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Final Report

Optimization of Emergency Traffic Patrols (ETP) Operations

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16. Abstract

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. This 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 proposed model is tested using data from part of the Tarrant County Courtesy Patrol (CP) network in Texas. 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.

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1 INTRODUCTION

1.1 Traffic Incidents as a Cause of Non-Recurring Congestion

Traffic congestion has always been a controversial issue in transportation studies because of its impact on daily life. Traffic incidents are one of the major factors responsible for increased congestion, accounting for 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 [1]. In the literature, an incident is defined as any occurrence (non-recurring event) that affects the capacity of a roadway [2]. Example of such incidents include, but are not limited to, disabled vehicles, stranded motorists, debris in the roadway, spilled loads, vehicle crashes, work zones, obstruction to traffic, dead animals, and other potential hazards [3].

According to the National Traffic Incident Management Coalition (NTIMC), traffic incidents cause about 25 percent of all congestion on U.S. roadways, which results in lane blockage during peak hours and adds 4 minutes to the travel time because of delay [4]. Also, it is estimated that about 20 percent of all crashes are because of a previous crash, and the amount of time it takes to clear the initial incident increases the probability of a secondary incident. According to the USDOT, 14–18% of all crashes result from other incidents [5].

To restore network performance as soon as possible, systematized procedures should be implemented to respond and clear incidents. State agencies and transportation professionals have achieved significant delay savings by implementing incident management programs for the efficient recovery from traffic incidents. Inarguably, the rapid removal of incidents is the most important factor in restoring the performance of the network [6].

1.2 Traffic Incident Management

The appropriate use of incident management procedures can significantly reduce the adverse effect of incidents. Incident management includes policies and strategies that play an essential role in decreasing the incident clearance duration [7], [8]. The purpose of Traffic Incident Management (TIM) is to recognize, report, and remove the incident to restore the normal traffic flow reliably in order to reduce congestion. A TIM program needs to be well designed and custom-made for the local region to be successful. The TIM program also must be dynamically managed, structurally planned, inter-jurisdictional, multidisciplinary, and thoroughly documented [9]. Generally, TIM consists of seven steps including detection, verification, response, site management, traffic management, clearance, and recovery [10].

Overall, the total delay incurred due to incidents includes Detection Time, Verification Time, Response Time, Clearance Time, and Recovery Time [11]. 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 variable message signs, ramp metering, temporary shoulder use or other strategies [12]. An example of a successfully applied TIM program is the one in New York State, where NYSDOT has fostered the development of a TIM program that defines a systematic, planned, and coordinated use of human, institutional, mechanical, and technology resources to reduce the duration and impact of incidents [13]. According to the Strategic Highway Safety Plan of New York, the goals of TIM are to (1) ensure the safety of motorists, crash victims, and incident responders, (2) conduct an appropriate response to investigate and safely clear an incident, (3) enhance collaboration of responsible agencies during preparation for planned events, and (4) get traffic moving again as soon as possible while managing the affected traffic until normal traffic conditions are restored. According to the Federal Highway Administration (FHWA), in a one-year period, the average number of responders' deaths on New York 's highways are 12 fire and rescue personnel, five police, 60 towing and recovery operators, and over 100 transportation professionals from DOTs, public works, and safety service patrol programs.

Strategies are available to implement or continue traffic incident management practices and programs that detect, respond to, and remove incidents as safely and quickly as possible. These strategies include (1) advance the correctness and use of TIM data, (2) diminish the clearance times of incidents through improved coordination between responders and motorist assistance programs, (3) increase the coordination between responders through training and communication enhancement, (4) support the Highway Emergency Local Patrol (HELP) program by increasing its operation and establishing a HELP truck operator academy and curriculum, (5) create regional TIM committees in regions where they don't already exist, (6) educate emergency responders and the public on existing laws and best practices, (7) promote the use of high-visibility apparel by emergency responders, highway workers, and tow operators, (8) increase the number of and identify the target audiences for TIM training classes, (9) establish statewide protocols for the end-of-queue notification to the traveling public and coordinate with ITS/TSMO operations strategies, (10) promote awareness of the "Move Over" law, (11) improve the public's knowledge of "steer it/clear it" best practices, and (12) continue to investigate and implement best practices for informing the traveling public leading up to and through temporary traffic control zones [13].

1.3 Emergency Traffic Patrol

Cellular phone call-in incident recognition from individuals on the scene has become the dominant method of first incident notification. The initial dispatch of law enforcement staff to the scene of incidents is a well-known method of incident verification. On an incident scene, the officer assesses the incident, then decides what responses are needed, and finally requests an appropriate response using dispatch.

However, this procedure is only useful when traffic congestion does not restrict travel time to the scene. On the other hand, service patrols can be more capable of noticing and confirming incidents by arriving at the location of quickly - especially during congestion. As a result, FSP programs have now become the primary factor not only for incident recognition and notification (by direct observation by the FSP operators) [14], but also for incident confirmation. For example, in Orange County, CA, 23% of the incidents were first noticed by FSP service patrols, and in Chicago, 28% of the incidents were confirmed by FSP operators [15]. In the Bay Area, FSP operators continuously monitor their coverage area for incidents during their shift, although they are allowed to stop at selected drop locations if they have any other tasks that cannot be accomplished while actively patrolling [9]. To increase the effectiveness of incident discovery, TMC supervisors for the TDOT HELP program are given the responsibility to dynamically adjust patrol routes based on current and evolving traffic conditions [16].

The FHWA handbook lists the roles of FSP in the national incident management timeline [17] as follows: 1) Incident detection and verification, 2) Communication about incident details and traffic conditions to the TMC or the TOC, 3) Traffic incident clearance (including response), 4) Traffic control and scene management (including Temporary Traffic Control: TTC), 5) Motorist assistance and debris removal, 6) Traveler information, 7) Onsite support of public safety, law enforcement, emergency response, and medical responders, 8) Lost and found service for items recovered from the roadway, 9) Administer DOT questionnaire/response forms, and 10) Special event assistance [17].

After discovery and confirmation, incident clearance is the main role of FSP. Fast incident clearance decreases the probability of secondary incidents and reduces potential disturbance and delay to other motorists. For example, San Francisco's I-880 corridor FSP decreased average response time from 28.9 to 18.4 (36%) minutes [18]. The Puget Sound region in Washington estimated reduction in response time between 2.4 to 5.8 minutes for incidents serviced by patrols [19]. Average clearance time decreased from 28.1 to 21.7 minutes in incidents monitored by the SHA patrol of the Coordinated Highway Action Response Team (CHART) in Maryland [20]. In Georgia Patrol Operators have patrolled more than 25,000,000 miles without a single loss of life [17].

As expected, efficient service patrols result in reduction in incident delays for traffic users, fuel consumption, air pollutant emissions, and incident response and clearance times [21]. These indices are 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 [21].

According to the estimate reported by USDOT, about 14% to 18% of all crashes are caused by an earlier incident [22]. The probability of 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 [22].

Figure 1 demonstrates how FSP programs can reduce 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 [21]. As shown, FSP service reduces the duration of the incident and, as a result, reduces the total incident-induced delay on the network.

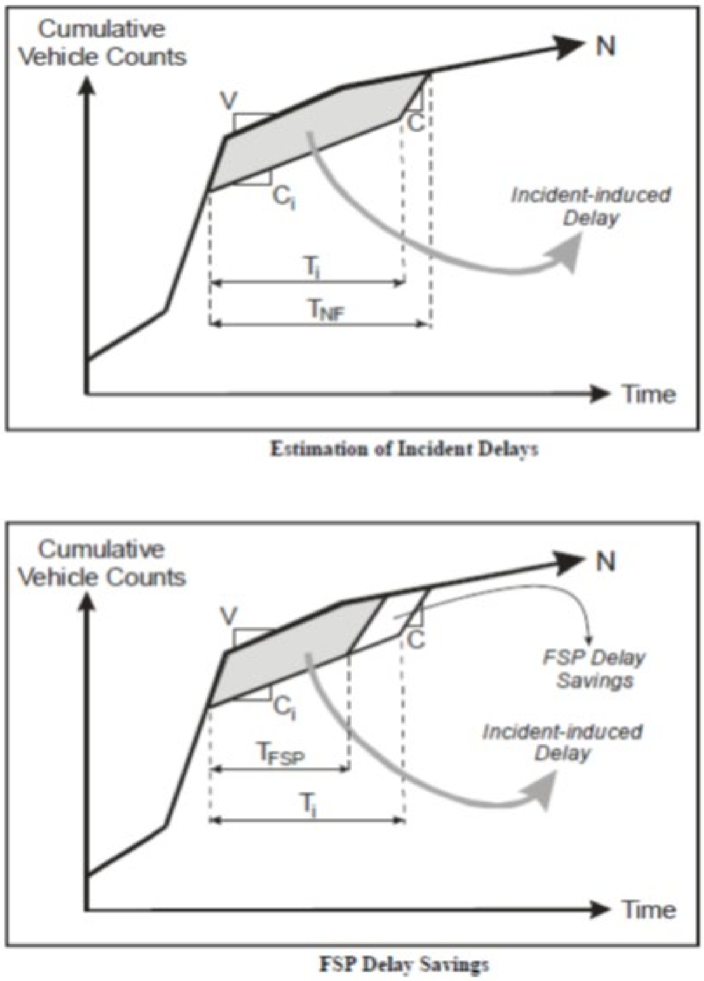


Figure 1 Incident Delay Reduction by FSP Program [21]

1.3.1 Examples of Emergency Patrol Programs

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. The first patrol program started in Chicago, Illinois in 1960, and now many metropolitan regions such as Los Angeles, Chicago, and Dallas-Fort Worth, implement patrol programs. Examples of patrol programs are the following:

- 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

In North Carolina, Freeway Service Patrols (FSPs), referred to as Incident Management Assistance Patrols (IMAP), provide the critically important service of reducing the congestion impact of incidents while simultaneously protecting the safety of the motorists and involved emergency responders. The mission of FSPs requires that operators, dispatchers, and system managers continuously cope with dynamic situations on the highway system within the constraints of the operating agencies. Working within these constraints, agencies can maximize overall FSP effectiveness through the development of deployment methods that take into account both the cost and benefits of FSP implementation at each location [15].

The New York State program is an example showing that a high level of coordination and cooperation can increase the effectiveness of filed verification by on-site responders. Highway Emergency Local Patrol (HELP) vehicles in the Hudson Valley in New York are equipped with a system that streams live video back to the Traffic Management Center (TMC) in the New York State Department of Transportation and State Patrol. Those dash cameras transmit real-time incident information to dispatchers, ensuring the expedited and appropriate dispatch of equipment. Using the streaming video systems was found to be remarkably helpful for remote transportation and law enforcement employees in determining the incident characteristics and subsequent response needs [23].

1.4 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.

1.5 Report Structure

This report is structured as follows: In Section 2, existing studies on freeway service patrolling are presented and their contribution to the field is clarified. In Section 3, the proposed mathematical model is presented and explained. Section 4 examines the application of the mathematical model and the heuristics to a subset of the freeway network in Maryland covered by Coordinated Highways Action Response Team (CHART). Extensions to the model are then analyzed in Section 5. Finally, Section 6 summarizes the results of the research and presents the main conclusions, as well as paths for future research.

2 LITERATURE REVIEW

Overall, we can divide the state-of-art literature on freeway patrolling in two main categories: Evaluation studies, which examine the benefits and costs of existing or proposed programs, and network design studies, which propose mathematical frameworks to design the patrol programs

2.1 Evaluation Studies

The effect of factors on the benefits of FSP operations have been studied by different researchers. FSP programs have been proven to be economically advantageous. Fenno and Ogden found that B/C ratios for FSP programs range from 2.1 to 36.2 nationwide [24]. 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 [25]. Another study by Nee and Hallenbeck [26] 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%. The decrease of incident duration and delay for motorists has been found to play the main role in benefit estimation [27], [28], [29], [30]. To estimate the delay, the comparison of the effects of incidents with and without an FSP program is considered [31]. Different methods have been used to estimate non-recurrent congestion delay including analytical methods using deterministic queuing diagram [32], shock wave theory [33], heuristic methods [34], and simulation methods [35].

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 [21]. Moore et al. [44] claim that secondary incidents in Los Angeles freeways where FSP is implemented occur much less frequently 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. [36] 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 [37]-[41] have similarly confirmed the effectiveness of such incident management programs to mitigate incident-incurred congestion [42].

Some studies estimate static or dynamic thresholds in space and time to define secondary incidents as a measure of the FSP benefits. Static thresholds employ a fixed spatial-temporal boundary for classifying secondary incidents are methodologies that are used to identify secondary incidents. For example, in Raub [43], secondary incidents are an incident that occurred within 15 minutes and within 1 mile upstream of a primary incident while Moore et al. [44] defined secondary incidents as those that occur within 2 hours and 2 miles of a primary incident using CA Highway Patrol data sources. In 2007, Sun and Chilukuri [45] established a dynamic threshold method by varying the back of the queue location throughout the whole duration of incident. This study showed that by using a dynamic method, the number of incidents classified as secondary can differ by up to 30%. In another study, Chou and Miller-Hooks [46] proposed a simulation-based secondary incident filtering method (SBSIF) using the CORSIM microscopic simulation model. A regression model was also implemented for corner point identification along with the SBSIF method. In another research study performed in Virginia, Zhang and Khattak [47] analyzed the cascading incident event duration. They identified and analyzed not only single-pair events (one primary and one secondary incident) but also large-scale cases (those with only one primary incident, but with multiple secondary ones) by categorizing them as either contained or extended, using a deterministic queuing method. In other words, if a secondary incident is the last one being cleared during such an event, it is considered an extended event; otherwise, it is classified as a contained event. Later, Zhang and Khattak [47] advanced an incident management integration tool to estimate dynamic incident duration prediction, secondary incident occurrence and incident delays. Also, Chung [48] presented a process to recognize secondary crashes caused by diverse types of primary crashes in the impact area and advanced a method to distinguish the non-recurring congestion from recurring congestion.

2.2 Network Design

Although patrol programs have been explored in several studies, the majority of these intend 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 aim 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 [49]. In this section, 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.

Some studies use historical data to identify the location of the patrol routes. For example, Khattak and Rouphail [28] used historical statistics of crashes per 100 million vehicle miles, crashes per mile per year, and average annual daily traffic (AADT) per lane and established a method to identify beneficial IMAP route locations. Also, Edara [50] developed the FSP-Assist Prediction Model (APM) to predict the number of incidents per year statistically using freeway segment AADT, length, average daily percent of ADT served, and truck percentage. The APM then assigns each segment a score using the predicted parameters and ranks the potential routes using a computed segment average score.

Other researchers applied simulation techniques to examine different FSP strategies. In this regard, Pal and Sinha [51] 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 [52] also proposed a mixed-integer programming model to determine the optimal locations of incident response units to minimize the operation cost. In a more recent study, Ma et al. [53] applied a quantitative assessment of the influences on the incident duration of different FSP service strategies in the Paramics microsimulation software tool with the goal of guiding FSP dispatching policy. Two dispatch policies were considered: (1) FSP vehicles following predetermined routes responding to incidents as they are encountered in the current direction of travel and (2) FSP using the next available interchange to turn around and serve incidents that are identified in the opposite direction of travel. These two policies were compared under varying patrol headways (assigning more FSP patrol vehicles to a route will result in shorter headways between patrolling vehicles). The simulation study, as would be expected, found that the benefit of allowing FSP vehicles to turn around at the next opportunity and provide assistance in the opposite direction increases as patrol headways become longer (fewer patrol vehicles) and lessens as the patrol headways become shorter (greater number of patrol vehicles). Given the intuitive nature of the study findings, this study was most valuable as a simple example of how microsimulation-based modeling can be used to evaluate FSP patrol strategies and vehicle allocation options.

Different versions of the optimal freeway patrol service design problem havc been formulated using mathematical programming techniques. In this context, Sherali et al. [54] 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. [55] developed an integer-programming model to minimize the total incident-incurred delay by optimizing the deployment locations of incident response units. Daskin [56] 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 [57] and Maryland CHART program [58] 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. [6] 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. [59] 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. [60] 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 [11] 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 [61] 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.

Khattak et al. [62] 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 [63] 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 et al. [64] 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 and Haghani [65] 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 [66]-[68] is that their methodologies only consider the major incidents [42] while our proposed model can fairly consider incidents with different severities and approximately take the clearance time into account as a factor.

2.3 Contribution

Among the 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 [69] 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 [69] 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.

The proposed model and heuristic approaches, as well as the examples, experiments, and results presented in sections 3-6 and 8, are part of the doctoral dissertation [70].

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 notation is 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 node to each node

$B =$ Maximum possible number of patrol beats

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

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

$f_{ij} =$ 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 trucks

$t_{ij} =$ 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

$C_{ij}^b =$ Variables 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 operating 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_{ijklme}^{b} = Binary varibles defined to resolve non-linearity of the model: $X_{ij}^{b}X_{kl}^{b}V_{me}^{b}$

W_{ijkl}^{b} = Binary variables defined to resolve non-linearity of the model : $X_{ij}^{b}X_{kl}^{b}$

O_{ijme}^{b} = Binary varibles defined to resolve non-linearity of the model : $X_{ij}^{b}V_{me}^{b}$

r_{ij}^{d} = Shortest distance from depot d to link ij

SD_{d}^{b} = Shortest distance from depot d to beat b ($Min\ r_{ij}^{d}|X_{ij}^{b}=1$)

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

V_{me}^{b}, Z_{e}^{b} = Binary variables defined to determine V_b

Q_{ij}^{b} = Variables defined to assure connectivity of beats

S_{ijb}^{k} , C_{ijb}^{k}, a_{ijk}^{1}, a_{ijk}^{2} = 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 studies 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.

3.1 Patrolling Response Time

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 that, 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:

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

Where X_{ij}^{b} determines 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 follows:

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

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:

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

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.

3.2 Non-Patrolling Detection: Response Time

The above calculations for the average response time refer to 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

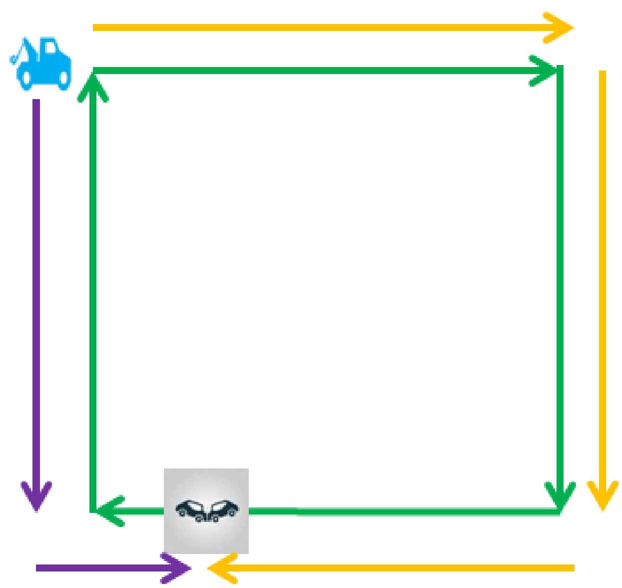


Figure 2 Patrolling vs. Non-Patrolling Detection Response

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.

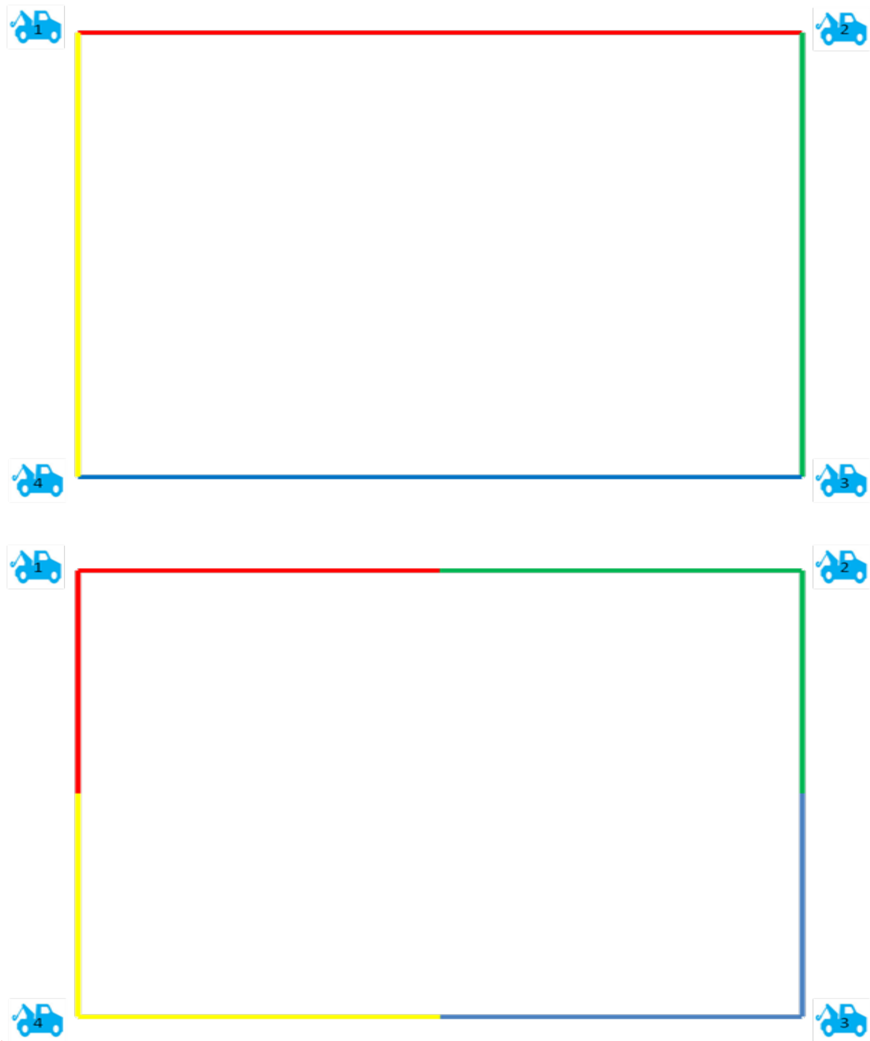


Figure 3 Truck Coverage for Patrolling Detection (Top) vs. Non-Patrolling Detection (Down)

3.3 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, service time here 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 [71], 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.

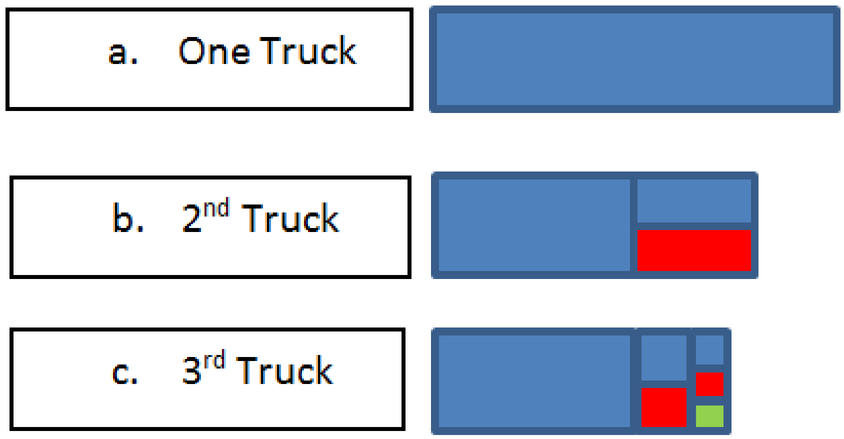


Figure 4 Additional Trucks Reduce the Service Time

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

	$S_{ij} < R$	$R < S_{ij} < 3R$	$S_{ij} > 3R$
$V_b = 1$	S_{ij}	S_{ij}	S_{ij}
$V_b = 2$	S_{ij}	$\frac{S_{ij}}{2} + \frac{R}{2}$	$\frac{S_{ij}}{2} + \frac{R}{2}$
$V_b \geq 3$	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. [36] 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.

3.4 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.

A few approaches are presented in the literature to estimate delay savings. Sun et al. [72] 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 [28] 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.

