	103	I-695
107	103	46	I-695
108	46	47	I-695
109	47	48	I-695
110	48	49	I-695
111	49	50	I-695
112	91	55	I-83
113	55	56	I-83
114	56	109	I-83
115	42	81	I-83
116	85	1	I-81
117	1	86	I-81
118	96	101	Cabin John Pkwy
119	80	108	I-795

Appendix C:

Non-Patrolling Detection: Number of Incident per Link

Link	Weekday Morning	Weekday Afternoon	Night & Weekend	Link	Weekday Morning	Weekday Afternoon	Night & Weekend
1	60	77	22	**31**	24	38	29
2	153	152	85	**32**	33	39	28
3	45	58	18	**33**	66	94	87
4	55	81	19	**34**	47	70	61
5	92	131	57	**35**	29	42	29
6	124	158	75	**36**	44	56	59
7	213	317	152	**37**	89	103	144
8	23	28	13	**38**	95	101	147
9	40	62	20	**39**	159	128	157
10	174	216	102	**40**	95	83	122
11	55	61	48	**41**	61	58	66
12	74	70	65	**42**	145	116	158
13	23	27	23	**43**	9	12	13
14	41	50	38	**44**	139	168	146
15	84	103	81	**45**	62	74	50
16	20	26	44	**46**	144	144	137
17	50	58	41	**47**	43	74	55
18	29	37	22	**48**	35	43	44
19	173	152	103	**49**	61	85	89
20	51	42	31	**50**	95	113	117
21	24	33	44	**51**	183	139	179
22	18	32	34	**52**	134	85	105
23	33	28	26	**53**	36	15	18
24	10	2	3	**54**	61	39	58
25	30	36	29	**55**	35	29	46
26	69	72	60	**56**	43	52	49
27	155	149	148	**57**	30	30	27
28	56	48	37	**58**	38	49	23
29	81	78	68	**59**	76	80	76
30	24	37	31	**60**	72	71	90

Link	Weekday Morning	Weekday Afternoon	Night & Weekend	Link	Weekday Morning	Weekday Afternoon	Night & Weekend
61	84	90	88	**91**	4	11	11
62	81	76	77	**92**	61	50	54
63	45	43	37	**93**	73	64	49
64	66	68	80	**94**	80	108	59
65	46	60	44	**95**	210	270	267
66	50	36	36	**96**	17	33	19
67	47	60	44	**97**	121	124	153
68	2	9	2	**98**	39	71	46
69	22	19	22	**99**	212	219	219
70	31	21	15	**100**	25	30	26
71	134	137	143	**101**	56	79	76
72	19	15	21	**102**	25	28	24
73	64	99	65	**103**	18	29	18
74	662	749	782	**104**	39	56	44
75	92	82	120	**105**	9	10	3
76	93	104	102	**106**	35	61	60
77	106	93	98	**107**	48	37	49
78	46	68	24	**108**	66	45	64
79	32	31	30	**109**	50	44	37
80	119	127	130	**110**	247	352	350
81	71	79	57	**111**	599	495	596
82	159	136	170	**112**	2	4	7
83	6	12	15	**113**	47	44	70
84	12	12	7	**114**	222	188	168
85	10	16	12	**115**	74	46	78
86	3	7	4	**116**	64	74	21
87	26	28	7	**117**	23	39	7
88	3	2	1	**118**	10	7	21
89	518	633	319	**119**	197	231	181
90	345	295	249				

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