3.5 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*:

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

3.6 Objective Function - Constraints

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:

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

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 [73]:

$$X_j \geq X_Q \quad for\ all\ j \in Q \qquad (9)$$

So, the following changes are made in the model:

$$X_{ij}^{b} X_{kl}^{b} V_{me}^{b} = U_{ijklme}^{b} \qquad (10)$$
$$X_{ij}^{b} X_{kl}^{b} = W_{ijkl}^{b} \qquad (11)$$
$$X_{ij}^{b} V_{me}^{b} = O_{ijklme}^{b} \qquad (12)$$
$$X_{ij}^{b} S_{ij}^{b} = C_{ij}^{b} \qquad (13)$$

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.

$$\sum_{b=1}^{B}\sum_{m=1}^{T}\sum_{e=1}^{V} C_m V_{me}^{b} * (hr * day) \qquad (14)$$
$$\sum_{d=1}^{D}\sum_{b=1}^{B} SD_{d}^{b} \qquad (15)$$

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

$$\alpha[\sum_{b=1}^{B} \sum_{ij\in L} f_{ij} C_{ij}^{b}\, I_{ij}^{n}(1+\frac{P_s}{2}) + 0.5\sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L} f_{ij} t_{kl}\, I_{ij}^{n}\, W_{ijkl}^{b} - 0.5\sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L} \sum_{m=1}^{T} \sum_{e=2}^{V} f_{ij} t_{kl} I_{ij}^{n}(\frac{1}{e-1} - \frac{1}{e})\, U_{ijklme}^{b}]$$

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

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

Subject to:

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

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

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

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

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

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

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

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

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

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

$\sum_{m=1}^{T} \sum_{e=1}^{V} V_{me}^{b} = V_b$ for each b (27)

$\sum_{m=1}^{T} V_{me}^{b} = Z_e^b$ for each $e = \{1..V\}, b = \{1..B\}$ (28)

$Z_e^b \geq Z_{e+1}^b$ for each $e = \{1..V\}, b = \{1..B\}$ (29)

$C_{ij}^{b} \leq M X_{ij}^{b}$ for each $ij \in L, b = \{1 \ldots B\}$ (30)

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

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

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

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

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

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

$R_{ij}^{b} - C_{ijb}^{k} \leq M a_{ijk}^{1}$ for each $ij \in L, b = \{1 \ldots B\}, k = \{1..V\}$ (37)

$S_{ijb}^{k} - C_{ijb}^{k} \leq M a_{ijk}^{2}$ for each $ij \in L, b = \{1 \ldots B\}, k = \{1..V\}$ (38)

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

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

$\sum_{ij\in L} h_{ij}^{b} = 1$ for each b (41)

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

$\sum_{b=1}^{B} X_{ij}^b = 1$ for all $ij \in L$ (43)

$X_{ij}^b = X_{ji}^b$ for all $ij \in L$ (44)

$\sum_{b=1}^{B} y_i^b \geq 1$ for each $i \in N$ (45)

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

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

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

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

$\sum_{ij \in L} X_{ij}^b \leq M V_b$ for each $b = \{1..B\}$ (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:

$$\alpha[\sum_{b=1}^{B} \sum_{ij\in L}(f_{ij}^{p} + 0.5f_{ij}^{d})\, C_{ij}^{b}\, I_{ij}^{n}(1+\tfrac{P_s}{2}) + 0.5\sum_{b=1}^{B}\sum_{ij\in L}\sum_{kl\in L}(f_{ij}^{p} + 0.5f_{ij}^{d})\, t_{kl}\, I_{ij}^{n}\, W_{ijkl}^{b} - 0.5\sum_{b=1}^{B}\sum_{ij\in L}\sum_{kl\in L}\sum_{m=1}^{T}\sum_{e=2}^{V}(f_{ij}^{p} + 0.5f_{ij}^{d})\, t_{kl}\, I_{ij}^{n}(\tfrac{1}{e-1} - \tfrac{1}{e})\, U_{ijklme}^{b}] \quad (51)$$

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

3.7 Heuristic Algorithms

For large size networks, the proposed model is combined with a number of heuristic approaches that can be used to generate near-optimal solutions. Such approaches include network decomposition combined with neighborhood search, model decomposition, and beat merging. Details on the heuristic procedures can be found in [70].

4 CHART APPLICATION

4.1 Overview

State of Maryland operates a patrol program which is implemented by the Coordinated Highways Action Response Team (CHART). CHART (Figure 5) 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) [74].

Figure 5 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 Figure 6 through Figure 8, 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 6 CHART Custom Response Vehicle – CRV

Figure 7 CHART Heavy-Duty Utility Truck

Figure 8 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 9 including Western, Baltimore, and National Capital region patrols.

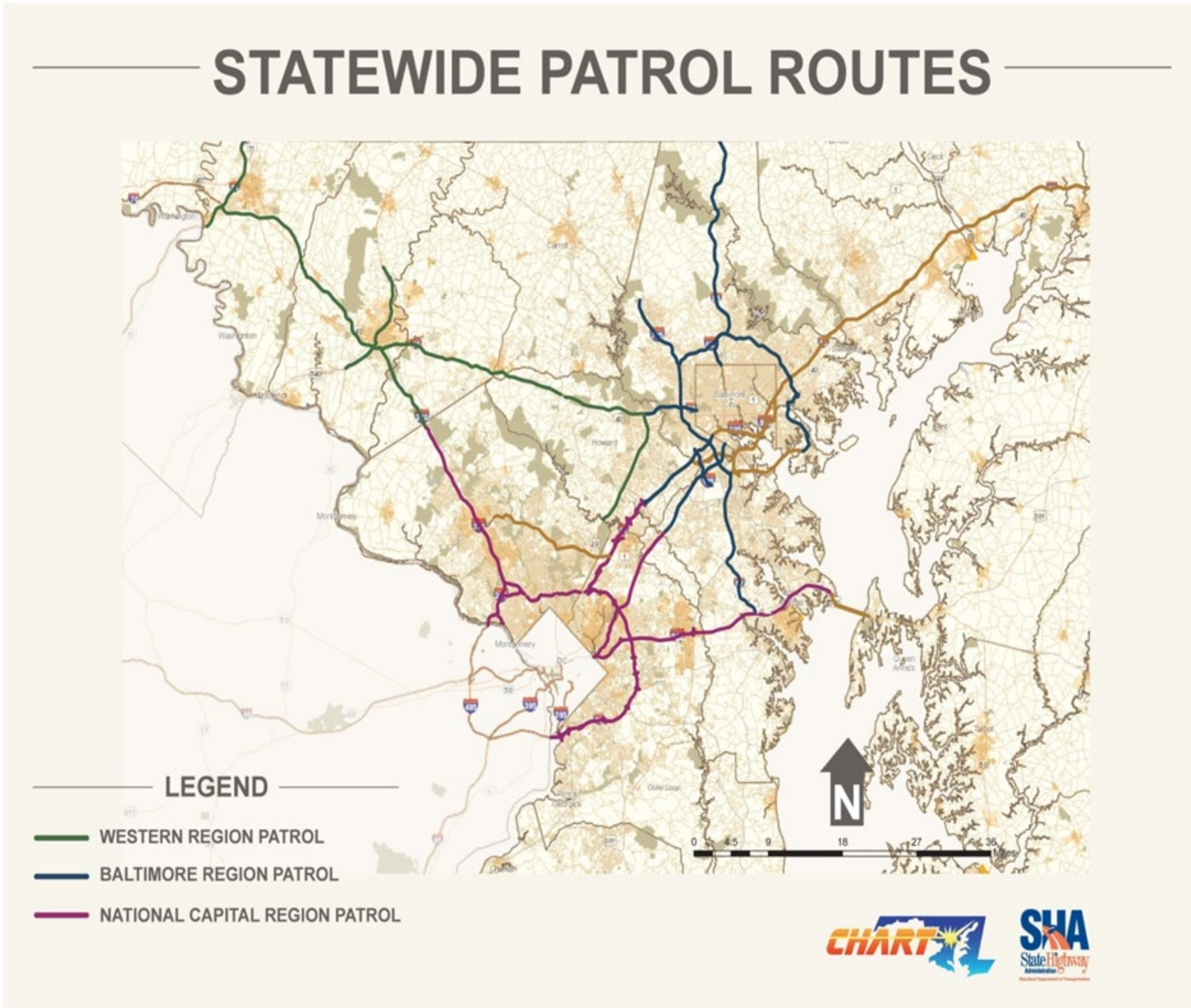


Figure 9 Statewide Patrol Routes

CHART field patrol routes operate based on the following regions [75]:

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

<u>Western:</u>

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 [76].

The analysis was carried out for two consecutive years, i.e., 2015 and 2016. In 2016, the network was modified in the Baltimore region and did not include I-97 and MD100. The network representation used in the analysis was modified accordingly, as will be explained in section 4.2. Details about the cases examined per year, as well as in the different assumptions used for each case, will be described in detail in the sections to follow.

4.2 Study Area

As indicated, the proposed model is applied to part of the Maryland's freeway network and data. Incident data during the years of 2015 and 2016 is investigated to determine the optimal design for each year.

For each of the two study years, a dataset of the incidents was provided. Please note that each 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 represented as a symmetric directed graph, with the edges (arcs) corresponding to road segments and the nodes corresponding to 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.

Based on the historic log data, the number of incidents that are detected and responded by CHART (not necessarily CHART units) in the network is estimated to be more than 11,000 during 2015. For 2016, the analysis was carried out based on the number of incidents that were responded by CHART units (not necessarily detected by CHART as well), which was equal to 30,873.

The analysis for 2015 was based on a network with 116 nodes and 119 links. For the 2016 analysis, the underlying network graph was modified according to the indications of CHART officials and eventually includes 112 nodes and 115 links.

Each number in Figure 10 and Figure 11 represents one segment. Details about the exact location of the nodes and links for 2015 and 2016 are summarized in Appendix A and Appendix B, respectively.

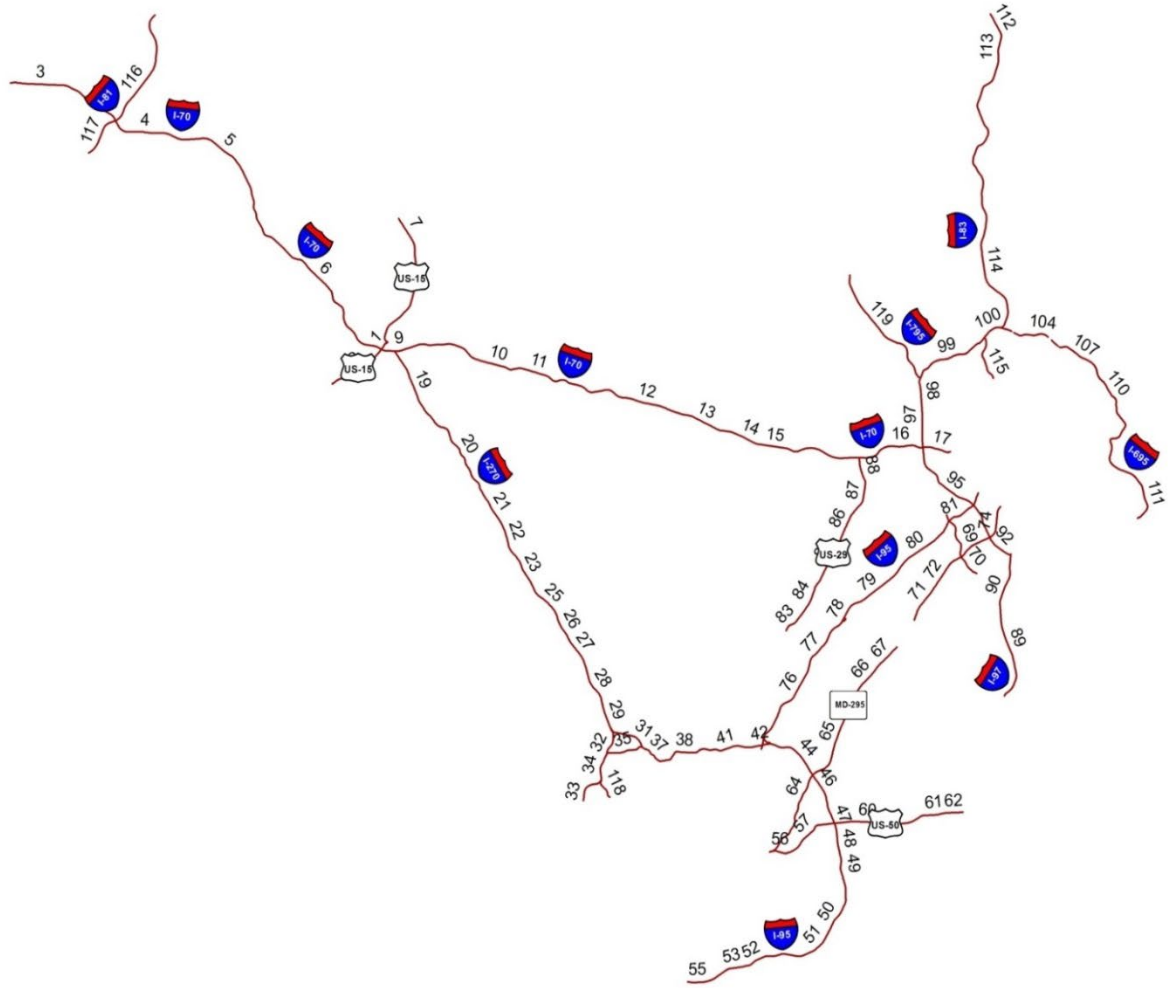


Figure 10 Network Links (2015 analysis)

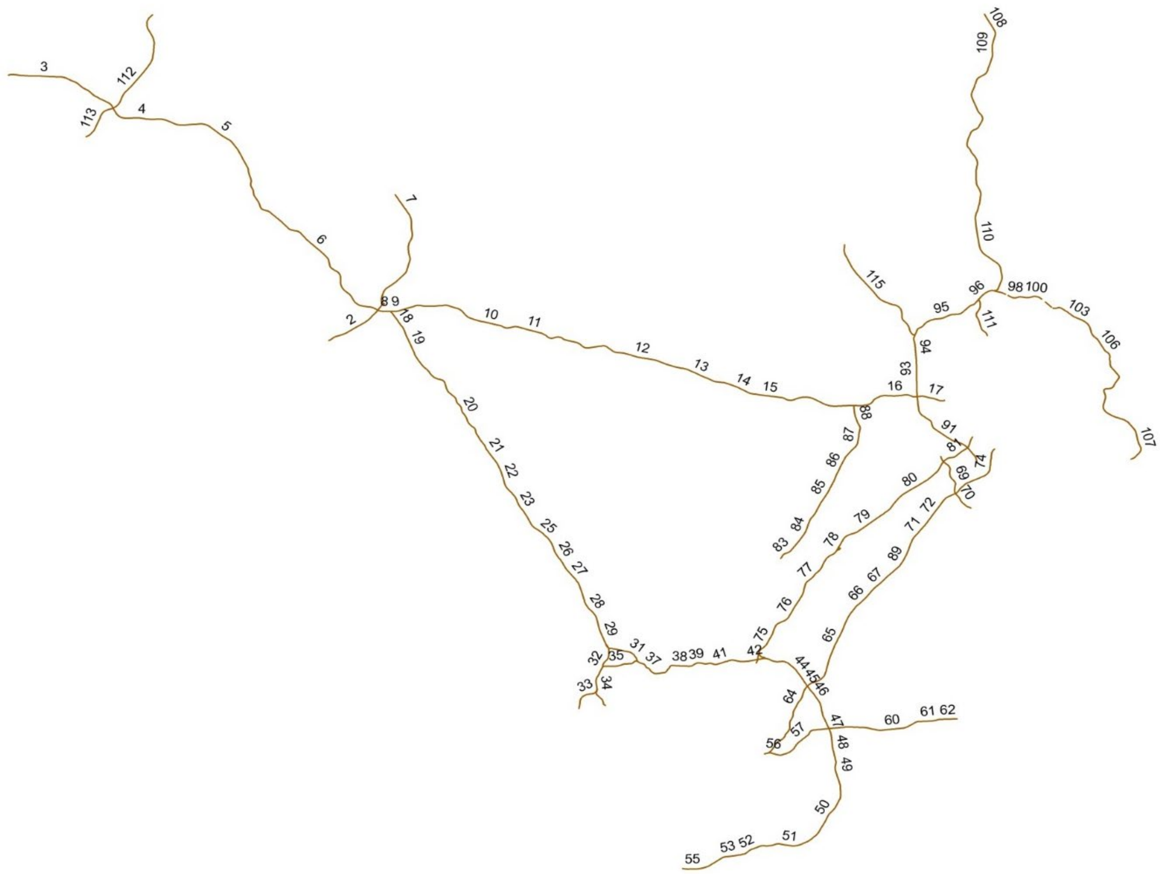


Figure 11 Network Links (2016 analysis)

In these experiments, unless otherwise stated, the 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 Table 4 through Table 6. Also, the sub-network to which each link belongs is listed.

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

Table 5 - 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

Linl	Travel Tim (min)	Number of Incidents	Sub-network	Link	Travel Tim (min)	Number of Incidents	Sub-networl
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 6 – Input: Night and Weekend

Link	Travel Tim (min)	No. of Incidents	Sub-networl	Link	Travel Tim (min)	No. of Inciden	Sub-networl
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				

4.3 Analysis for 2015 Data

4.3.1 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 [77] and 2012 [78] based on two types of intercity and local trips for surface modes. The values for the intercity trip are listed in Table 7, and the values for the local trip are listed in Table 8. 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 7 - 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 8 - 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 [78].

Another study [79] 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 12. 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.

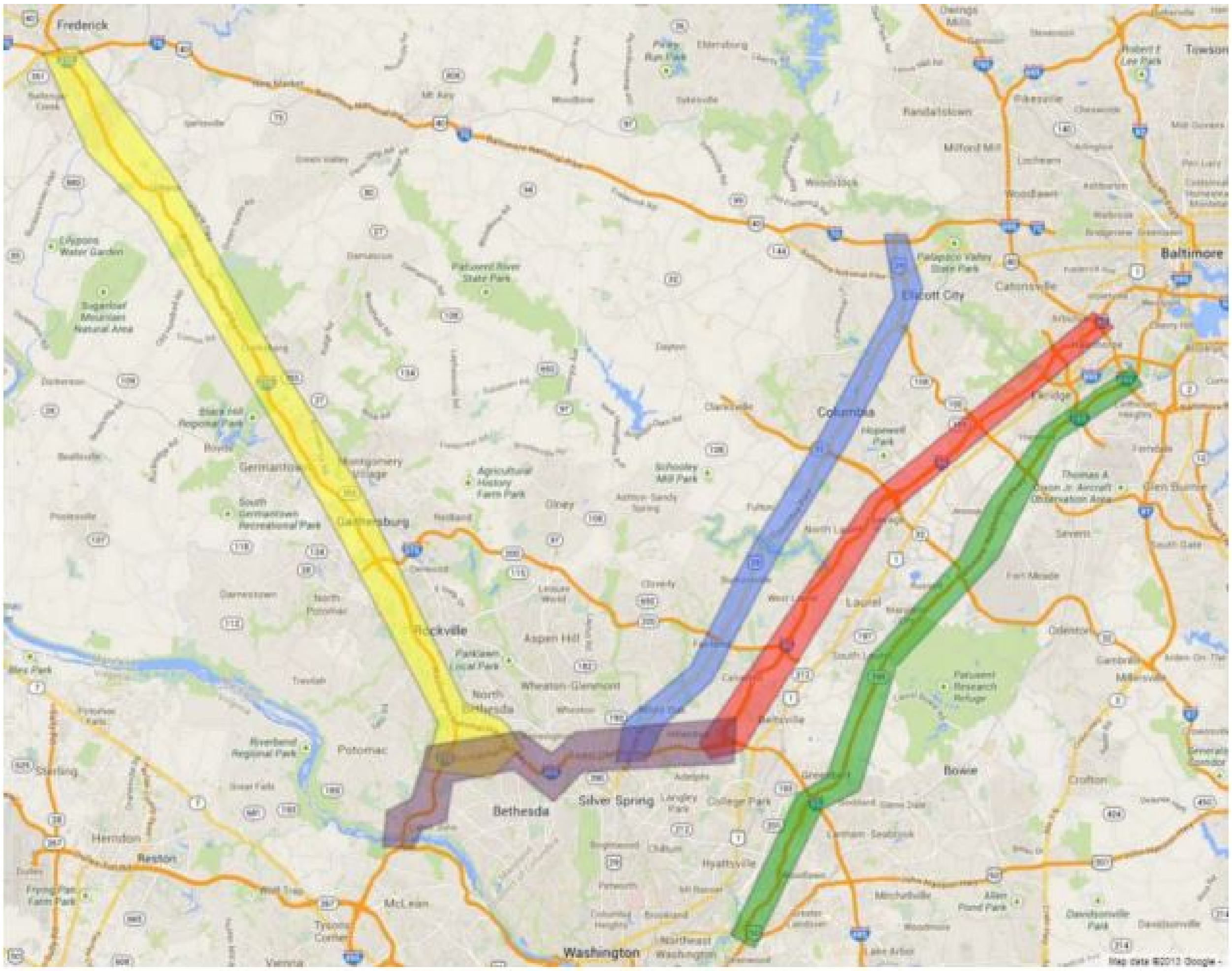


Figure 12 Corridors Analyzed [47]

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 [80]-[82], 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 9. Based on this, parameter α is estimated to be about 15 for the subject network.

Table 9 - Parameter α Estimated for the CHART Network

Scenario	TR (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					

4.3.2 *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 13 through Figure 15, respectively. Also, the result of the fleet size and fleet allocations for each case are listed in Table 10 through Table 12. 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.

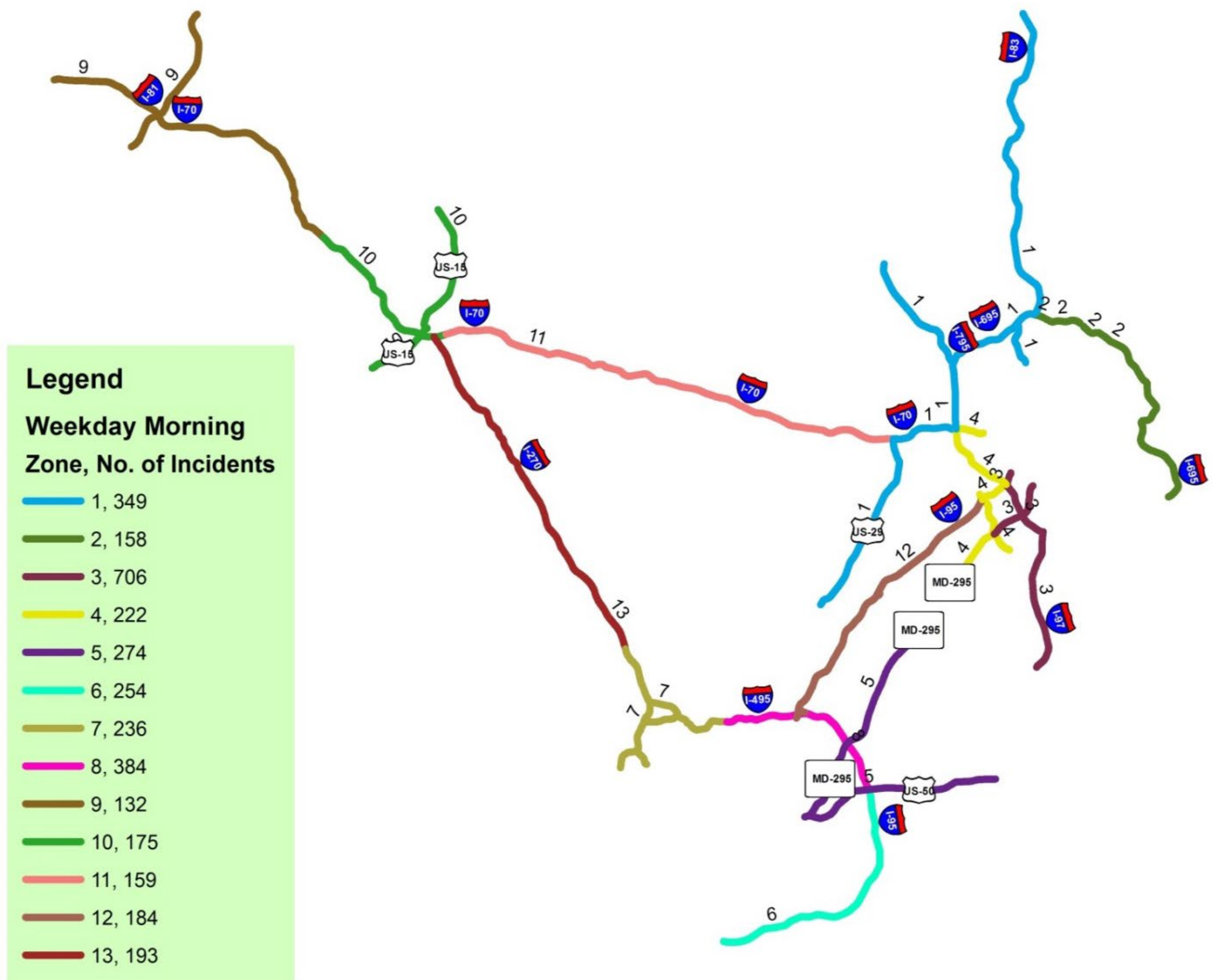


Figure 13 Beat Configuration for the Weekday Morning Shift

Table 10 – 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**

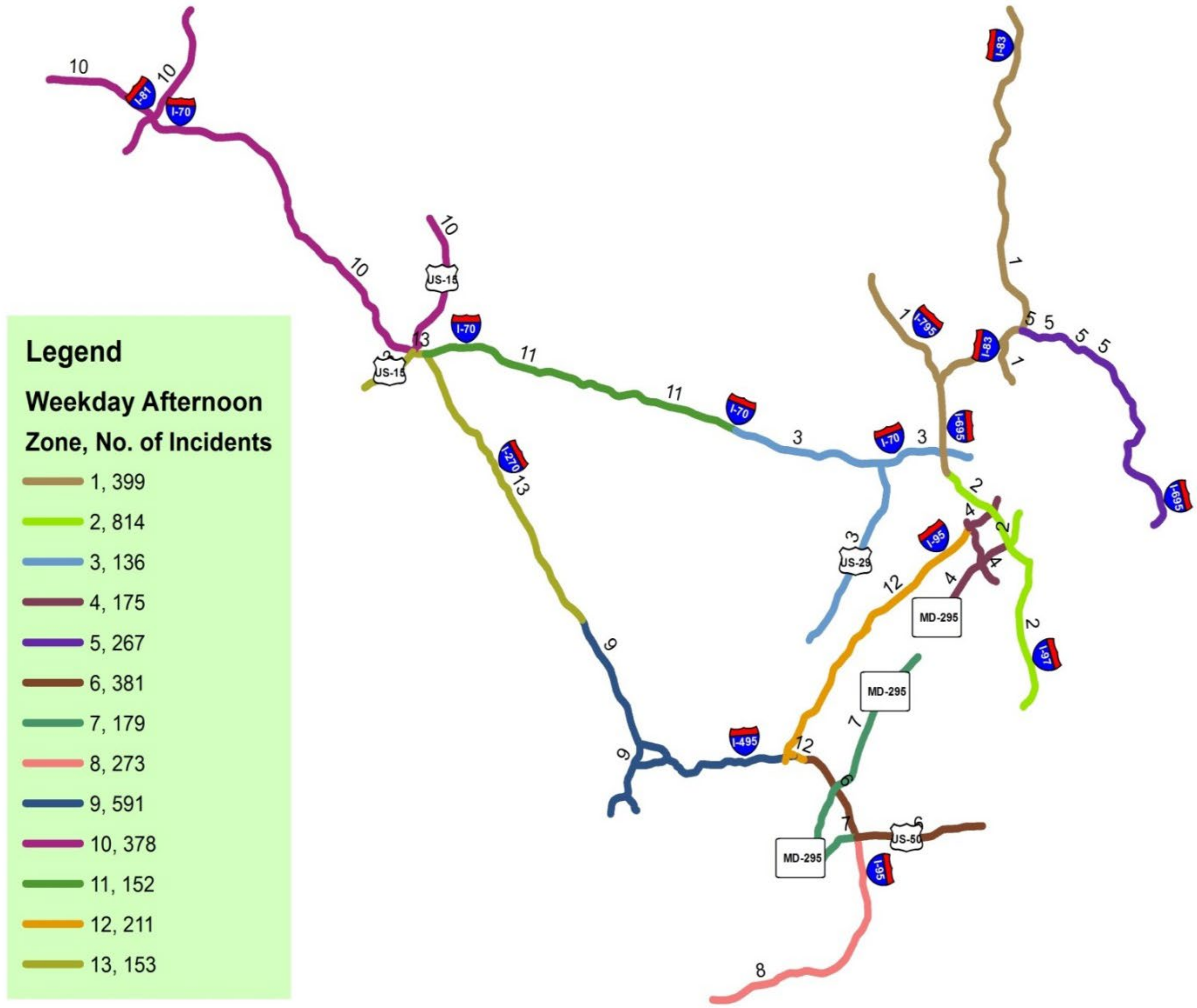


Figure 14 Beat Configuration for the Weekday Afternoon Shift

Table 11 – 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**

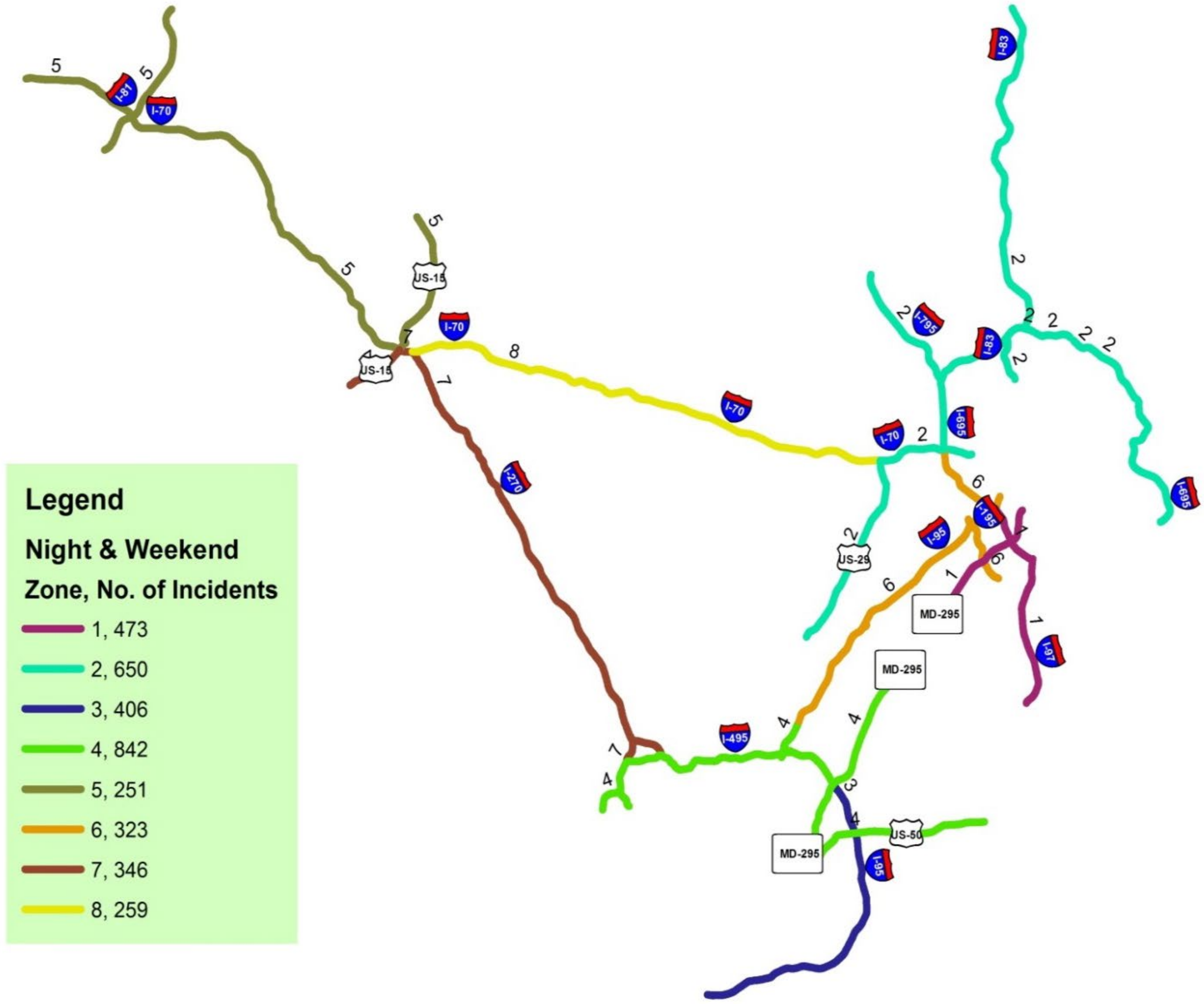


Figure 15 Beat Configuration for the Night and Weekend Shift

Table 12 – 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 13. 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 13 - Performance Measures

Description	Weekday Morning	Weekday Afternoon	Night and Weekend Shift	Total
Shift Duration (hours per year)	2080	2080	4576	8736
Average Patrolling Response Time [including detection and verification times] (min)	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

4.3.3 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.

A. 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 16 and Figure 17, 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 14 and Table 15, 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.

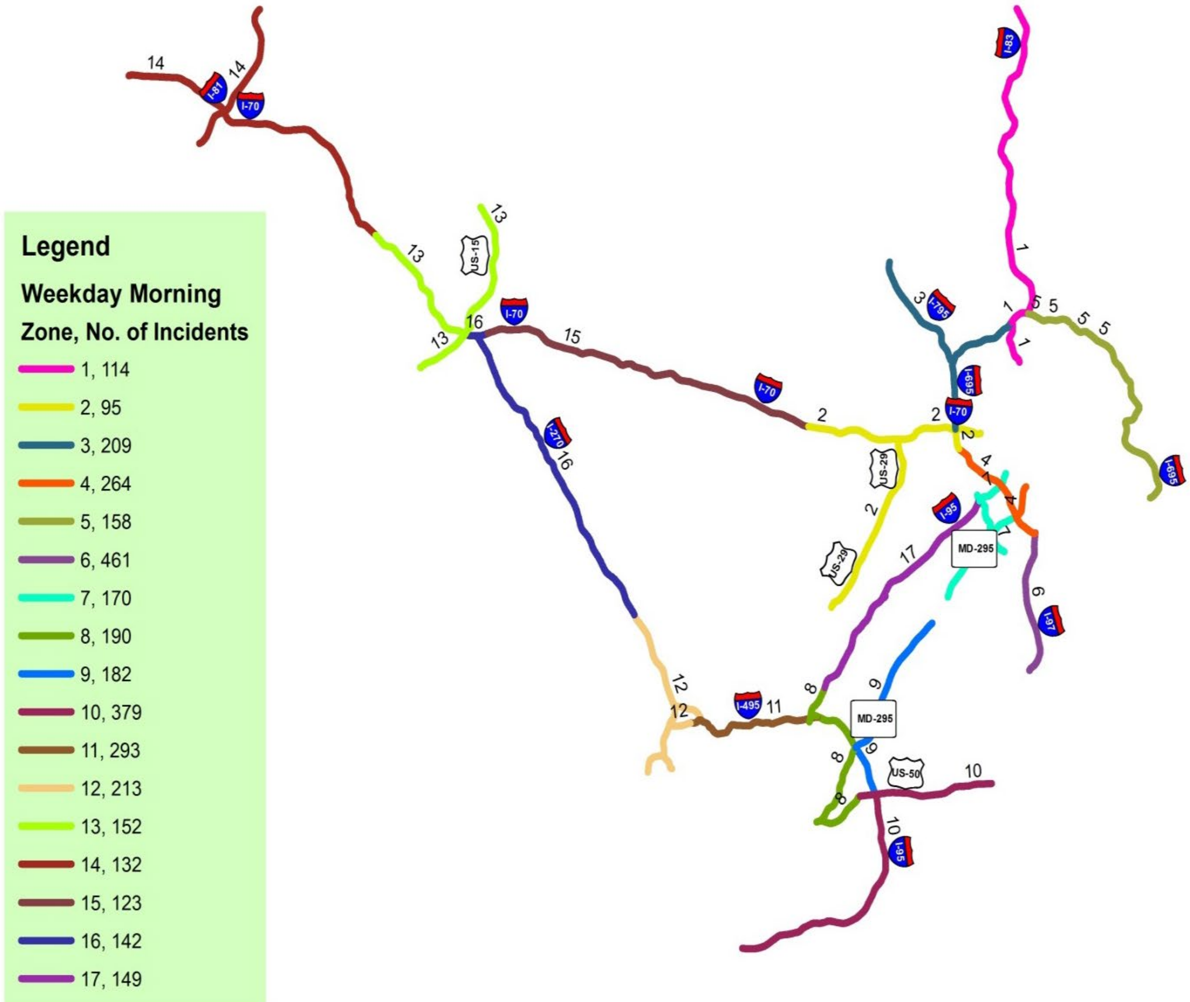


Figure 16 Beat Configuration for the Weekday Morning Shift - VOT=30$/hr

Table 14 – 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**

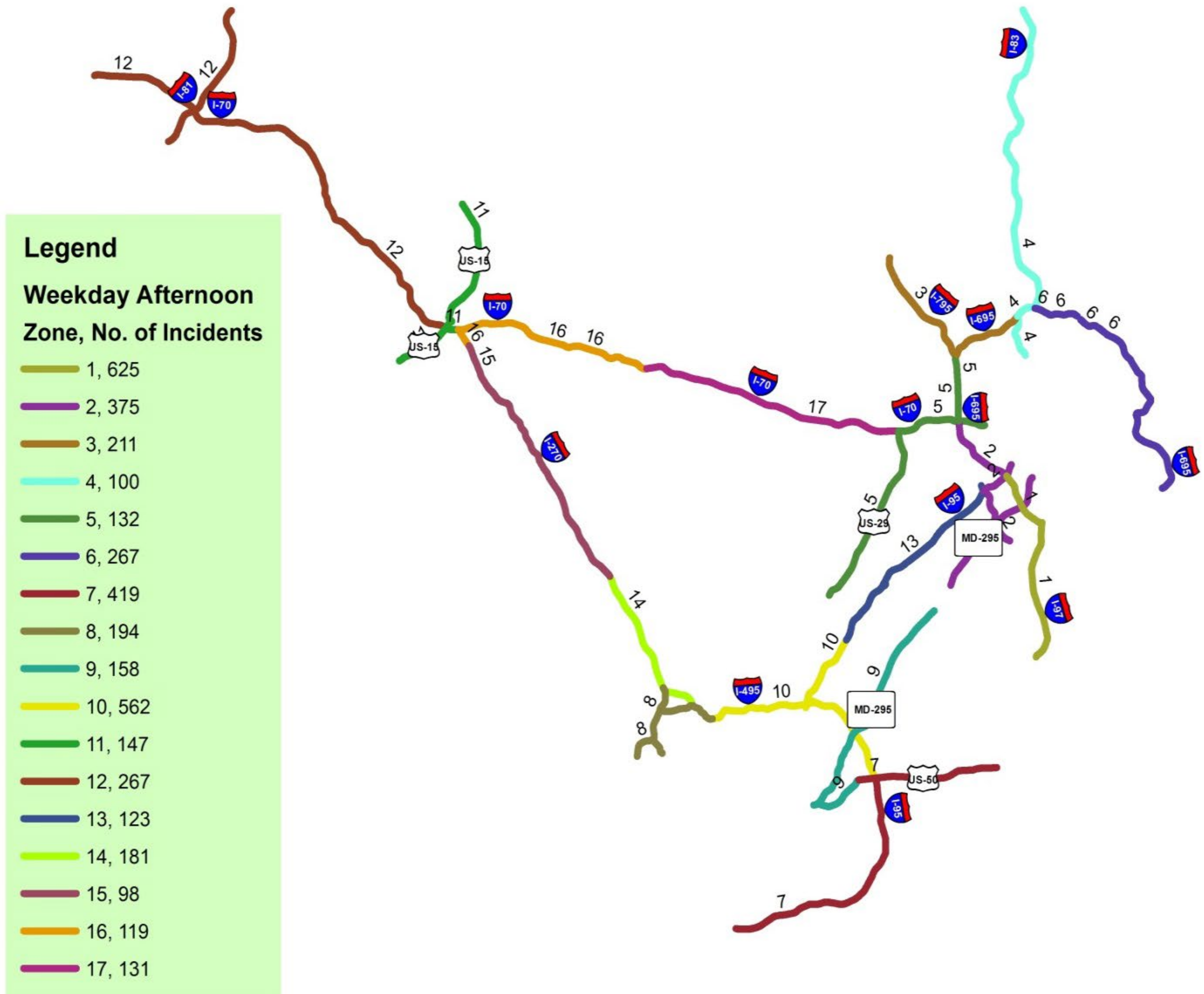


Figure 17 Beat Configuration for the Weekday Afternoon Shift - VOT=30$/hr

Table 15 - 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**

B. 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 18 and Figure 19, respectively. Also, the beat configuration for the weekday afternoon shift based on the maximum number of three trucks per beat is shown in Figure 20. 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 16. 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 17. 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 17, 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.

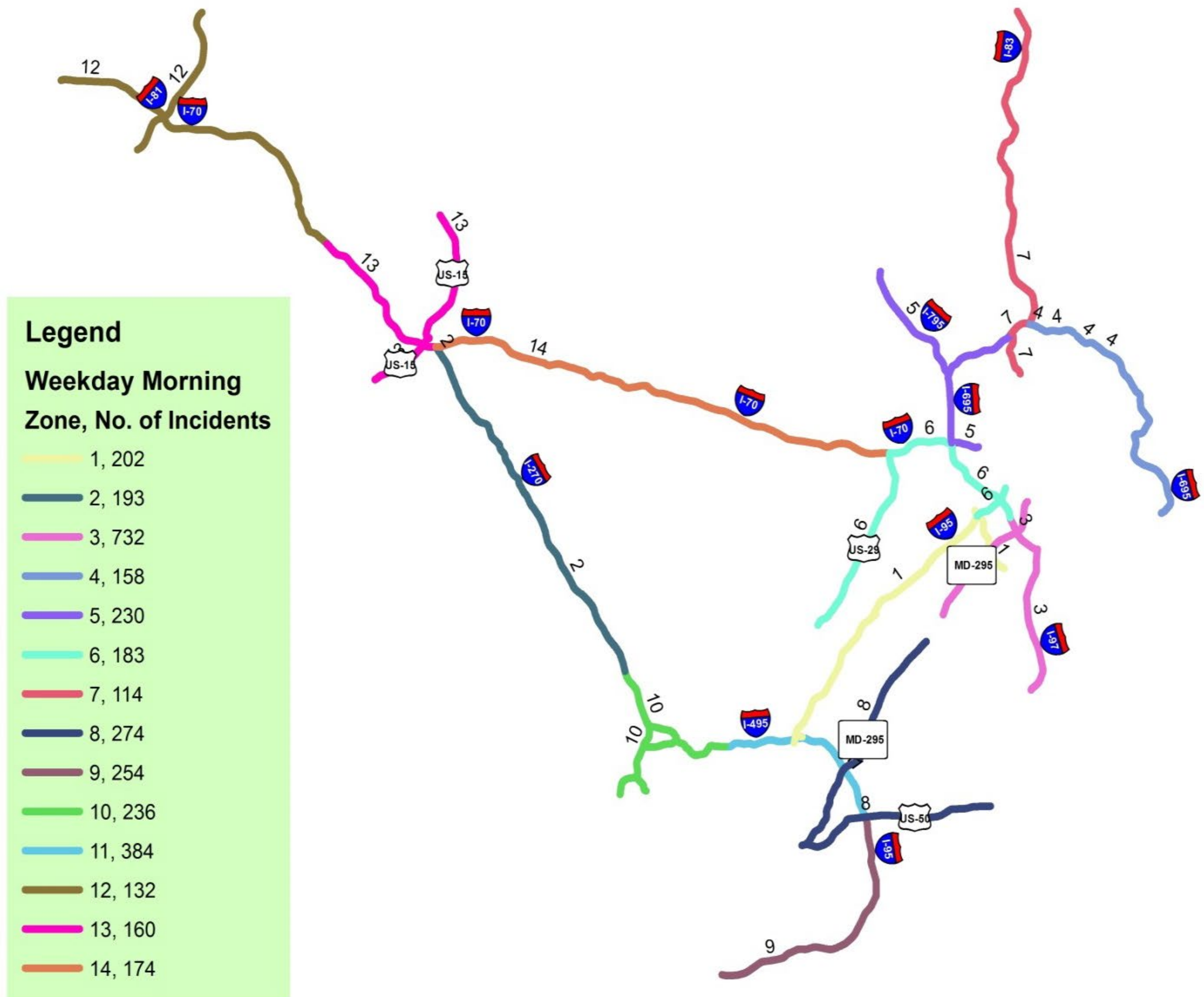


Figure 18 Beat Configuration for the Weekday Morning Shift – One Truck per Beat

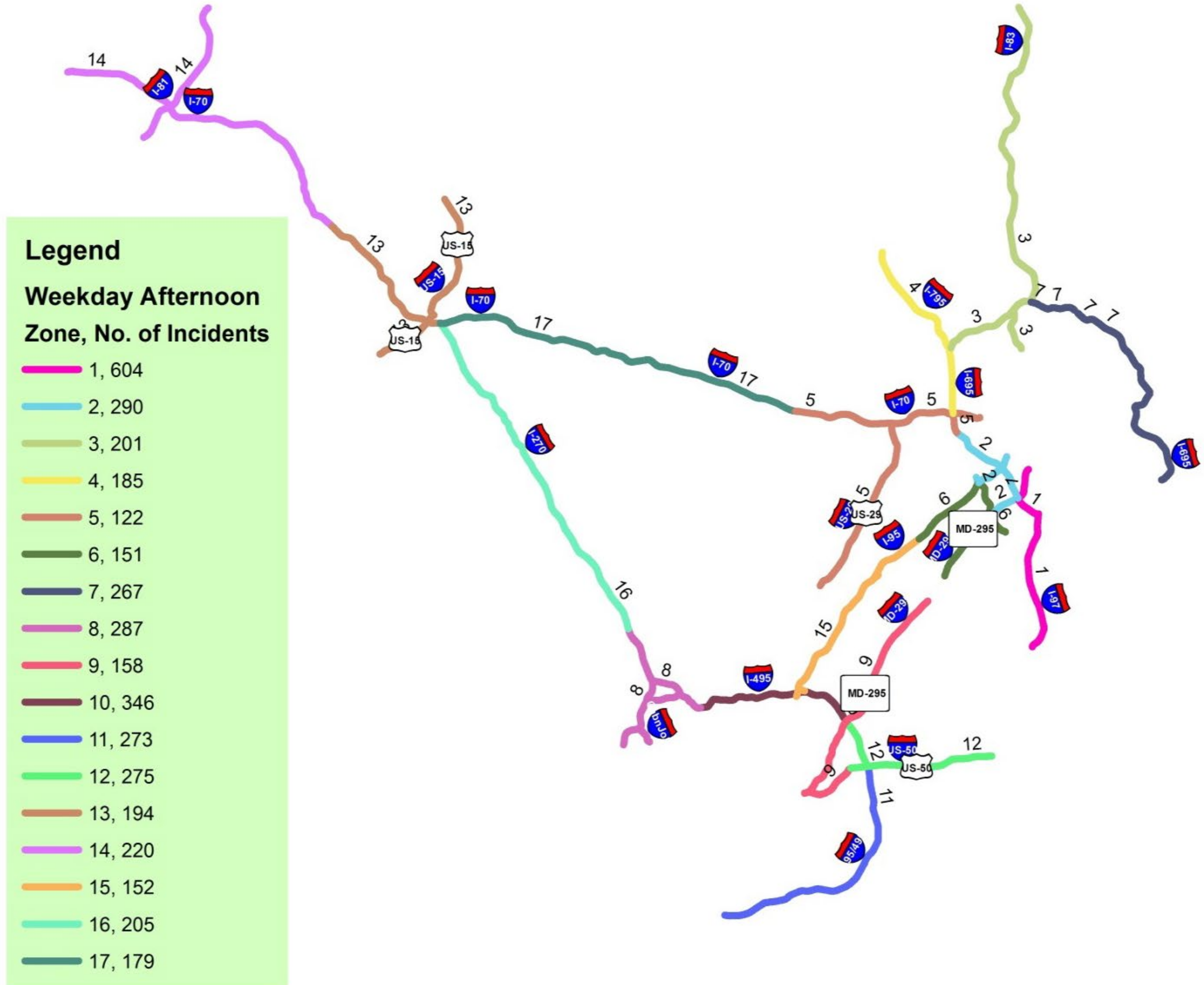


Figure 19 Beat Configuration for the Weekday Afternoon Shift – One Truck per Beat

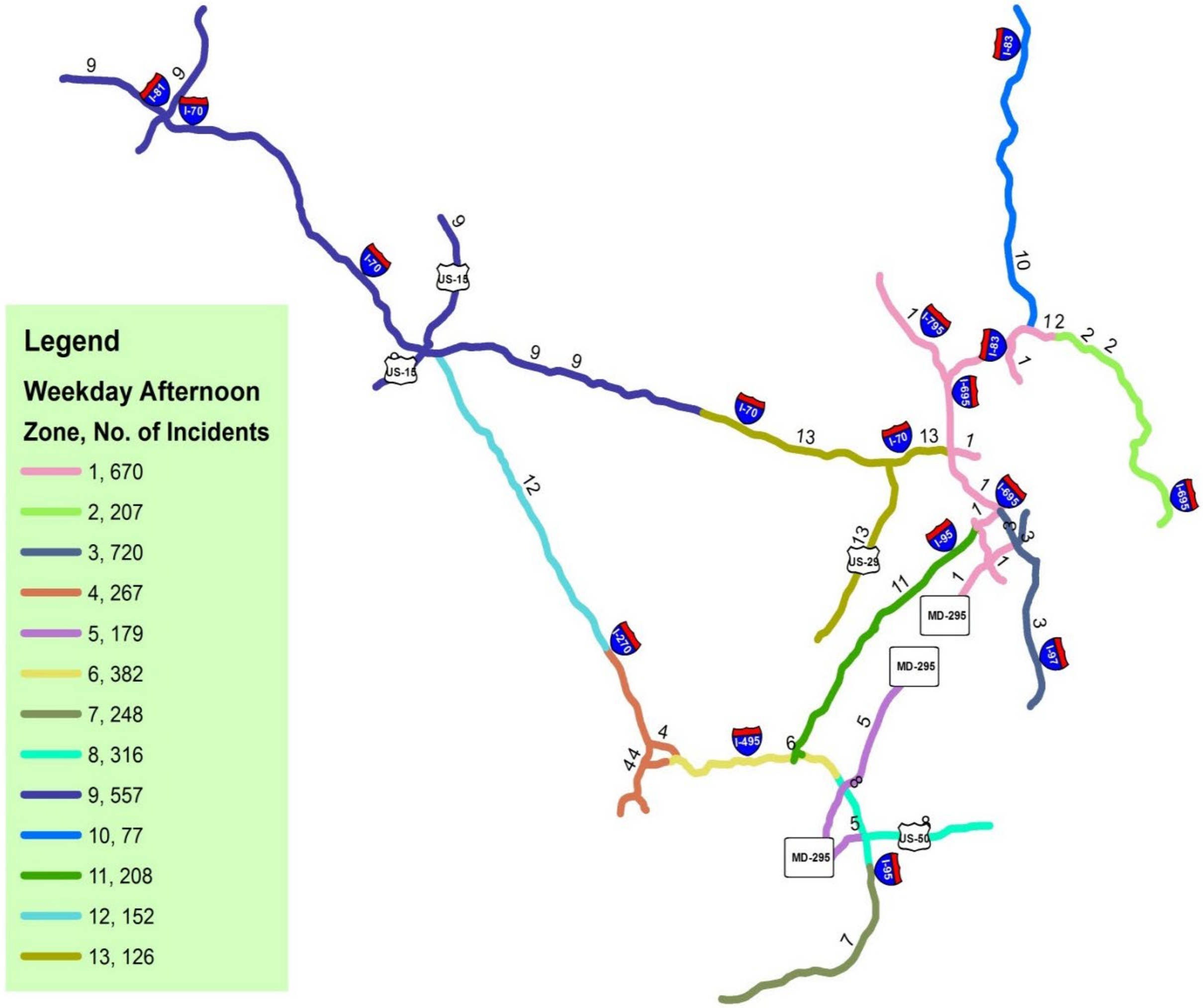


Figure 20 Beat Configuration for the Weekday Afternoon Shift – Maximum Three Trucks per Beat

Table 16 - 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 17 - Maximum Number of Trucks per Beat

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

C. 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 21 and Figure 22, respectively. Also, the fleet size and fleet allocation for the weekday morning and weekday afternoon shifts are listed in Table 18 and Table 19, 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.

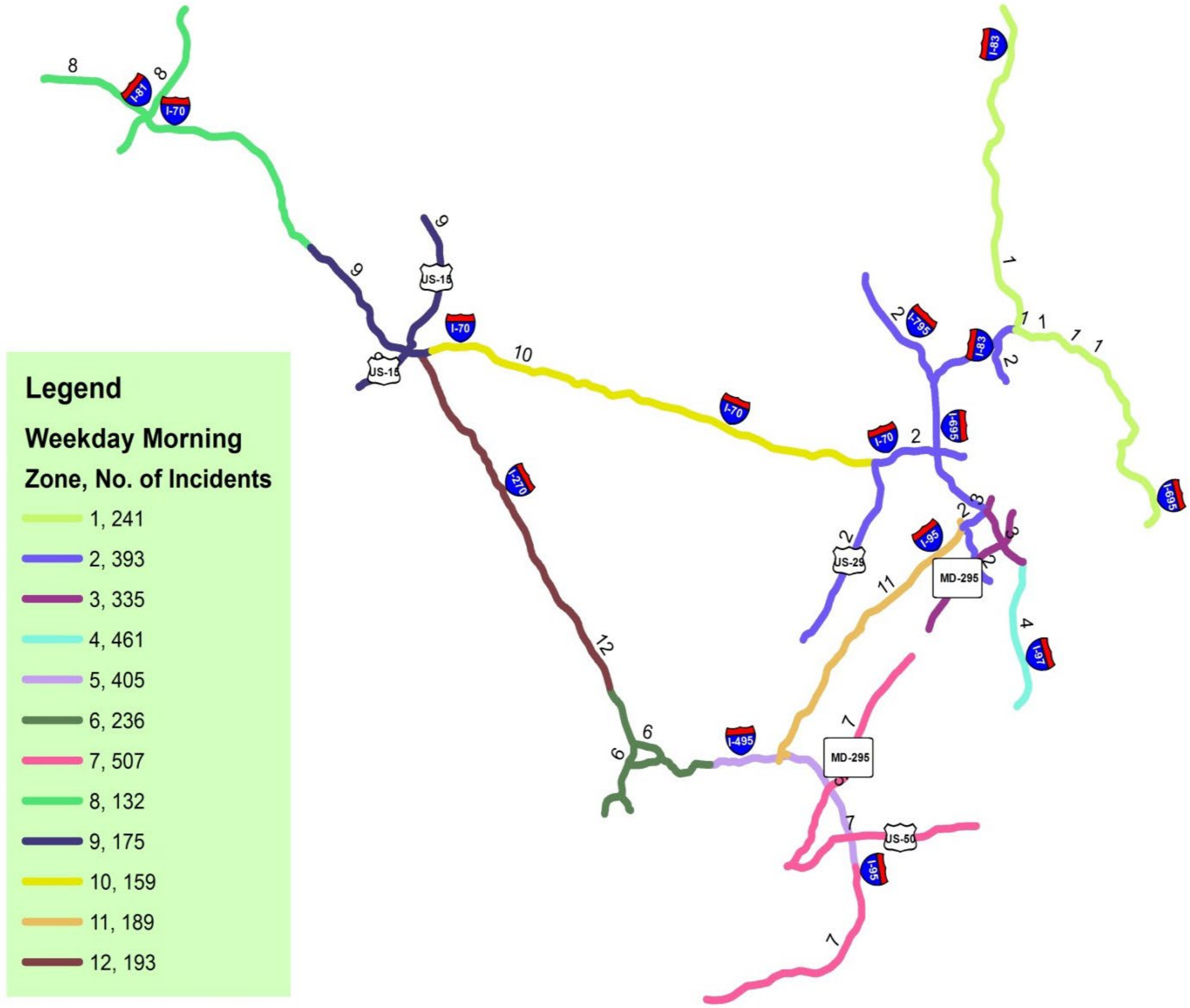


Figure 21 Beat Configuration for the Weekday Morning Shift - 55 MPH

Table 18 - 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**

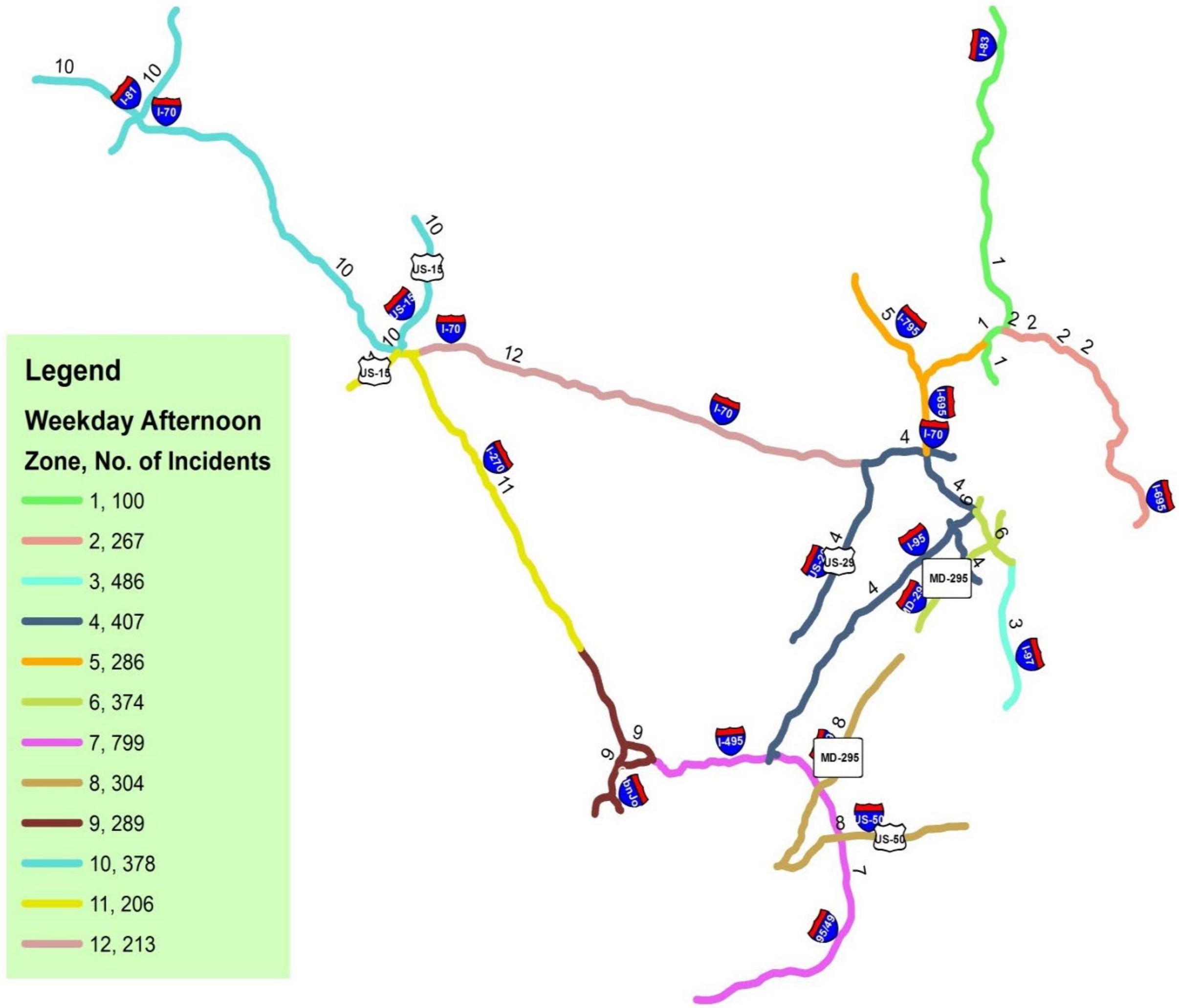


Figure 22 Beat Configuration for the Weekday Afternoon Shift - 55 MPH

Table 19 - 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**

4.3.4 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 23 through Figure 25, respectively. Also, for each shift, the details regarding links covered by each beat are presented in Table 20 to Table 22. 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 Table 20 through Table 22. 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 23. 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 23. 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.

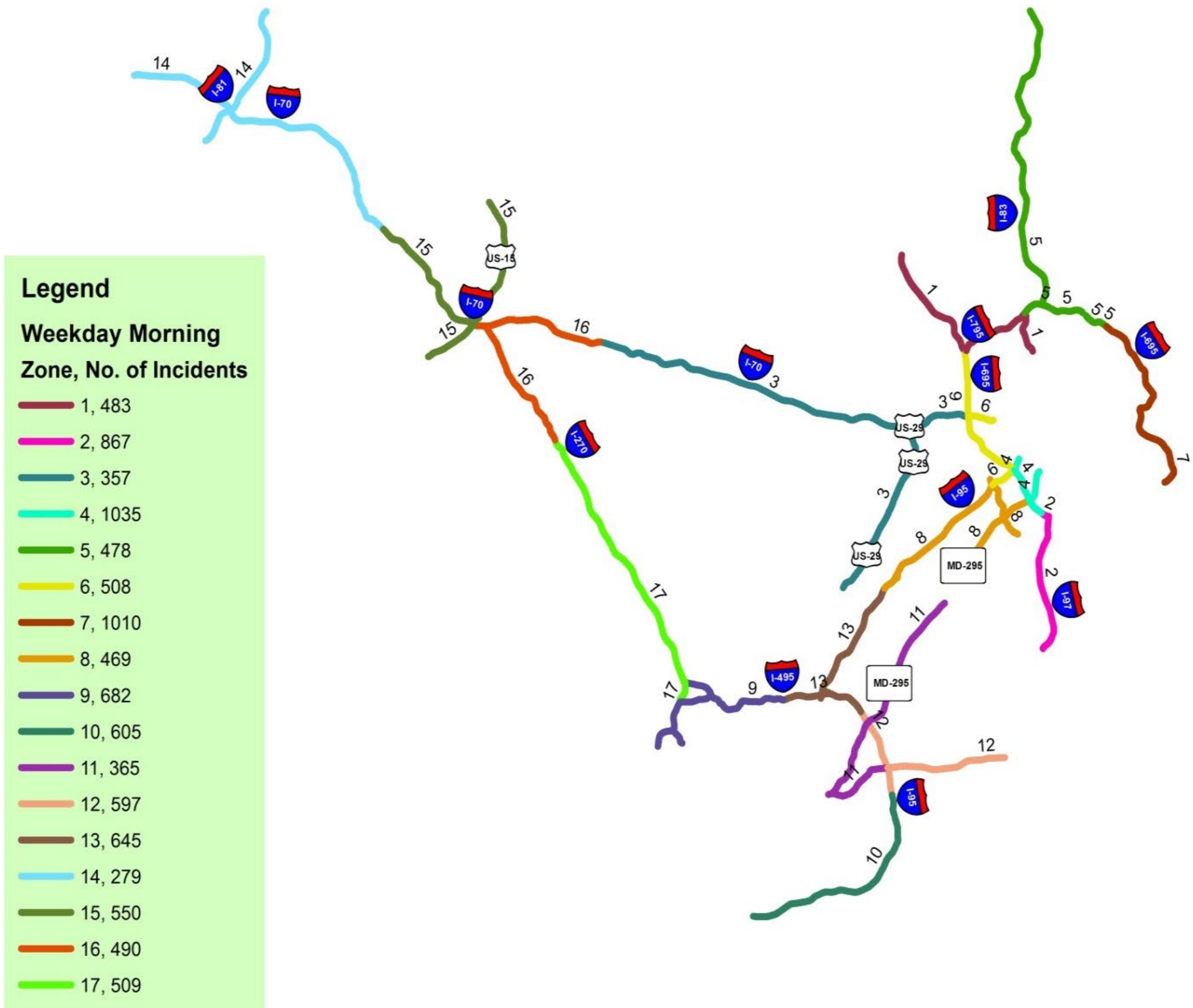


Figure 23 Non-Patrolling Detection: Beat Configuration for the Weekday Morning Shift

Table 20 - 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

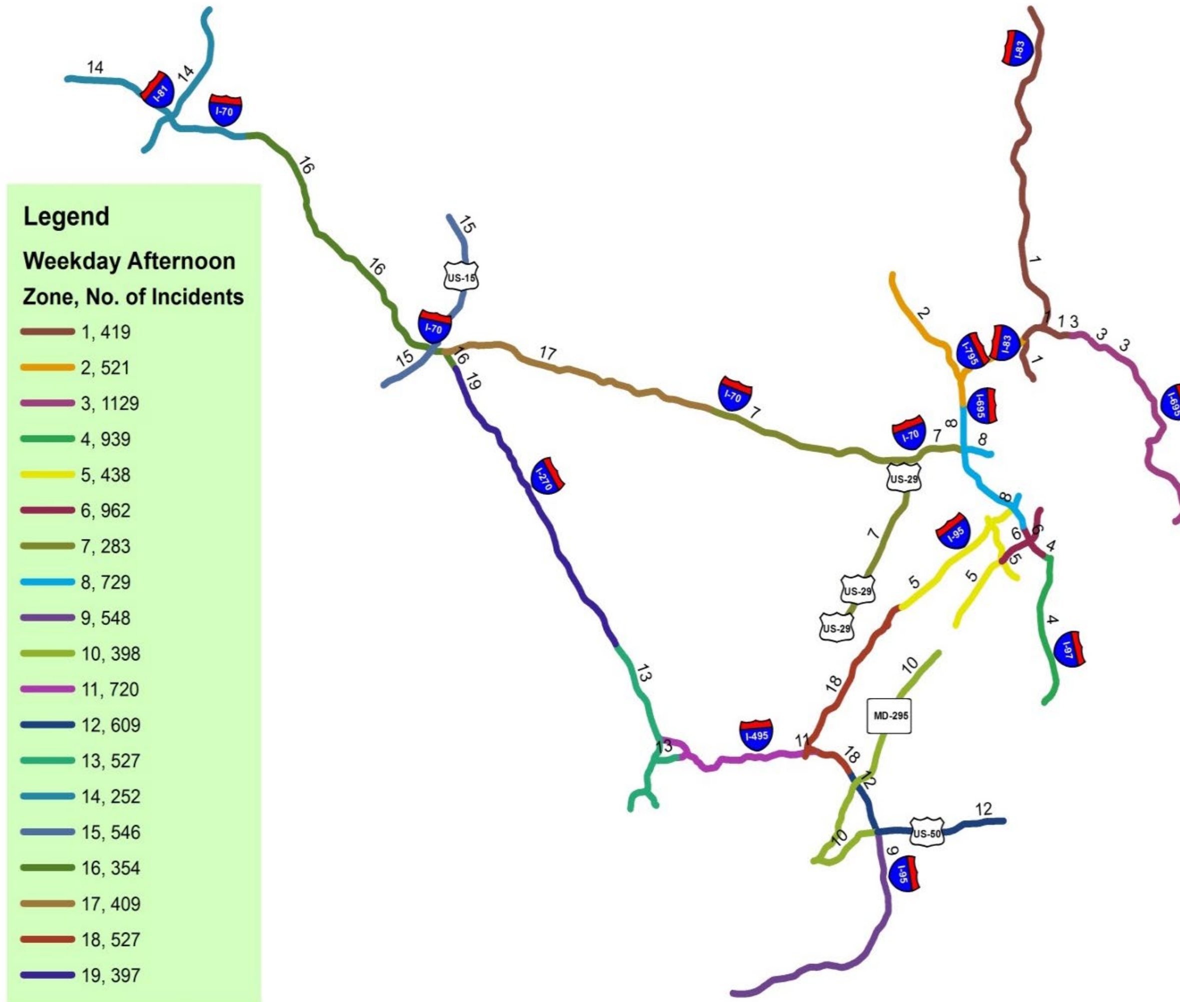


Figure 24 Non-Patrolling Detection: Beat Configuration for the Weekday Afternoon Shift

Table 21 - 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

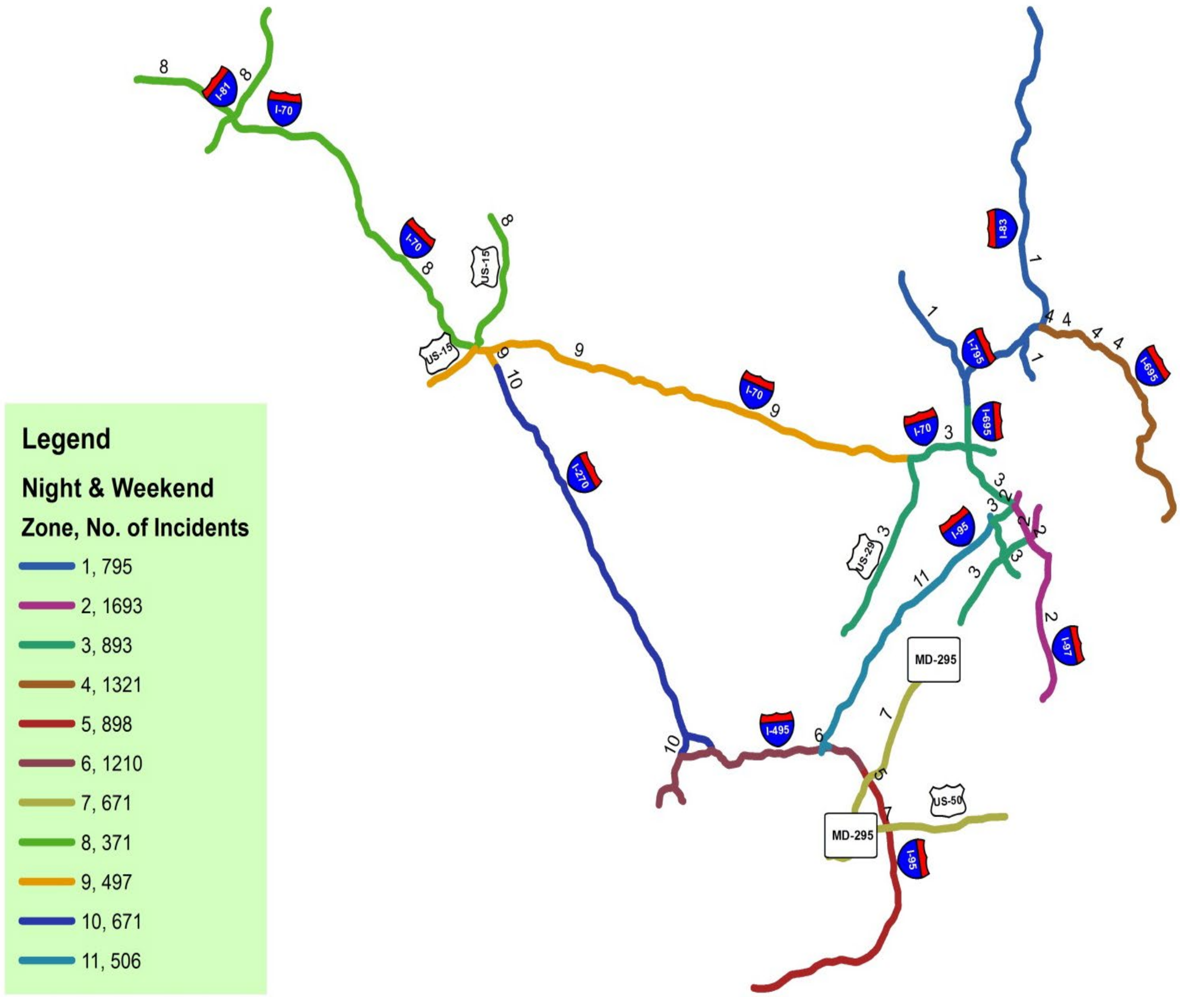


Figure 25 Non-Patrolling Detection: Beat Configuration for the Night and Weekend Shift

Table 22 - Non-Patrolling Detection: Beat Configuration for the Night and Weekend Shift

Beat	Covered Links	Number of Incidents
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, 96, 97	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 23 - 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

4.3.5 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 Figure 26 through Figure 30.

Performance measures for the sensitivity analysis results, based on the mentioned average response speeds for each shift, are summarized in Table 24. 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.

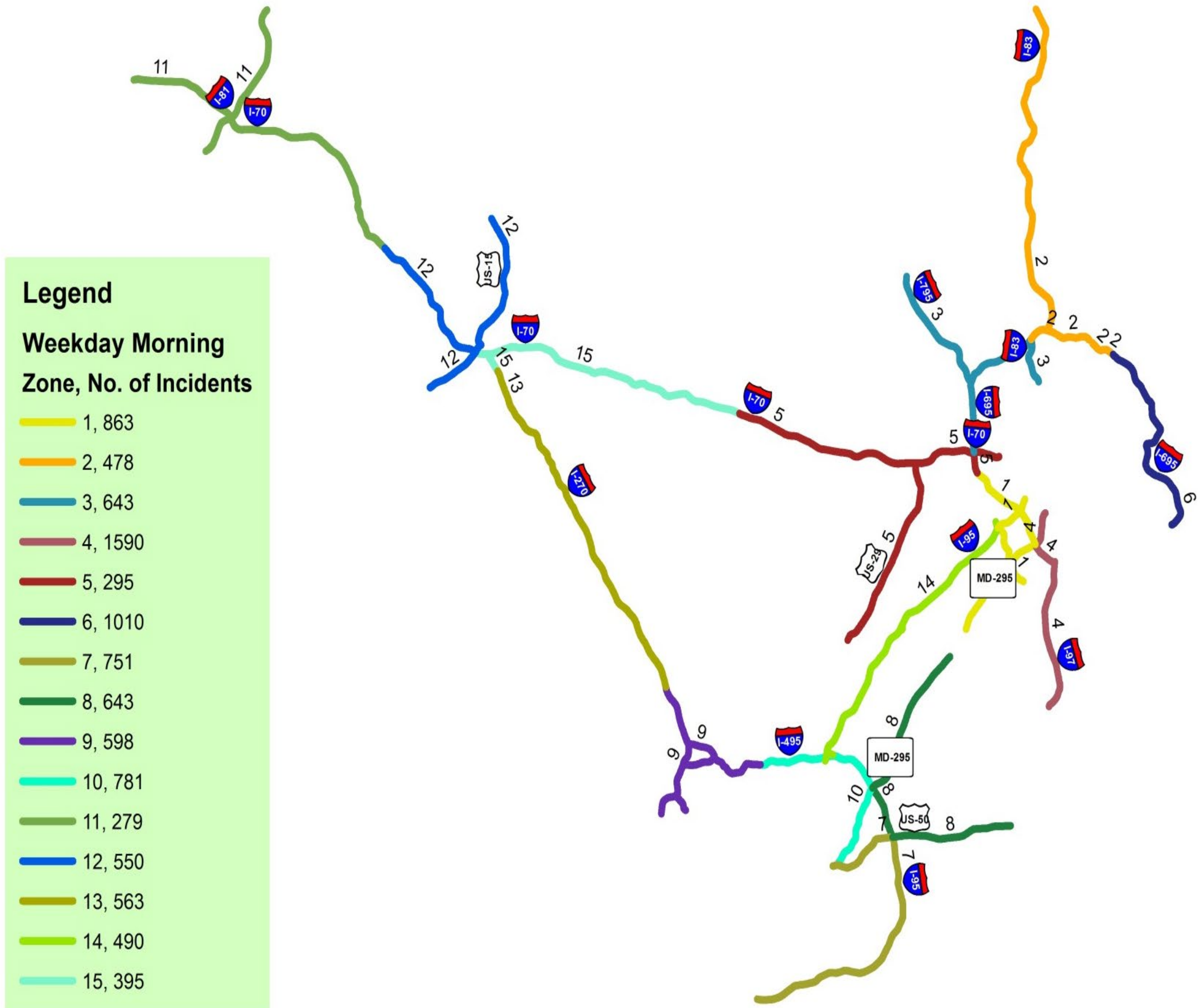


Figure 26 Non-Patrolling Detection: Beat Configuration for the Weekday Morning Shift – 55 MPH

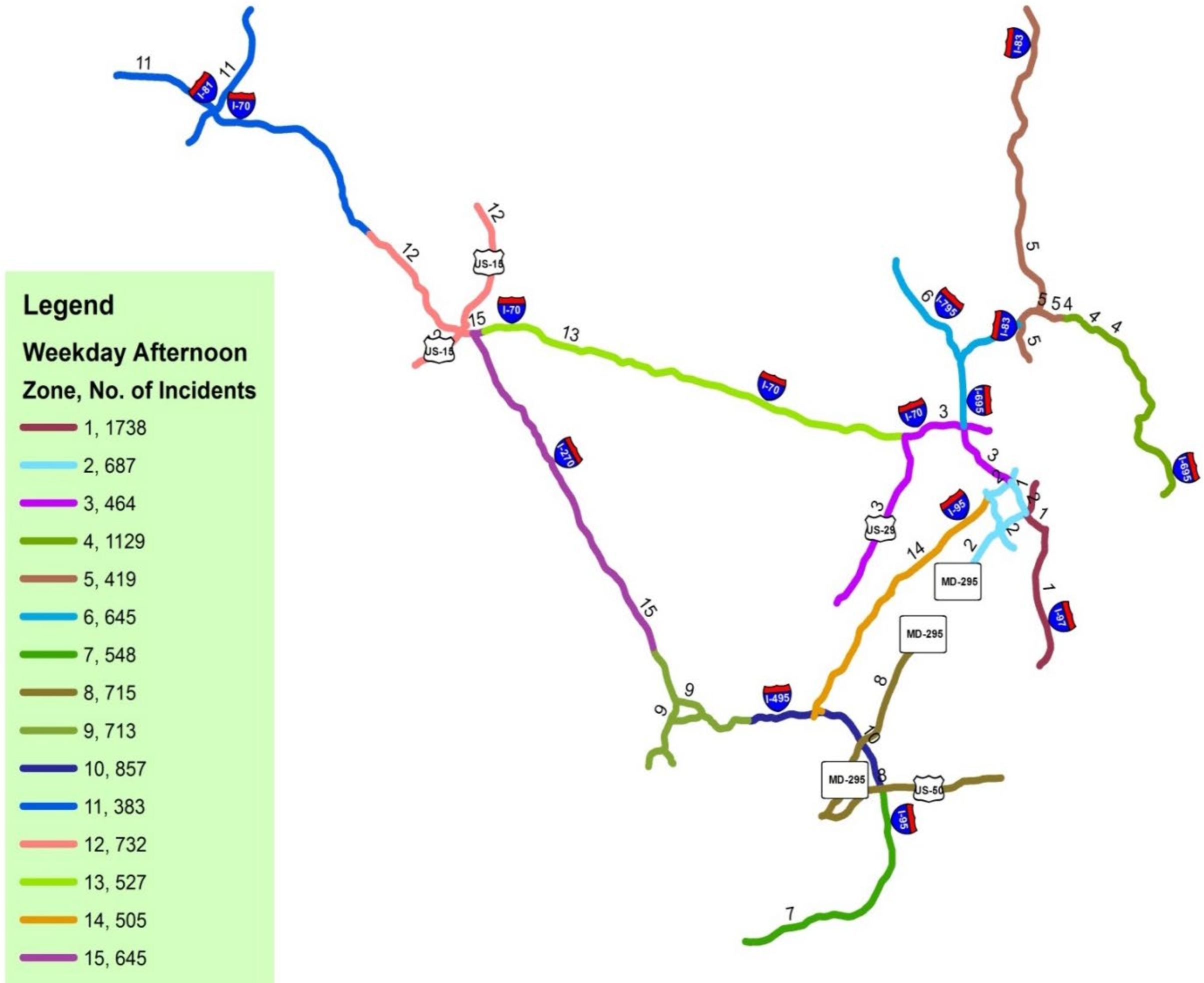


Figure 27 Non-Patrolling Detection: Beat Configuration for the Weekday Afternoon Shift – 55 MPH

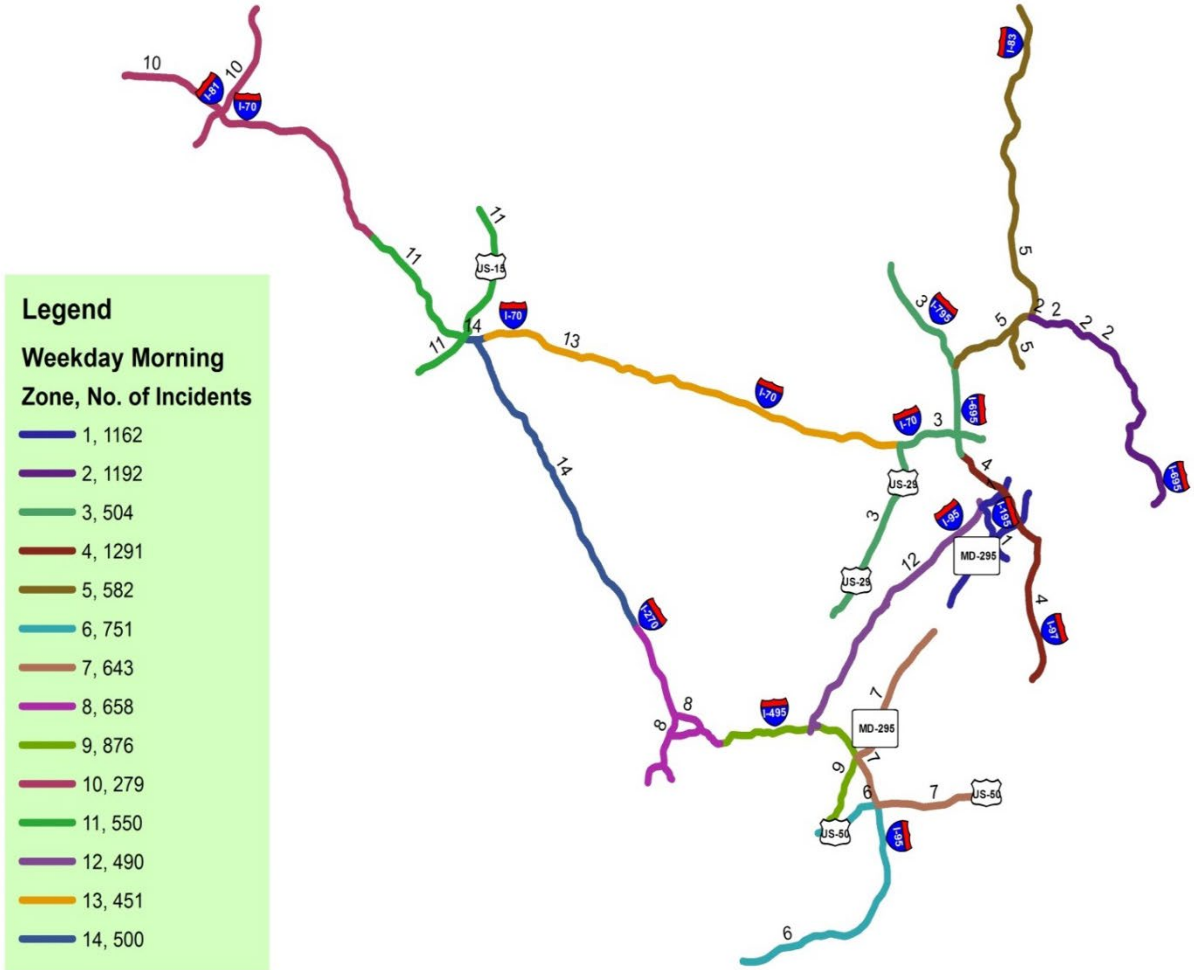


Figure 28 Non-Patrolling Detection: Beat Configuration for the Weekday Morning Shift – 65 MPH

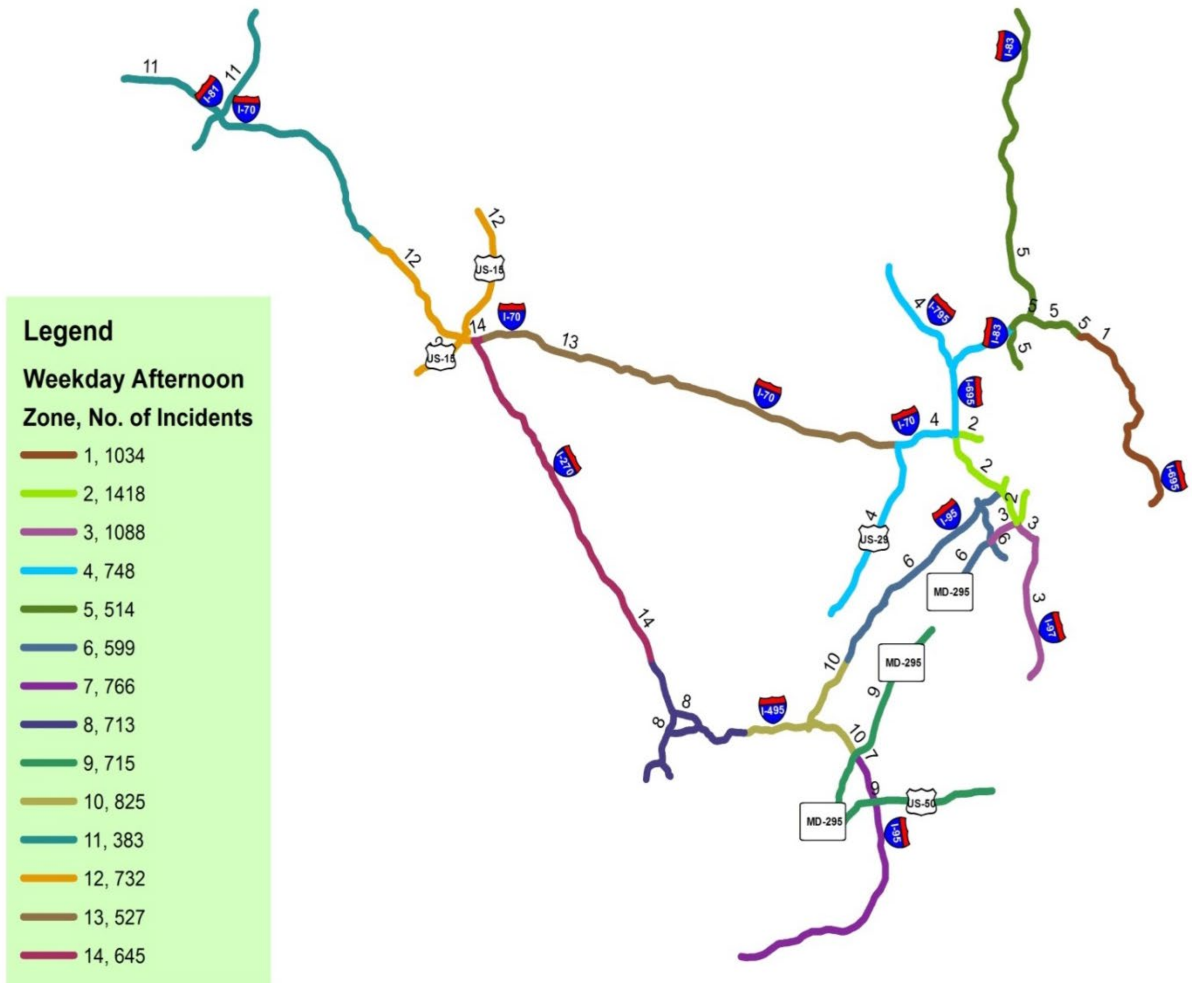


Figure 29 Non-Patrolling Detection: Beat Configuration for the Weekday Afternoon Shift – 65 MPH

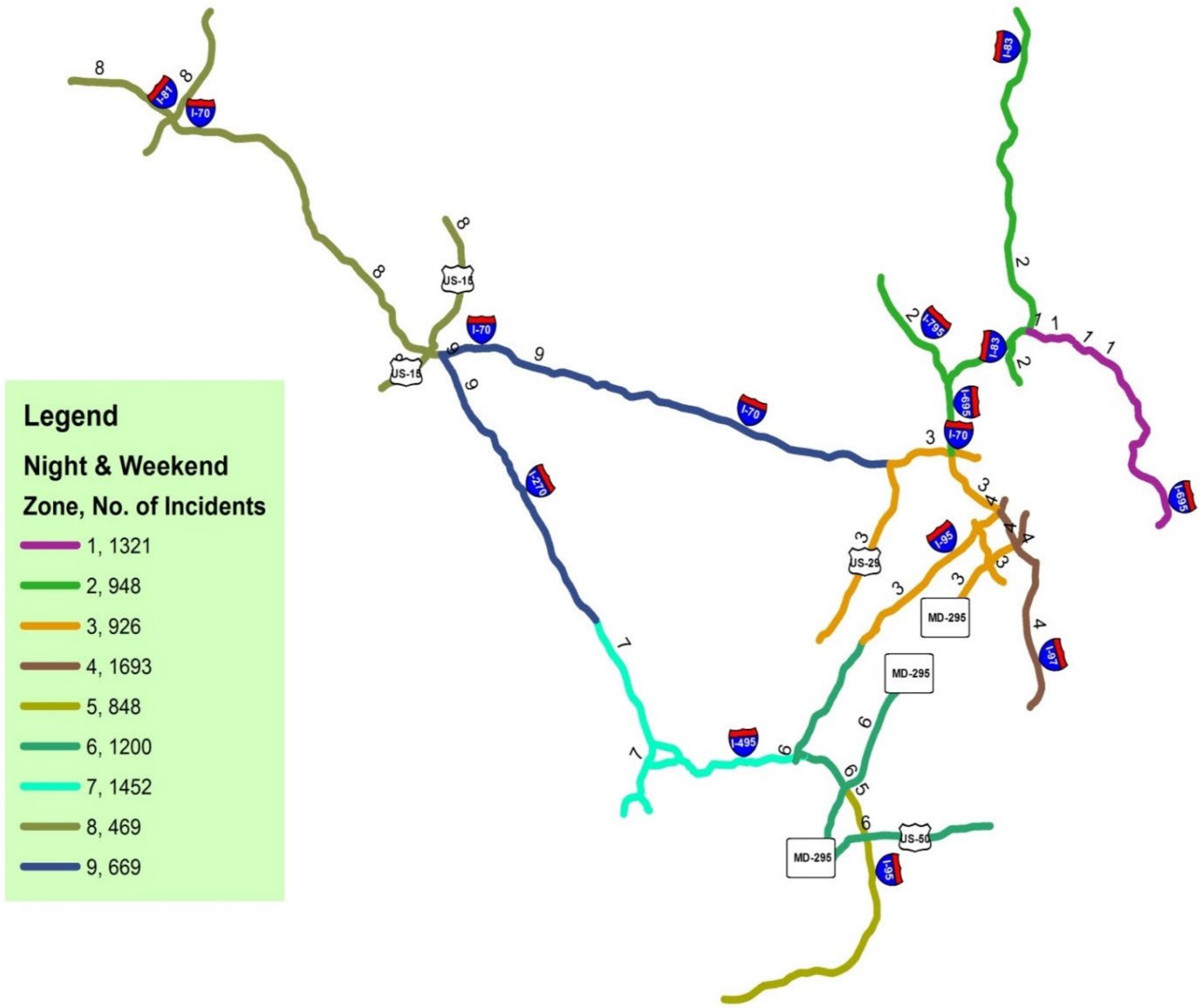


Figure 30 Non-Patrolling Detection: Beat Configuration for the Night and Weekend Shift – 65 MPH

Table 24 - 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 31 and Figure 32, respectively.

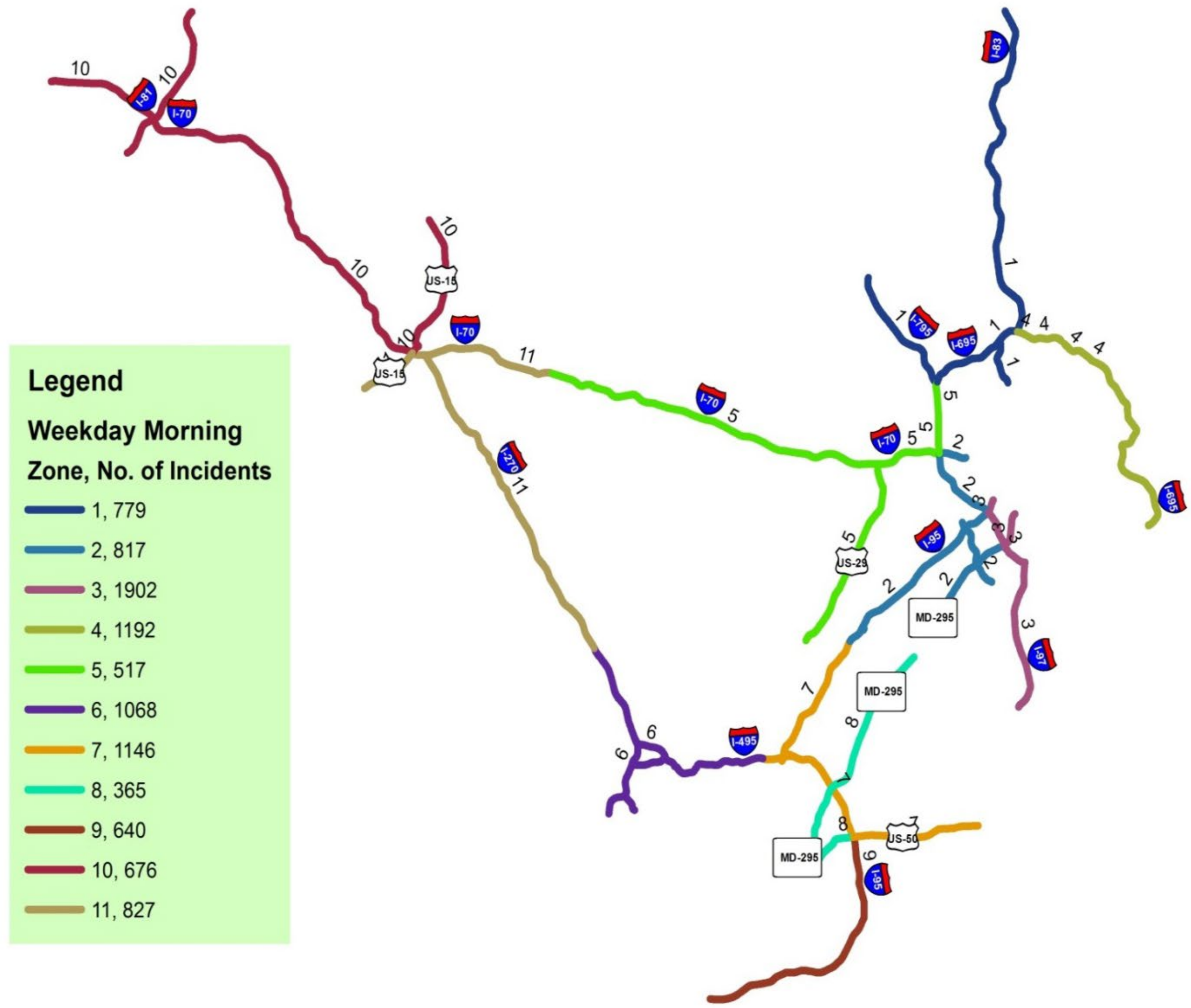


Figure 31 Non-Patrolling Detection: Beat Configuration for the Weekday Morning Shift – Pre-Specified 11 Beats

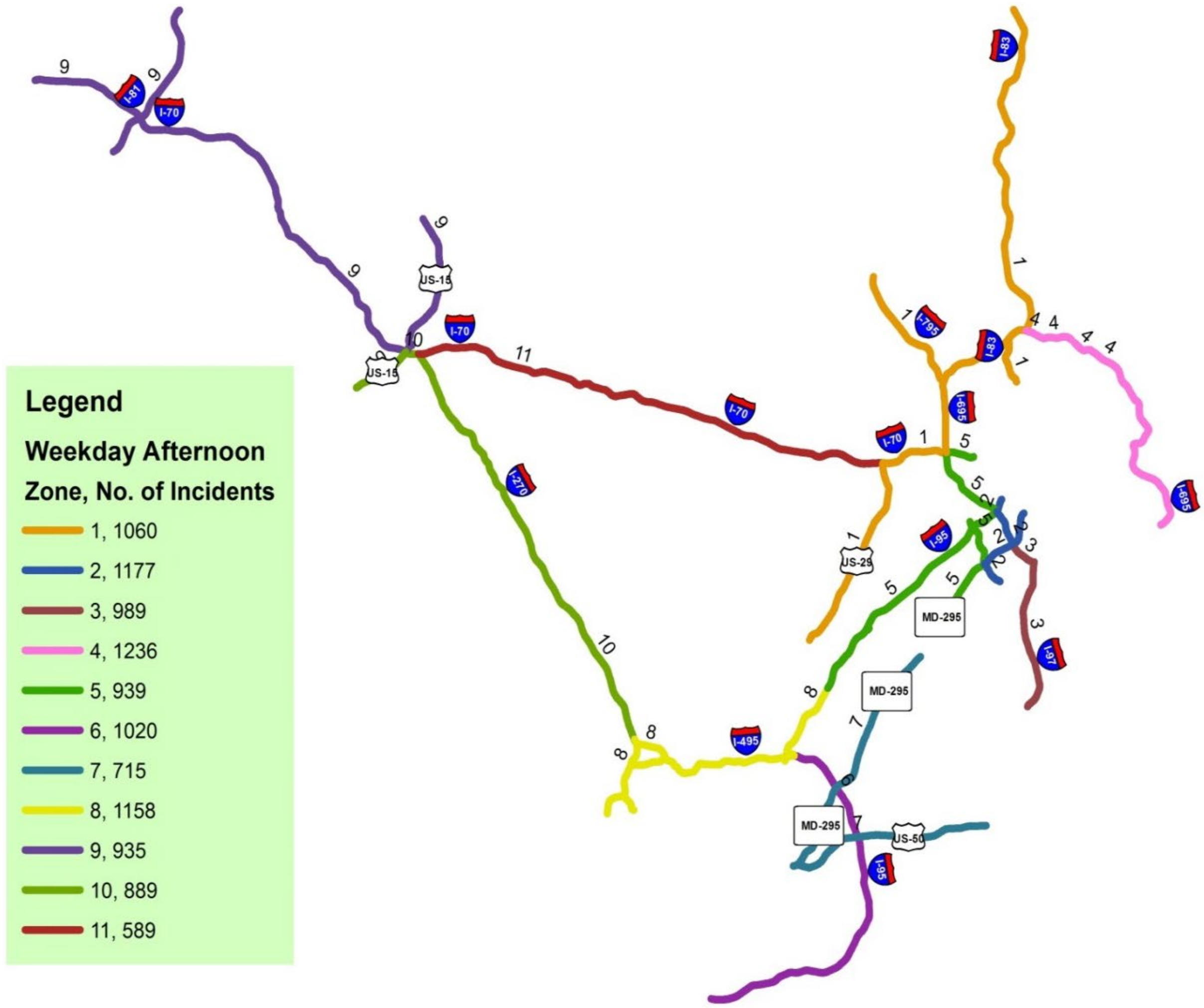


Figure 32 Non-Patrolling Detection: Beat Configuration for the Weekday Afternoon Shift: Pre-Specified 11 Beats

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 33, 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 25. These results are based on assuming constant headway between patrol units on the same beat.

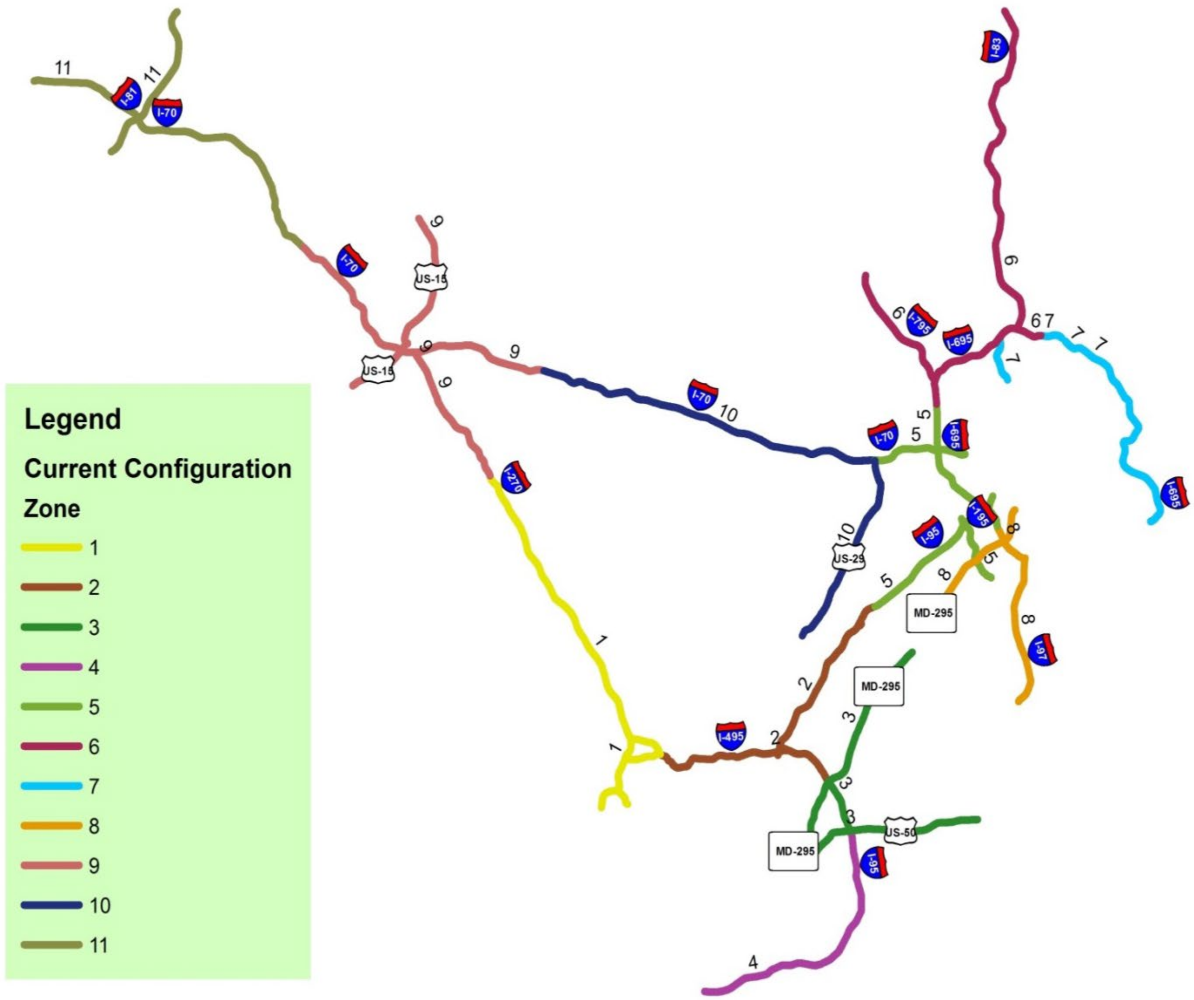


Figure 33 CHART Current Beat Configuration

Table 25 – 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**

4.3.6 Conclusions

The results of our analysis specify 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 results, 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 here. 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.

4.4 Analysis for 2016 Data

As explained in section 4.2, for the analysis of 2016, an updated dataset was used, and the network structure was modified. The incident data during the year 2016 was then studied to determine the optimal zone design. Based on the historical log data, the number of incidents that were responded by CHART patrol units is estimated to be 30,873 incidents during the year of 2016. Please note that this only 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 of this boundary limit. Incidents that did not occur on the patrol routes (still within the 10 miles vicinity) were assigned to the closest patrol route to the incident location. This increased the number of incidents assigned to the patrol boundary routes. The dataset includes incidents that CHART units responded to but were not necessarily detected by CHART.

For the analysis purposes, the CHART network is divided into 115 two-way segments, as was previously shown in Figure 11. Since the CHART patrol service network has slightly changed from 2015 to 2016, in Table B2, we are providing not only the link numbers for the new 2016 network, but also the corresponding link numbers in 2015 network.

Similarly to the 2015 analysis, we design the network with the objective to minimize the total response time considering the operation cost. For this analysis, based on operational facts, it is assumed that one patrol unit could be assigned to every single zone. We also assume the same hourly cost of each truck as in 2015 ($50 per hour) and use the same shifts: Weekday Mornings (5 AM- 1 PM), Weekday Afternoons (1 PM – 9 PM), and Weekday Nights (9 PM – 5 AM) and Weekends. For one year of operation, we assume again 2080 hours for the morning and the afternoon shifts during weekdays and 4576 hours during the night and weekend shifts. Finally, the average value of time is $20 per hour, as provided by CHART officials.

4.4.1 Results

We solved the problem for three cases and zone configurations for the weekday morning shift, weekday afternoon shift, and night and weekend shift are presented in Figure 34 through Figure 36. Also, for each shift, the details regarding links covered by each zone are presented in Tables 3 through 5. The results indicate 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 anticipated, the night and weekend shifts require less number of patrol units, compared to the weekday morning and weekday afternoon shifts, because of lower incident frequencies. Ten patrol units are needed to patrol during the night and weekend shift. Please note that, for each shift, the number of incidents per each zone is provided in Tables 3 through 5. Details regarding the number of incidents per each link, during each shift, are also presented in the appendix. 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 6. The results 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 the table. According to the results, the total operations cost is estimated to be $6,032,000 for one year of full-time operation. Also, the total response time for the designed network is estimated to be about 7020 hours for responding to 30,873 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 shift) and obviously will decrease if patrol units can drive faster.

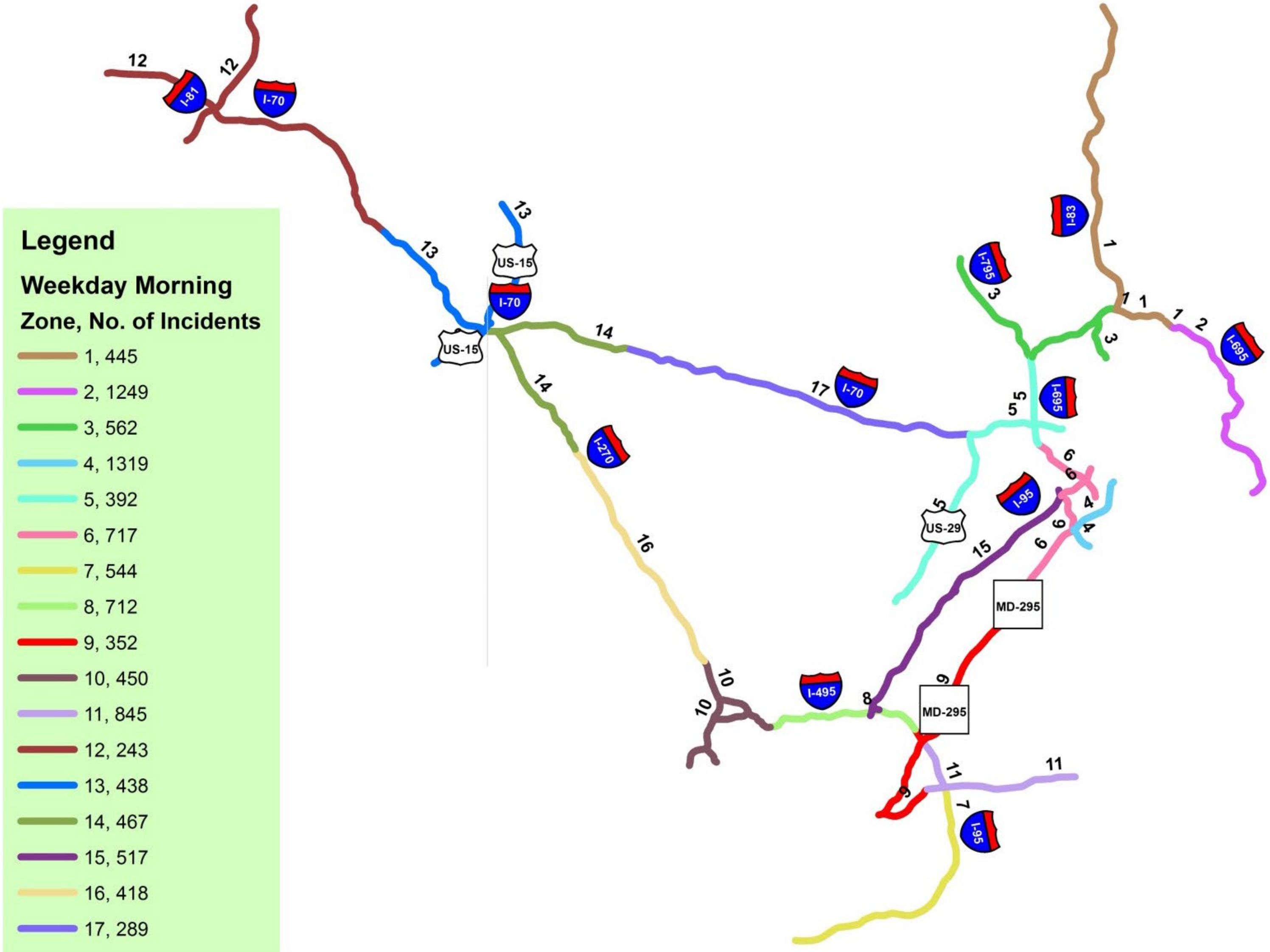


Figure 34 Zone Configuration for the Weekday Morning Shift

Table 26 Zone Configuration for the Weekday Morning Shift

Zone	Covered Links	No. of Incidents
1	97, 98, 99, 100, 101, 108, 109, 110	445
2	102, 103, 104, 105, 106, 107	1249
3	95, 96, 111, 115	562
4	70, 73, 74	1319
5	16, 17, 83, 84, 85, 86, 87, 88, 92, 93, 94	392
6	69, 71, 72, 81, 82, 90, 91	717
7	48, 49, 50, 51, 52, 53, 54, 55	544
8	38, 39, 40, 41, 42, 43, 44	712
9	45, 56, 57, 63, 64, 65, 66, 67, 89	352
10	29, 30, 31, 32, 33, 34, 35, 36, 37, 114	450
11	46, 47, 58, 59, 60, 61, 62	845
12	3, 4, 5, 112, 113	243
13	1, 2, 6, 7	438
14	8, 9, 10, 18, 19, 20	467
15	68, 75, 76, 77, 78, 79, 80	517
16	21, 22, 23, 24, 25, 26, 27, 28	418
17	11, 12, 13, 14, 15	289

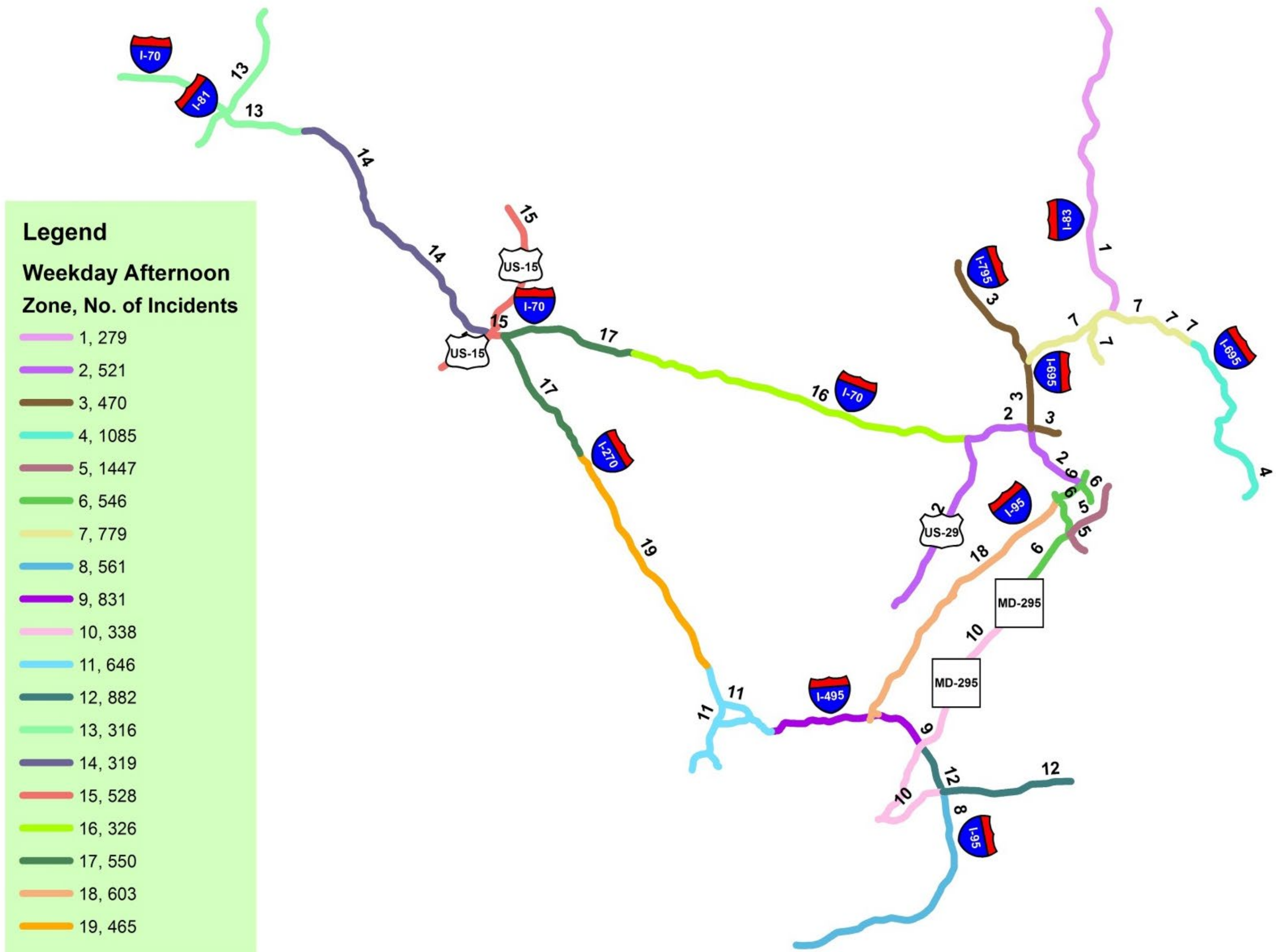


Figure 35 Zone Configuration for the Weekday Afternoon Shift

Table 27 Zone Configuration for the Weekday Afternoon Shift

Zone	Covered Links	No. of Incidents
1	108, 109, 110	279
2	16, 83, 84, 85, 86, 87, 88, 91, 92	521
3	17, 93, 94, 115	470
4	104, 105, 106, 107	1085
5	70, 73, 74	1447
6	68, 69, 71, 72, 81, 82, 89, 90	546
7	95, 96, 97, 98, 99, 100, 101, 102, 103, 111	779
8	48, 49, 50, 51, 52, 53, 54, 55	561
9	38, 39, 40, 41, 42, 43, 44, 45	831
10	56, 57, 58, 63, 64, 65, 66, 67	338
11	29, 30, 31, 32, 33, 34, 35, 36, 37, 114	646
12	46, 47, 59, 60, 61, 62	882
13	3, 4, 112, 113	316
14	5, 6	319
15	1, 2, 7, 8	528
16	11, 12, 13, 14, 15	326
17	9, 10, 18, 19, 20	550
18	75, 76, 77, 78, 79, 80	603
19	21, 22, 23, 24, 25, 26, 27, 28	465

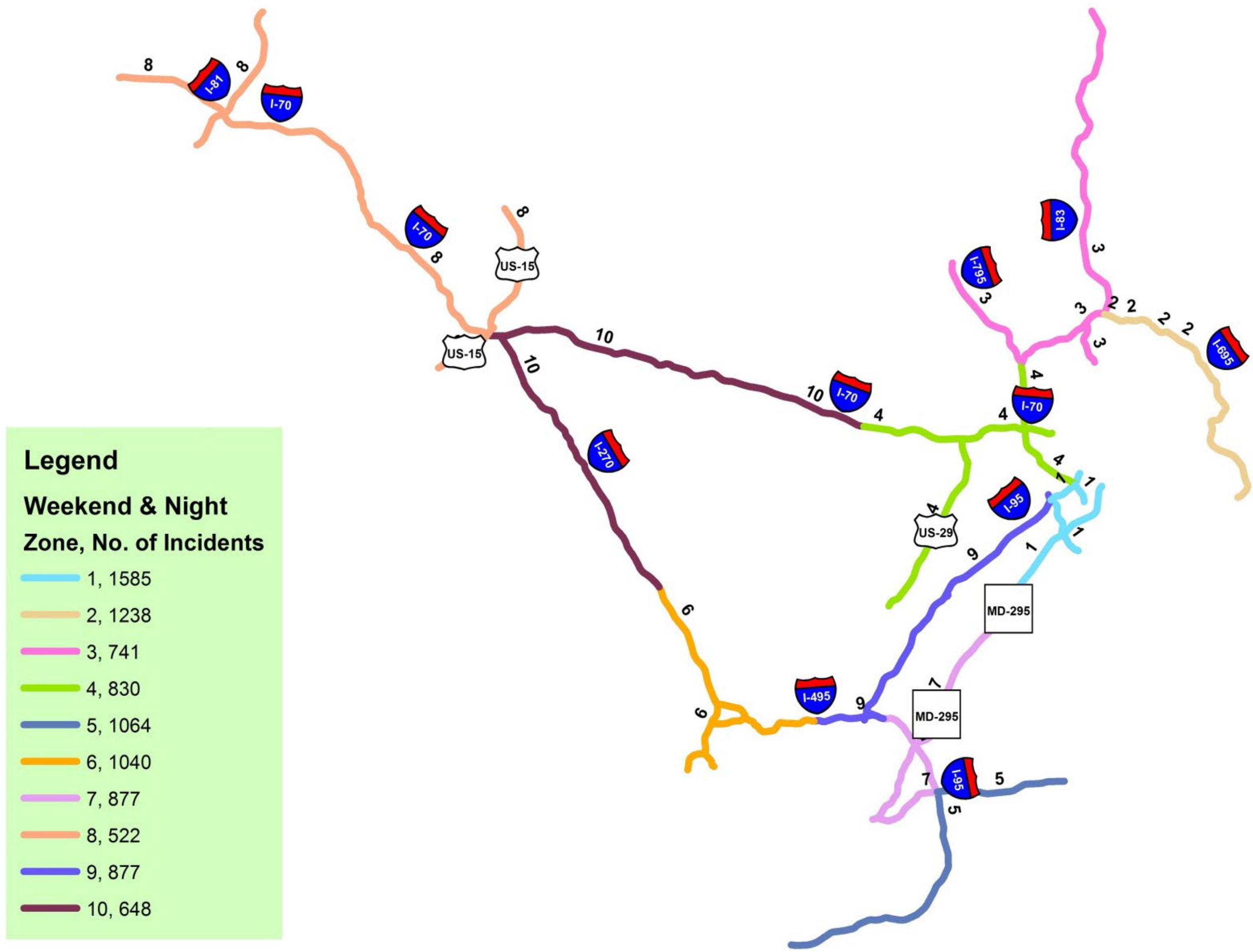


Figure 36 Zone Configuration for the Night and Weekend Shift

Table 28 Zone Configuration for the Night and Weekend Shift

Zone	Covered Links	No. of Incidents
1	69, 70, 71, 72, 73, 74, 81, 82, 90	1585
2	97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107	1238
3	95, 96, 108, 109, 110, 111, 115	741
4	15, 16, 17, 83, 84, 85, 86, 87, 88, 91, 92, 93, 94	830
5	48, 49, 50, 51, 52, 53, 54, 55, 59, 60, 61, 62	1064
6	26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 114	1040
7	44, 45, 46, 47, 56, 57, 58, 63, 64, 65, 66, 67, 89	877
8	1, 2, 3, 4, 5, 6, 7, 112, 113	522
9	40, 41, 42, 43, 68, 75, 76, 77, 78, 79, 80	877
10	8, 9, 10, 11, 12, 13, 14, 18, 19, 20, 21, 22, 23, 24, 25	648

Table 29 Performance Measures

Performance Measures	Weekday Morning	Weekday Afternoon	Night & Weekend
Fleet Size	17	19	10
Shift Duration (hours/year)	2080	2080	4576
Avg. Response Time (min) - 40 MPH	13.0	11.8	-
Avg. Response Time (min) - 55 MPH	-	-	16.6
Number of Incidents	9959	11492	9422
Total Response Time (hours) - 40 MPH	2150	2270	-
Total Response Time (hours) - 55 MPH	-	-	2600
Operation Cost ($1000)	1,768	1,976	2,288

4.4.2 Sensitivity Analysis

Sensitivity analysis is performed to determine the impact of varying parameters on the zone configuration and fleet size. One of the most influential parameters is the average response speed of emergency units to arrive at the incident location once they are informed of the incident occurrence. Therefore, one additional scenario of the average response speed of 55 MPH is considered for the weekday morning and weekday afternoon shifts. Also, the problem is solved for one additional scenario for night and weekend shift assuming the average response speed of 65 MPH. The zone configuration for the weekday morning shift (based on 55 MPH average response speed), weekday afternoon shift (55 MPH), and night and weekend shift (65 MPH) are illustrated in Figure 37 through Figure 39.

Performance measures for the sensitivity analysis, based on the above average response speeds for each shift, are summarized in Table 7. 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, reduces the number of required patrol units while the average response time is decreased, too. Therefore, as long as safe operations are maintained, 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.

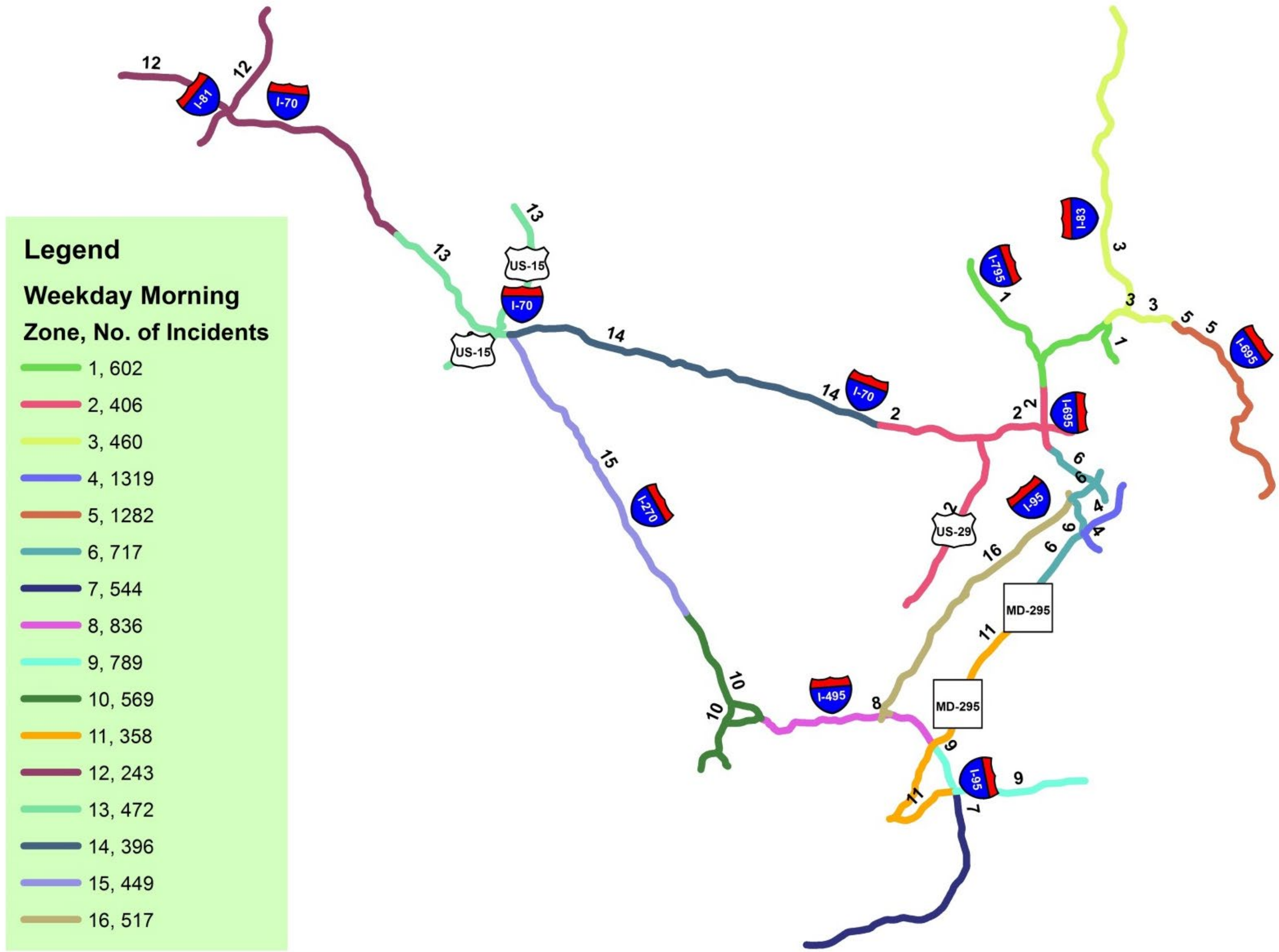


Figure 37 Zone Configuration for the Weekday Morning Shift – 55 MPH

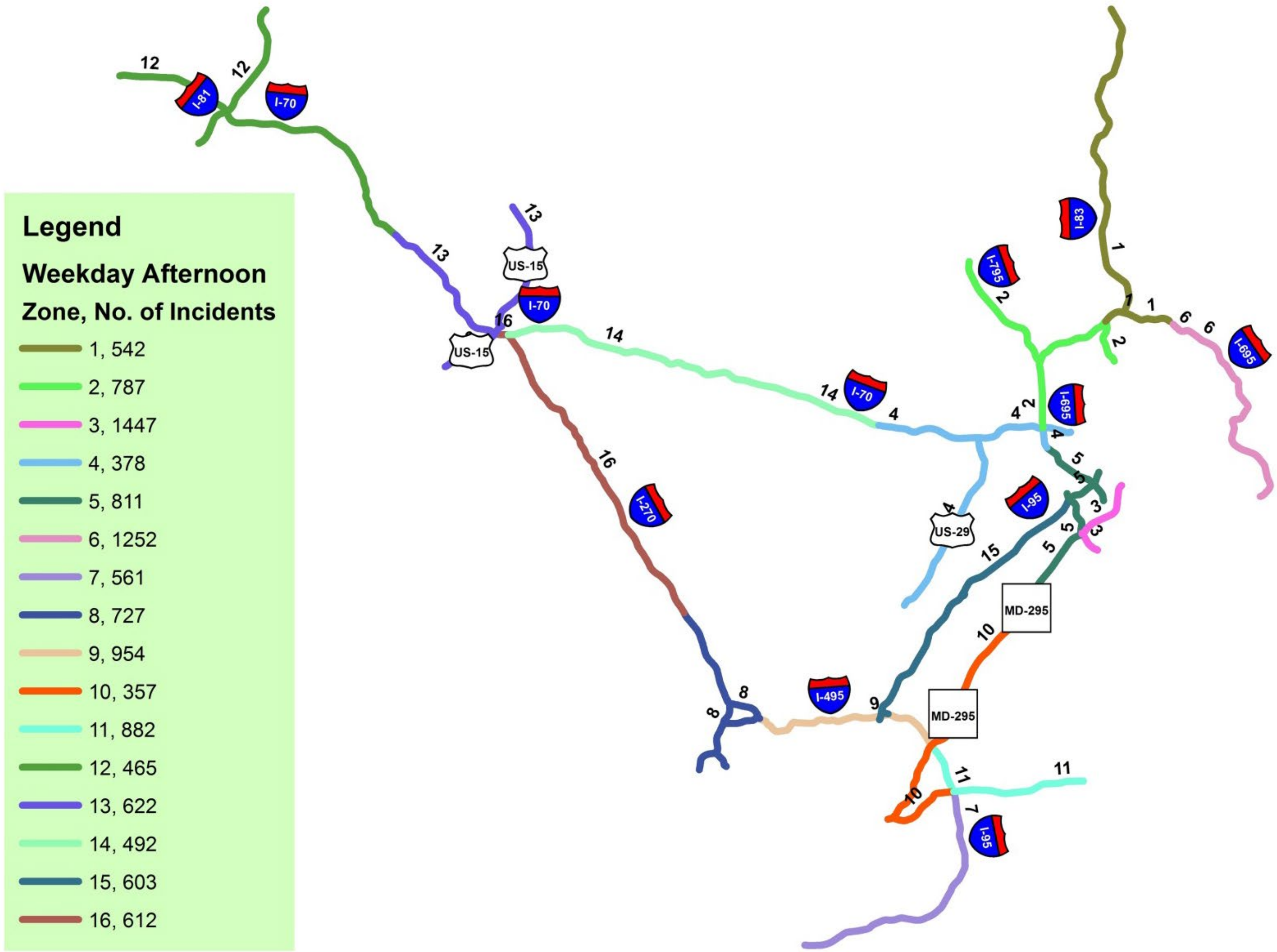


Figure 38 Zone Configuration for the Weekday Afternoon Shift - 55 MPH

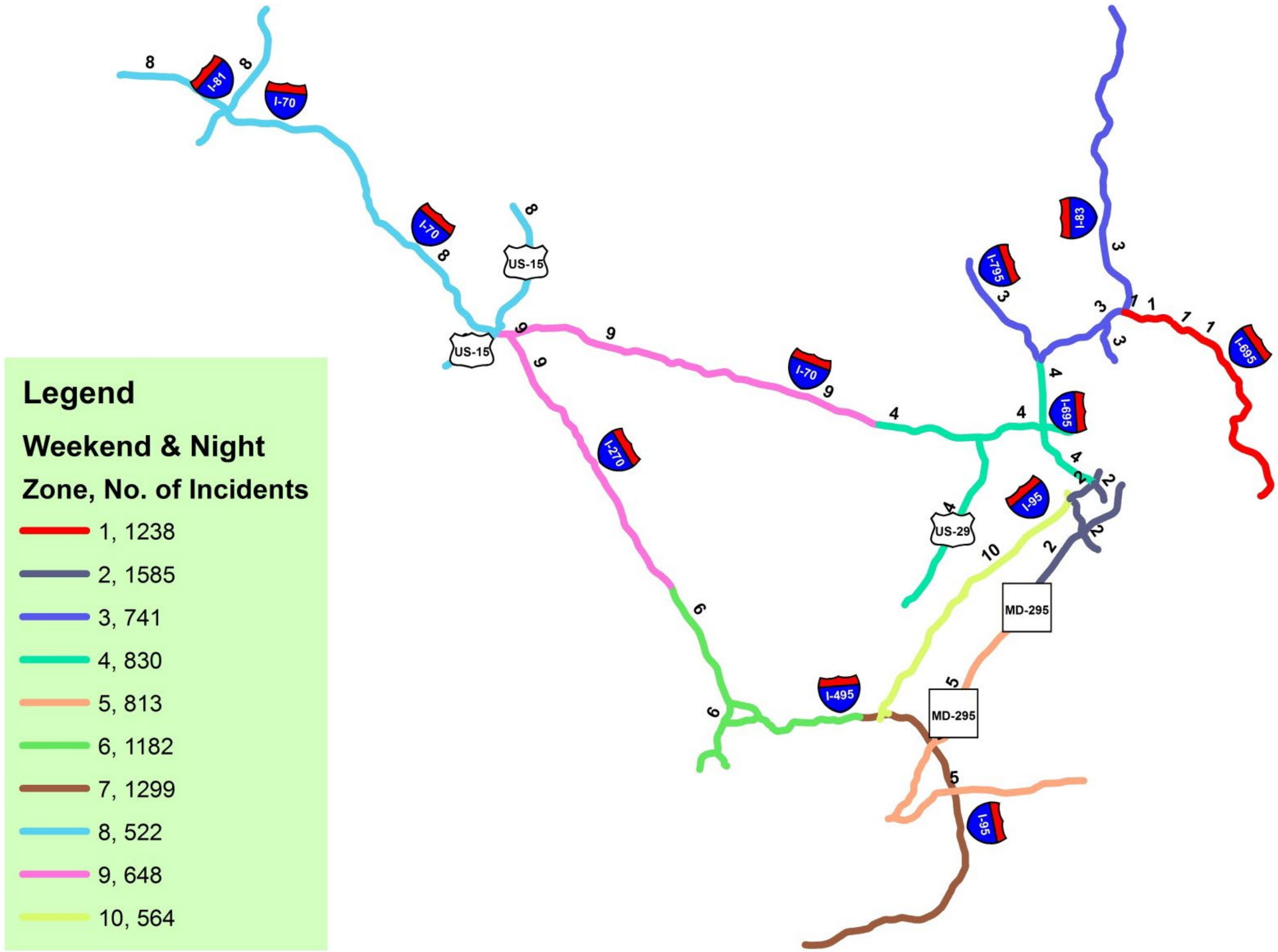


Figure 39 Zone Configuration for the Night and Weekend Shift - 65 MPH

Table 30 Performance Measures for Sensitivity Analysis

Performance Measures	Weekday Morning	Weekday Afternoon	Night & Weekend
Fleet Size 55 MPH	16	16	-
Fleet Size 65 MPH	-	-	10
Shift Duration (hours/year)	2080	2080	4576
Avg. Response Time (min) 55 MPH	9.9	10.2	-
Avg. Response Time (min) 65 MPH	-	-	14.1
Number of Incidents	9959	11492	9422
Total Response Time (hours) 55 MPH	1650	1962	-
Total Response Time (hours) 65 MPH	-	-	2217

Sometimes enough resources are not available, and we may prefer to design the network based on the available number of patrol units assuming that one patrol unit serves each zone. Although the proposed model can determine optimal zone configuration and number of zones, it is also possible to design the zone configuration based on the pre-specified number of zones. In this section, we assumed a fixed number of zones and designed the network based on 11 zones. The zone configurations for the weekday morning and weekday afternoon shifts are shown in Figure 40 and Figure 41, respectively.

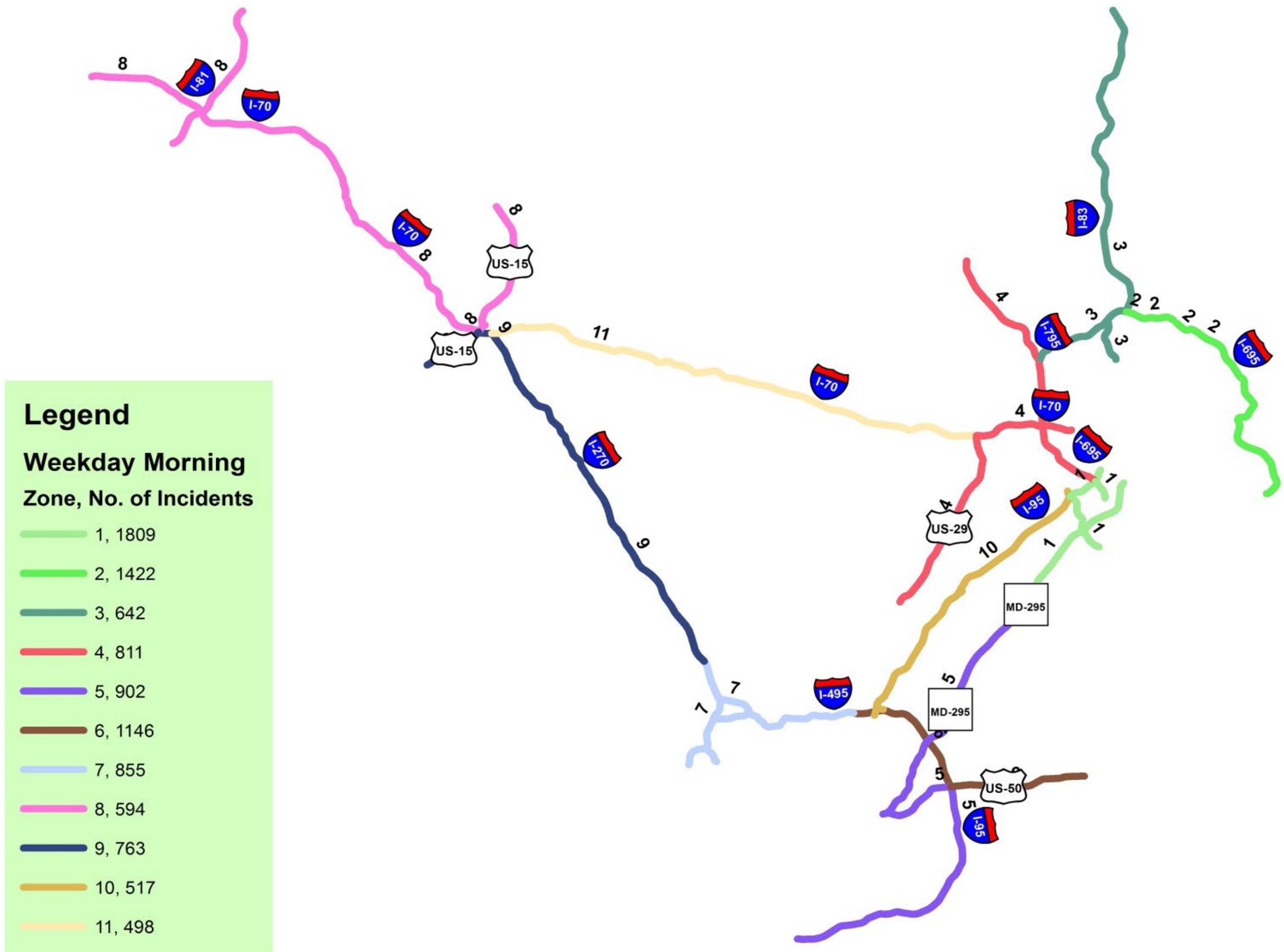


Figure 40 Zone Configuration for the Weekday Morning Shift - Pre-Specified Number of Zones (11 Zones)

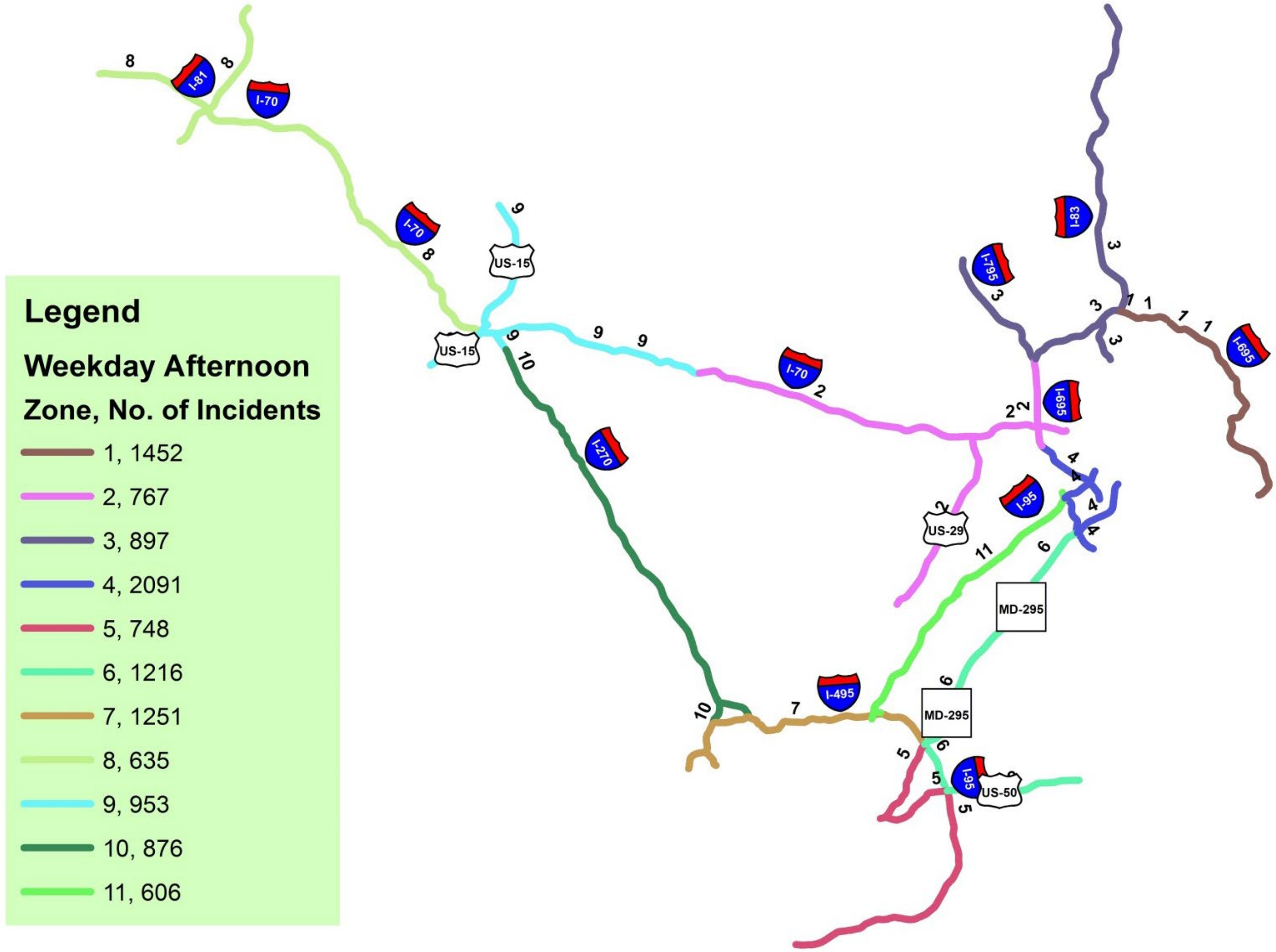


Figure 41 Zone Configuration for the Weekday Afternoon Shift - Pre-Specified Number of Zones (11 Zones)

Furthermore, the problem is solved based on the current CHART operating zone configuration which includes 11 zones as shown in Figure 42. This run is performed to determine the optimal fleet size and fleet allocation among 11 zones in the current zone configuration. The results for fleet size and fleet allocations based on each shift are presented in Table 8. These results are based on assuming constant headway between patrol units on the same zone.

Table 31 Truck Allocation Based on the Current Zone Configuration (11 Zones)

Zone	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	1	1	1
9	2	3	1
10	1	1	1
11	1	1	1
Fleet Size	**18**	**19**	**11**

Figure 43 shows the comparison of the current CHART operating zone configuration with the proposed 11 zone structure for the weekday morning. The proposed configuration for the weekday morning, based on 11 zones, is almost similar to the current configuration in covering the North of Baltimore (zone 2 & zone 3) but there are some differences in covering the south side of Baltimore (zone 1 & zone 4). Also, the proposed configuration suggests covering the Frederick area with one larger zone (zone 8) compared to the current configuration. The proposed configuration also suggests a different zoning structure for the National Capital Region although the number of zones is similar.

Figure 44 shows the comparison of the current CHART zone configuration with the proposed 11 zone structure for the weekday afternoon. The proposed configuration for the weekday afternoon, based on 11 zones, is again almost similar to the current configuration in covering the North of Baltimore (zone 1 & zone 3) but there are some differences in covering the south side of Baltimore (zone 2 & zone 4). Also, the proposed configuration suggests covering the Fredrick area with one large zone (zone 8), but US-15 is not covered with that subject zone. Again, the proposed configuration suggests slightly different zoning for the National Capital Region by using three zones.

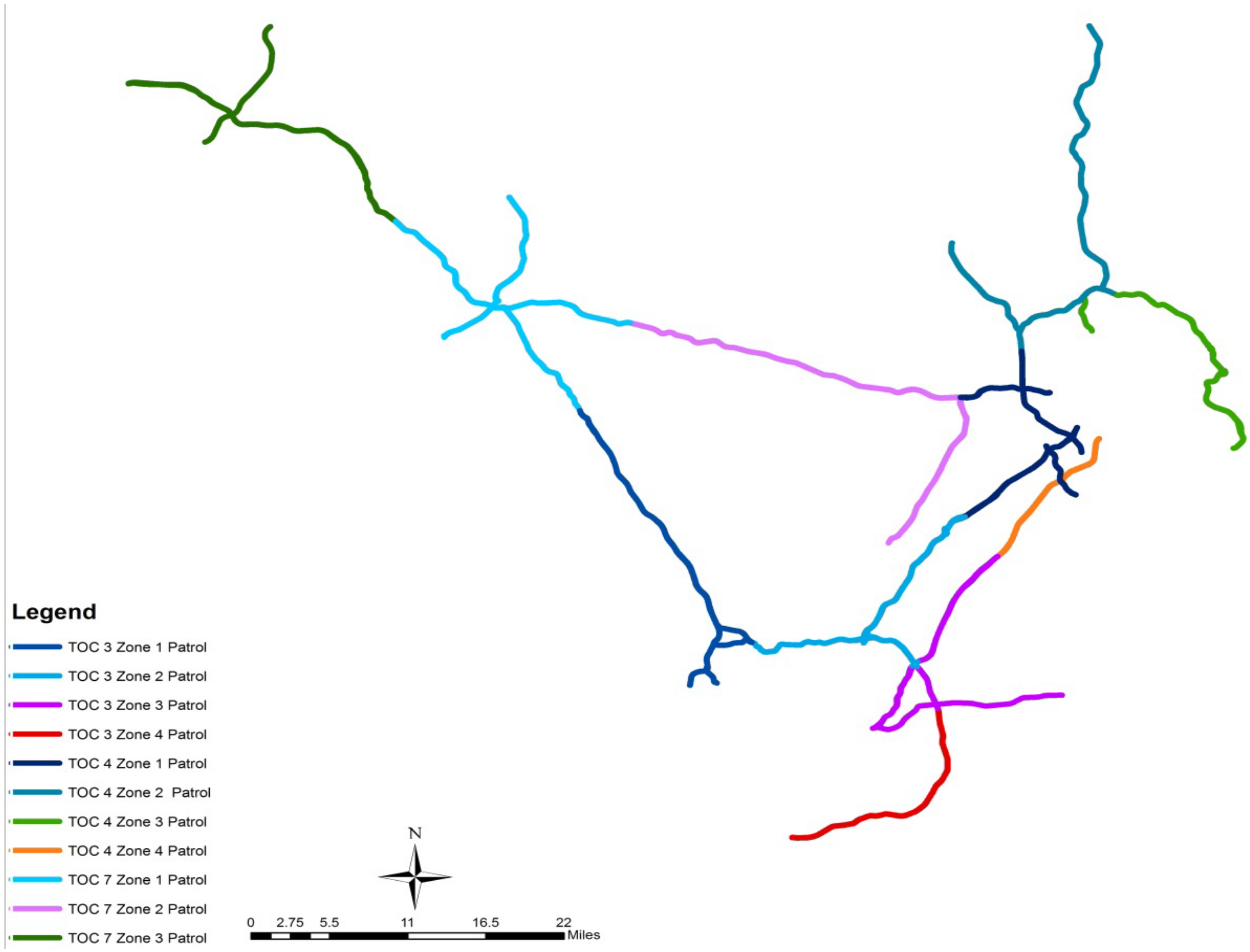
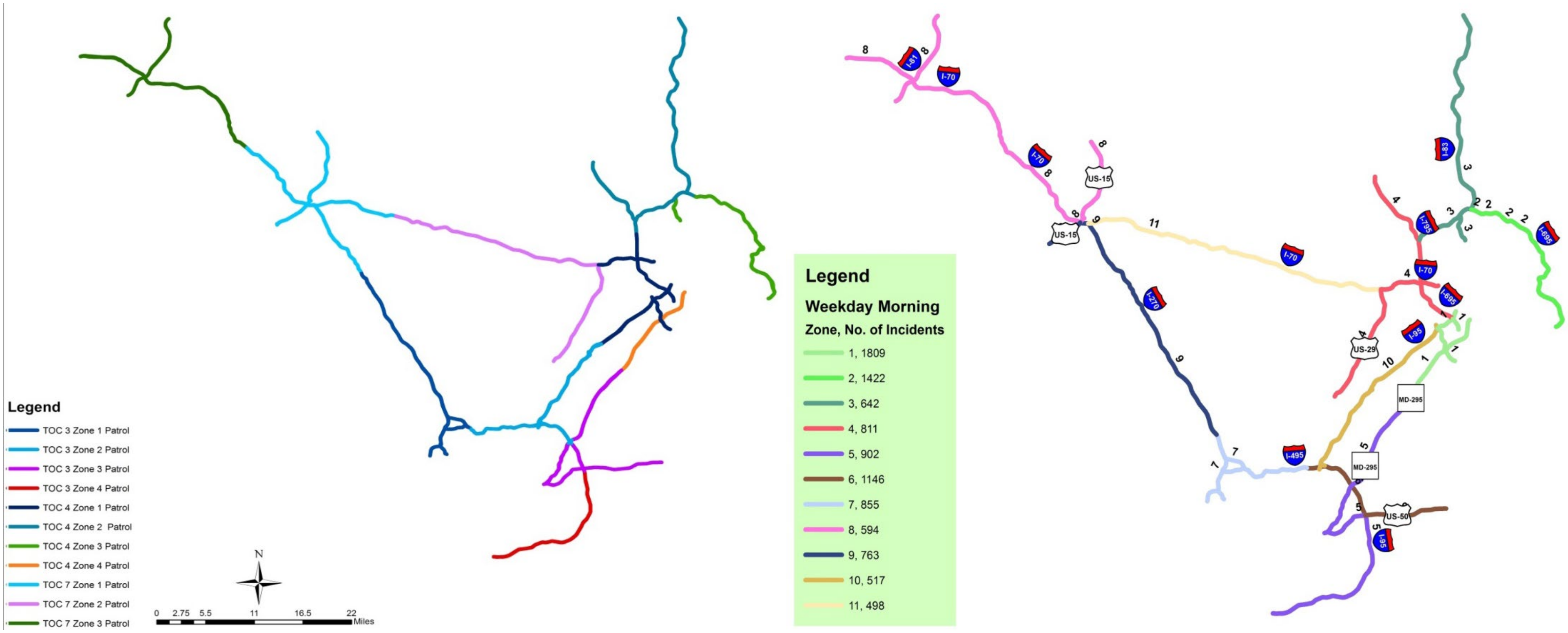
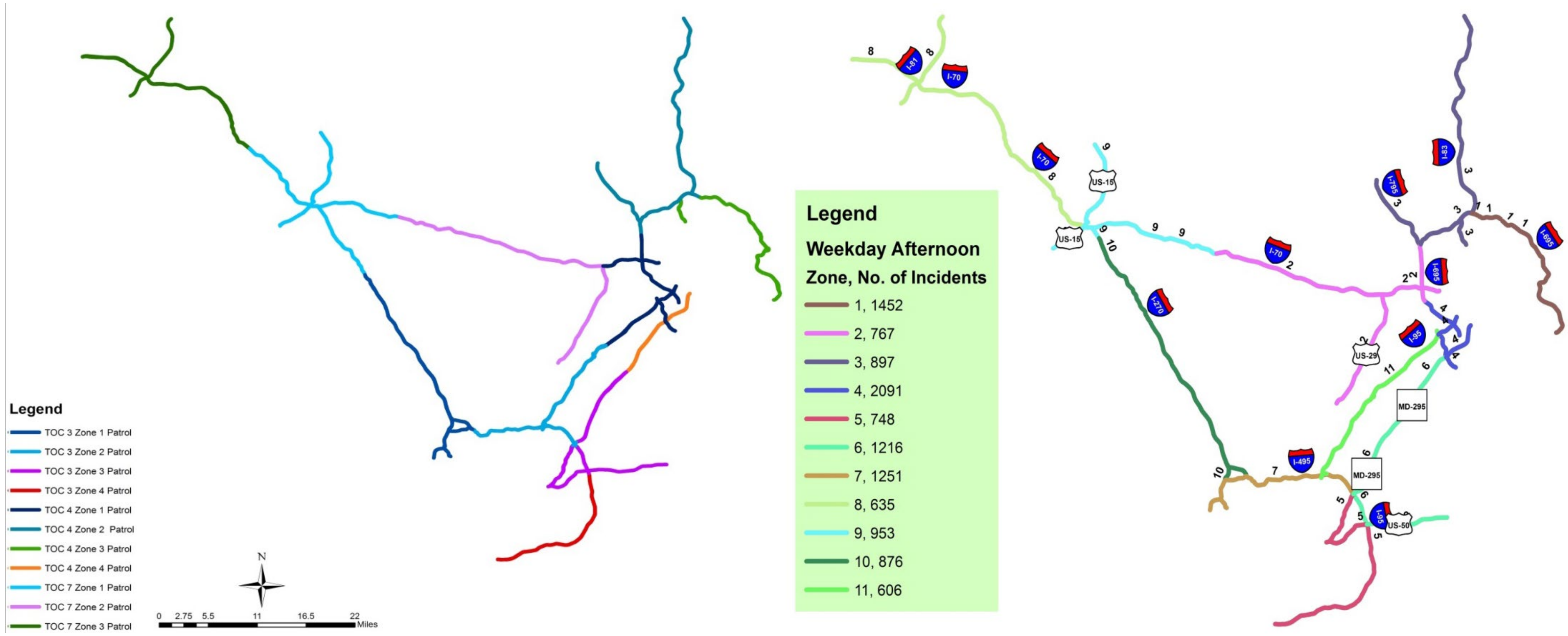


Figure 42 Current Zone Configuration



- The North of Baltimore zones (2 & 3) are similar to the current zones
- The South of Baltimore zones (1 & 4) are somewhat different from current zones
- Frederick area is covered by one larger zone (8) compared with the current zone structure
- The zoning structure for the National Capital Region is different from the current zoning structure although the number of zones is the same

Figure 43 Weekday Morning Configuration Comparison



- The North of Baltimore zones (1 & 3) are similar to the current zones
- The South of Baltimore zones (2 & 4) are somewhat different from current zones
- Frederick area is covered by one larger zone (8) compared with the current zone structure although US-15 is not covered in that zone
- The zoning structure for the National Capital Region is different from the current zoning structure (3 Zones)

Figure 44 Weekday Afternoon Configuration Comparison

4.4.3 Analysis of the Hot Spots

As part of the analysis, the research team tried to identify the areas with the highest number of incidents. These areas are the "Hot Spots" which may require more attention and more patrolling from the program. Table 9 shows the number of incidents in each link of the network. Based on the number of incidents in each link, we developed an Incident Risk Index (IRI) for each shift for each link. The IRI is calculated as follows:

$$\text{IRI} = \text{No. of Incidents Per Hour Per Mile} * 1000$$

As an example, we show the calculation of IRI for link number 1 for different shifts. This link has a length of 1.2 miles. The weekday morning and afternoon shifts are 2,080 hours each and the night and weekend shift is 4,576 hours. The number of incidents on this link for morning, afternoon, and night and weekend shifts are 35, 55, and 28 respectively. Therefore, the IRI values for these shifts are as follows:

$$\text{Morning shift IRI} = (35 / (2080 * 1.2)) * 1000 = 14.02$$

$$\text{Afternoon shift IRI} = (55 / (2080 * 1.2)) * 1000 = 22.04$$

$$\text{Night and Weekend IRI} = (28 / (4576 * 1.2)) * 1000 = 5.10$$

Table 10 shows the IRI for all the links in the network. The cells in this table are color coded from green to yellow to orange to red. Basically, the color green represents the lowest risk links, and the color red represents the highest risk links (hot spots). As the cell colors go from green to red the risk of incidents increase so the hot spots can be identified from this table and more attention can be paid to these areas during the patrolling service.

Table 32 Number of Incidents in Each Link

Link	Weekday Morning	Weekday Afternoon	Night & Weekend	Link	Weekday Morning	Weekday Afternoon	Night & Weekend
1	35	55	28	**41**	56	66	79
2	87	108	93	**42**	161	150	149
3	51	72	21	**43**	9	24	22
4	39	99	24	**44**	137	189	150
5	82	149	73	**45**	50	72	46
6	115	170	88	**46**	173	205	191
7	201	289	157	**47**	79	85	93
8	34	76	31	**48**	16	34	30
9	14	30	17	**49**	78	78	99
10	195	245	139	**50**	104	140	123
11	50	60	46	**51**	136	123	156
12	53	60	54	**52**	85	81	91
13	40	44	33	**53**	47	48	32
14	44	53	31	**54**	41	34	67
15	102	109	81	**55**	37	23	50
16	45	92	90	**56**	42	36	51
17	47	32	33	**57**	31	37	50
18	55	90	39	**58**	56	41	40
19	99	106	68	**59**	50	54	37
20	70	79	48	**60**	102	123	117
21	33	36	42	**61**	83	63	70
22	42	43	31	**62**	302	352	192
23	31	17	20	**63**	35	32	30
24	10	19	9	**64**	38	41	60
25	37	42	40	**65**	55	61	53
26	72	104	49	**66**	49	22	38
27	121	150	103	**67**	39	68	57
28	72	54	45	**68**	1	3	0
29	95	108	79	**69**	17	16	15
30	23	36	25	**70**	361	385	244
31	50	49	57	**71**	132	147	108
32	35	33	31	**72**	15	17	16
33	70	130	91	**73**	36	68	32
34	38	77	43	**74**	922	994	859
35	23	39	31	**75**	104	132	140
36	40	46	44	**76**	109	102	106
37	74	123	142	**77**	86	99	89
38	94	102	140	**78**	49	48	55
39	187	177	156	**79**	19	43	36
40	68	51	63	**80**	149	179	138

Link	Weekday Morning	Weekday Afternoon	Night & Weekend	Link	Weekday Morning	Weekday Afternoon	Night & Weekend
81	64	78	88	**99**	32	52	52
82	131	132	119	**100**	14	24	17
83	15	6	5	**101**	33	49	34
84	10	17	11	**102**	83	83	87
85	16	29	8	**103**	33	35	24
86	4	5	3	**104**	78	66	50
87	29	37	20	**105**	58	53	42
88	5	6	5	**106**	357	395	328
89	13	19	18	**107**	640	571	537
90	131	134	104	**108**	4	9	9
91	227	284	330	**109**	54	43	47
92	39	45	36	**110**	214	227	175
93	94	131	133	**111**	85	85	63
94	88	101	75	**112**	51	85	25
95	237	264	230	**113**	20	60	13
96	48	63	48	**114**	2	5	4
97	79	82	45	**115**	192	206	169
98	15	42	22				

Table 33 Incident Risk Index for Each Link in Each Shift

Link	Weekday Morning	Weekday Afternoon	Night & Weekend	Link	Weekday Morning	Weekday Afternoon	Night & Weekend
1	14.02	22.04	5.10	**41**	8.59	3.69	5.51
2	4.86	6.04	2.36	**42**	19.68	3.66	8.28
3	1.52	2.15	0.28	**43**	2.95	3.91	3.28
4	1.59	4.03	0.44	**44**	15.20	5.98	7.56
5	1.92	3.49	0.78	**45**	9.75	3.55	4.08
6	2.71	4.01	0.94	**46**	15.79	6.24	7.93
7	5.14	7.39	1.82	**47**	18.99	2.15	10.16
8	9.43	21.08	3.91	**48**	2.31	7.08	1.97
9	3.88	8.32	2.14	**49**	10.82	3.47	6.24
10	5.43	6.82	1.76	**50**	6.25	10.77	3.36
11	2.37	2.85	0.99	**51**	9.43	6.27	4.92
12	2.33	2.64	1.08	**52**	6.89	5.65	3.35
13	3.04	3.34	1.14	**53**	7.37	3.13	2.28
14	2.88	3.47	0.92	**54**	7.04	2.32	5.23
15	3.49	3.73	1.26	**55**	6.35	1.74	3.90
16	2.33	4.77	2.12	**56**	3.65	4.74	2.01
17	5.74	3.91	1.83	**57**	5.59	3.18	4.10
18	10.17	16.64	3.28	**58**	11.22	1.76	3.64
19	4.67	5.00	1.46	**59**	16.39	1.58	5.51
20	4.85	5.48	1.51	**60**	4.38	13.51	2.28
21	1.93	2.11	1.12	**61**	14.25	2.13	5.46
22	3.61	3.69	1.21	**62**	57.31	2.95	16.56
23	5.59	3.06	1.64	**63**	5.74	2.68	2.23
24	4.81	9.13	1.97	**64**	1.96	10.07	1.40
25	3.61	4.09	1.77	**65**	2.36	12.42	1.03
26	8.65	12.50	2.68	**66**	3.43	3.08	1.21
27	9.70	12.02	3.75	**67**	5.21	6.28	3.46
28	14.42	10.82	4.10	**68**	0.60	2.40	0.00
29	8.67	9.86	3.28	**69**	1.53	5.02	0.61
30	6.91	10.82	3.41	**70**	53.13	3.48	16.32
31	7.51	7.36	3.89	**71**	12.36	5.72	4.60
32	4.28	4.03	1.72	**72**	1.24	6.57	0.60
33	7.32	13.59	4.32	**73**	3.66	8.94	1.48
34	6.37	12.91	3.28	**74**	97.78	4.89	41.41
35	2.91	4.93	1.78	**75**	6.70	9.48	4.10
36	9.95	11.44	4.97	**76**	8.54	5.74	3.78
37	9.53	15.84	8.31	**77**	5.64	8.44	2.65
38	10.27	11.15	6.95	**78**	4.11	5.62	2.10
39	32.11	30.39	12.18	**79**	1.71	12.07	1.48
40	23.35	17.51	9.83	**80**	6.11	14.10	2.57

Link	Weekday Morning	Weekday Afternoon	Night & Weekend	Link	Weekday Morning	Weekday Afternoon	Night & Weekend
81	7.69	9.38	4.81	**99**	15.38	1.63	11.36
82	36.34	36.61	15.00	**100**	2.97	3.89	1.64
83	5.15	2.06	0.78	**101**	15.87	1.48	7.43
84	0.82	1.39	0.41	**102**	18.70	2.13	8.91
85	1.13	2.05	0.26	**103**	8.21	2.05	2.71
86	0.85	1.06	0.29	**104**	29.61	1.07	8.63
87	2.38	3.03	0.74	**105**	12.30	2.07	4.05
88	0.92	1.11	0.42	**106**	27.98	6.79	11.69
89	3.94	5.76	2.48	**107**	17.03	16.12	6.50
90	23.04	23.57	8.31	**108**	0.78	5.55	0.80
91	12.99	16.25	8.59	**109**	1.46	14.17	0.58
92	6.86	7.92	2.88	**110**	3.96	27.58	1.47
93	7.53	10.50	4.84	**111**	6.81	6.00	2.29
94	12.69	14.57	4.92	**112**	1.50	27.22	0.33
95	10.49	11.68	4.63	**113**	1.60	18.00	0.47
96	8.24	10.82	3.75	**114**	0.29	8.17	0.27
97	22.79	23.65	5.90	**115**	5.19	19.10	2.07
98	3.86	10.82	2.58				

4.4.4 Conclusions

In this section, we applied the mathematical model described in section 3 to determine the zone configuration and fleet size for the freeway network covered by CHART in Maryland based on the 2016 incident dataset. The results indicate that determining influential elements in CHART patrol program such as the number of zones, zone configuration and fleet size can have a significant impact on the performance of the CHART patrol program to reduce the total incident duration and minimize total operating cost.

As also shown in the 2015 analysis, it is important to consider several configurations based on different times of the day and week. Therefore, different zone configuration and fleet size are provided based on the weekday morning, weekday afternoon, night and weekend shifts. The night and weekend shifts require a smaller number of patrol units compared to the weekday morning and weekday afternoon shifts as the incident intensity is lower during nights and weekends.

The experiments found that, as in 2015, Baltimore and National Capital regions need more patrol units than Western region. The sensitivity analysis also revealed that as the patrol unit's average response speed increases, less number of patrol units are needed to cover the CHART network and the average response time reduces, too. However, it is clear 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.

Although the model can determine the optimal zone configuration and number of zones, it is also possible to design the zone configuration based on the pre-specified number of zones. As an example, the zone configuration was determined based on assuming 11 pre-specified zones. Also, fleet size and allocation could be determined for any given zone configuration assuming constant headway between patrol units in the same zone. Based on the analysis of the incidents and their locations, the areas with high risk of incidents could also be identified.

Results show that the best configuration, fleet size, and allocation may change based on design period as the incident distribution may change during different years. Therefore, designing the network based on the newest set of incident data provides the opportunity to determine the best current strategy. Also, investigating additional incident data provides much more reliable solutions over time. The results based on the 2016 incident dataset are in accordance with the result obtained based on the 2015 incident dataset.

5 MODEL EXTENSIONS

5.1 Proposed Model

Previously, we developed a comprehensive mathematical model to design the network for patrol programs. The developed model is able to concurrently determine the zone configuration, fleet size, and allocation, to minimize incident incurred delay while the operations cost is taken into account. Now, this research aims at extending and modifying the mathematical model to determine the most efficient patrol coverage area, given an underlying transportation network. In other words, we intend to relax the assumption that the patrol service network is given. An important question for incident management officials is to determine where patrol units are required and where other strategies such as dispatch response are desired. Given the transportation network, we plan to determine the patrol coverage area by taking into account elements such as incident frequency, patrolling operations cost, and cost associated with not covering incidents through the patrol program (cost for alternative program). Determining the patrol coverage area and the non-patrolling area will significantly save the operation cost by avoiding non-necessary patrolling.

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 three major decision variables in the model that need to be determined. The first binary decision variable is Y_{ij} which determines whether link *ij* is covered by the patrol program. The second binary decision variable is X_{ij}^{b} which determines whether link *ij* is covered by beat *b* (obviously, if Y_{ij} is zero for link *ij*, then X_{ij}^{b} is zero for every beat) and the third 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 network G plus dummy links from the hypothetical origin node to each node

$B =$ Maximum possible number of patrol beats

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

$$Y_{ij} = \begin{cases} 1 & \text{if link } ij \in L \text{ is covered by the patrol program} \\ 0 & \text{Otherwise} \end{cases}$$

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

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

V_b = Number of patrol trucks assigned to beat b
α = Coefficient to monetize the benefit of incident duration reduction

γ_{ij} = Coefficient to monetize the cost of not covering an incident by the patrol program on link ij

R_{ij}^b = Average response time in case of an incident on link ij in beat 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)
U_{ijklme}^b = Binary varibles defined to resolve non-linearity of the model: $X_{ij}^b X_{kl}^b V_{me}^b$
W_{ijkl}^b = Binary variables defined to resolve non-linearity of the model : $X_{ij}^b X_{kl}^b$

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

V_{me}^b, Z_e^b = Binary variables defined to determine V_b
Q_{ij}^b = Variables defined to assure connectivity of beats

I_{ij}^n = Normalized importance factor

5.2 *Patrolling Response Time*

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:

$$\boldsymbol{R^b} = \frac{\sum_{ij\in L} t_{ij} X_{ij}^b}{2V_b} \tag{52}$$

For the purpose of having a linear term, response time could be re-calculated as follow:

$$R^b = \frac{\sum_{ij\in L} t_{ij} X_{ij}^b}{2V_b} = \frac{\sum_{ij\in L} t_{ij} X_{ij}^b}{2} [1 - \sum_{m=1}^{T} \sum_{e=2}^{e=V} (\frac{1}{e-1} - \frac{1}{e}) V_{me}^b \tag{53}$$

Equation (52) initially calculates the average response time based on one truck in the beat *(V_b =1)* and reduces the response time for each additional truck assigned to the beat. Given equation (53) we may calculate the following statement:

$$\sum_{ij\in L} X_{ij}^{b} R_{ij}^{b} = \sum_{ij\in L} X_{ij}^{b} \frac{\sum_{kl\in L} t_{kl} X_{kl}^{b}}{2} \left[1 - \sum_{m=1}^{T} \sum_{e=2}^{e=V} \left(\frac{1}{e-1} - \frac{1}{e}\right) V_{me}^{b}\right] = \frac{\sum_{ij\in L} \sum_{kl\in L} t_{kl} X_{kl}^{b} X_{ij}^{b}}{2} - \frac{\sum_{ij\in L} \sum_{kl\in L} t_{kl} X_{kl}^{b} X_{ij}^{b}}{2} \sum_{m=1}^{T} \sum_{e=2}^{e=V} \left(\frac{1}{e-1} - \frac{1}{e}\right) V_{me}^{b} = 0.5\left[\sum_{ij\in L} \sum_{kl\in L} t_{kl} X_{kl}^{b} X_{ij}^{b} - \sum_{ij\in L} \sum_{kl\in L} \sum_{m=1}^{T} \sum_{e=2}^{V} \left(\frac{1}{e-1} - \frac{1}{e}\right) t_{kl} X_{kl}^{b} X_{ij}^{b} V_{me}^{b}\right] \quad (54)$$

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 (54) is presented to linearize the statement $X_{ij}^{b} R_{ij}^{b}$ which will be used in the objective function.

5.2.1 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 a normalized importance factor value based on its class.

5.2.2 Objective Function – Constraints

The first term in the objective function, to minimize the total response time during the planning horizon, is as follows:

$$Min \sum_{b=1}^{B} \sum_{ij\in L} X_{ij}^{b} f_{ij} R_{ij}^{b} \quad (55)$$

This term is non-linear but could be linearized by writing it in the following form:

$$0.5 \sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L} f_{ij} t_{kl} X_{kl}^{b} X_{ij}^{b} - 0.5 \sum_{b=1}^{B} \sum_{ij\in L} \sum_{kl\in L} \sum_{m=1}^{T} \sum_{e=2}^{V} f_{ij} t_{kl} \left(\frac{1}{e-1} - \frac{1}{e}\right) X_{kl}^{b} X_{ij}^{b} V_{me}^{b} \quad (56)$$

In the second step to linearize the model, a new set of binary variables are introduced. So, the following changes are made in the model:

$$X_{ij}^{b}X_{kl}^{b}V_{me}^{b} = U_{ijklme}^{b} \tag{57}$$

$$X_{ij}^{b}X_{kl}^{b} = W_{ijkl}^{b} \tag{58}$$

In the following, expression (59) is added up to the objective function to capture the patrolling operations cost during the planning horizon. Also, the cost associated with not covering incidents through patrol program (cost for alternative program) is shown by term (60):

$$\sum_{b=1}^{B}\sum_{m=1}^{T}\sum_{e=1}^{V} C_m V_{me}^{b} * (hr * day) \tag{59}$$

$$\gamma_{ij}\sum_{b=1}^{B} f_{ij}(1 - Y_{ij}) \tag{60}$$

Parameter γ_{ij} is added up to monetize the cost of not covering an incident by patrol program on link ij. 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

$\frac{1}{2}\alpha[\sum_{b=1}^{B}\sum_{ij\in L}\sum_{kl\in L} f_{ij}t_{kl}\ I_{ij}^{n}\ W_{ijkl}^{b} - \sum_{b=1}^{B}\sum_{ij\in L}\sum_{kl\in L}\sum_{m=1}^{T}\sum_{e=2}^{V} f_{ij}t_{kl}I_{ij}^{n}(\frac{1}{e-1}-\frac{1}{e})\ U_{ijklme}^{b}]$
$+\sum_{b=1}^{B}\sum_{m=1}^{T}\sum_{e=1}^{V} C_m V_{me}^{b}(hr * day)\ +\ \gamma_{ij}\sum_{b=1}^{B} f_{ij}(1-Y_{ij})$

(61)

Subject to:

$U_{ijklme}^{b} \leq\ X_{ij}^{b}$ $\quad$ $for\ each\ ij \in L, kl \in L, m = \{1..T\}, e = \{1..V\}, b = \{1..B\}$ (62)

$U_{ijklme}^{b} \leq\ X_{kl}^{b}$ $\quad$ $for\ each\ ij \in L, kl \in L, m = \{1..T\}, e = \{1..V\}, b = \{1..B\}$ (63)

$U_{ijklme}^{b} \leq\ V_{me}^{b}$ $\quad$ $for\ each\ ij \in L, kl \in L, m = \{1..T\}, e = \{1..V\}, b = \{1..B\}$ (64)

$W_{ijkl}^{b} \leq\ X_{ij}^{b}$ $\quad$ $for\ each\ ij \in L, kl \in L, = \{1..B\}$ (65)

$W_{ijkl}^{b} \leq\ X_{kl}^{b}$ $\quad$ $for\ each\ ij \in L, kl \in L, = \{1..B\}$ (66)

$W_{ijkl}^{b} \geq\ X_{ij}^{b} + X_{kl}^{b} - 1$ $\quad$ $for\ each\ ij \in L, kl \in L, = \{1..B\}$ (67)

$\sum_{b=1}^{B}\sum_{e=1}^{V} V_{me}^{b} \leq\ 1$ $\quad$ $for\ each\ m$ (68)

$\sum_{m=1}^{T}\sum_{e=1}^{V} V_{me}^{b} =\ V_b$ $\quad$ $for\ each\ b$ (69)

$\sum_{m=1}^{T} V_{me}^{b} =\ Z_e^{b}$ $\quad$ $for\ \ each\ e = \{1..V\}, b = \{1..B\}$ (70)

$Z_e^{b} \geq\ Z_{e+1}^{b}$ $\quad$ $for\ \ each\ e = \{1..V\}, b = \{1..B\}$ (71)

$\sum_{b=1}^{B} X_{ij}^{b} =\ Y_{ij}$ $\quad$ $for\ all\ ij \in L$ (72)

$X_{ij}^{b} = X_{ji}^{b}$ $\quad$ $for\ all\ ij \in L$ (73)

$\sum_{b=1}^{B} o_i^{b} \geq 1$ $\quad$ $for\ each\ i \in N$ (74)

$o_i^{b} \leq \sum_{j\in N, ij\in L} X_{ij}^{b} +\ \sum_{j\in N, ji\in L} X_{ji}^{b}\ \leq M o_i^{b}$ $\quad$ $for\ each\ i \in N\ and\ b$ (75)

$$\sum_{j\in N, ij\in L} Q_{ij}^{b} - \sum_{j\in N, ji\in L} Q_{ji}^{b}\ =\ -o_i^{b} \qquad for\ each\ i \in N, ij \in LL\ and\ b = \{1..B\}$$

(76)

$Q_{ij}^{b} \leq\ M X_{ij}^{b}$ $\quad$ $for\ each\ ij \in LL\ and\ b = \{1..B\}$ (77)

$\sum_{ij\in(LL-L)} X_{ij}^{b} = 1$ $\quad$ $for\ each\ b = \{1..B\}$ (78)

$\sum_{ij\in L} X_{ij}^{b} \leq M V_b$ $\quad$ $for\ each\ b = \{1..B\}$ (79)

In the above model, the objective function (61) minimizes the monetized value of the total response time during the time horizon plus the costs associated with the patrol program and the cost associated with alternative response strategy (not covering by the patrol program). In the model, constraints 62 through 67 define a new set of binary variables to resolve the non-linearity of the model as explained in the previous section. Constraint 68 makes sure that each vehicle is assigned not more than once; constraint 69 calculates the total number of trucks in each beat, and constraints 70 and 71 are added to calculate number of patrol trucks in each beat.

The rest of constraints, constraints 72 through 79, are general constraints of the model. Constraint 80 ensures that each link is assigned to a beat only if it is covered by the program. Then, if a link *ij* is not covered by the patrol program, the subject link will be assigned to no beat. Constraint 81 ensures that link *ij* is covered by the same beat that covers link *ji*. Constraints 76 through 79 are essentially just added to ensure connectivity of nodes covered by the same beat.

5.3 Heuristic

A heuristic algorithm is required to solve the problem for large size networks. For this purpose, we may take advantage of the previously developed 2-phase algorithm. Then, let’s first generate a few adequately small sub-networks and solve the problem for each sub-network. Obviously, for each sub-network, the model may decide not to cover some part of the subject sub-network. Next, given the results from sub-network, we may solve the problem for the whole network. Now, we have a solid initial solution to apply the next phase. The next phase is kind of similar to neighbor search algorithm with two additional steps. As before, in the neighbor search algorithm, we assume that in each round, we investigate one beat, and for the subject beat, we check all neighbor links to see if adding them to the subject beat will improve the solution. In addition to this step, in the modified approach, we also check all neighbor links that are not covered by any beat to see if covering them by the subject beat will improve the solution. Also, another addition is that for each beat, we check to see whether dropping any possible link from the subject beat will improve the solution. We continue this process for each beat until no better solution could be obtained.

6 SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

6.1 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.

6.2 Conclusions

Overall, the results from both 2015 and 2016 indicate that the proposed approach for network design based on the joint model can significantly improve the efficiency of the freeway service patrol program. Our analysis highlights the importance of explicitly determining each of the involved factors (number of beats, beat configuration, fleet size, and fleet allocation) in the model instead of simply assuming them.

To optimize the performance of the program while minimizing operating costs, several configurations for different times of the day, week, or year should be considered, to account for the variation in incident density for the same network during different periods.

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.

6.3 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 [83]. Meter reading and snow plowing problems are among other arc routing problems that could be similarly solved.

APPENDIX A: 2015 NETWORK

Table A1: Nodes for the 2015 Network

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			

Table A2: Links for the 2015 Network

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

APPENDIX B: 2016 NETWORK

Table B1: Nodes for the 2016 Network

Node	Patrol Highway	Interchange with	Node	Patrol highway	Interchange with
1	I-70	I-81	40	I-95	MD 216
2	I-70	US 40	41	I-95	MD 175
3	I-70	MD 17	42	I-695	I-83
4	I-70	MD 85	43	I-695	MD 45
5	I-70	MD 75	44	I-695	MD 146
6	I-70	MD 27	45	I-695	MD 542
7	I-70	MD 94	46	I-695	MD 147
8	I-70	MD 97	47	I-695	MD 43
9	I-70	MD 32	48	I-695	US 1
10	I-70	US 29	49	I-695	US 40
11	I-70	Endpoint	50	I-695	Endpoint
12	I-270	MD 85	51	I-695	MD 295
13	I-270	MD 80	52	I-695	I-895 b
14	I-270	MD 109	53	I-83	MD 439
15	I-270	MD 121	54	I-83	MD 137
16	I-270	MD 118	55	US 50	Endpoint
17	I-270	MD 119	56	US 50	MD 202
18	I-270	MD 124	57	US 50	MD 410
19	I-270	I-370	58	US 50	MD 704
20	I-270	MD 28	59	US 50	MD 197
21	I-270	MD 189	60	US 50	MD 3 (US 301)
22	I-270	MD 187	61	MD 295	MD 450
23	I-495	US 29	62	MD 295	Endpoint
24	I-495	US 1	63	MD 295	MD 32
25	I-495	MD 201	64	MD 295	MD 175
26	I-495	MD 295	65	MD 295	MD 100
27	I-495	MD 202	66	US 29	US 40
28	I-495	MD 450	67	US 29	MD 108
29	I-495	MD 214	68	US 29	MD 175
30	I-495	MD 4	69	US 29	MD 32
31	I-495	MD 5	70	US 29	MD 216
32	I-495	MD 210	71	I-97	Endpoint
33	I-495	MD 414	72	MD 295	Endpoint
34	I-495	I-295	73	I-83	Endpoint
35	I-495	MD 97	74	US 29	Endpoint
36	I-495	MD 193	75	MD 295	Endpoint
37	I-495	MD 650	76	US 50	Endpoint
38	I-95	MD 212	77	I-795	Endpoint
39	I-95	MD 200	78	I-83	Endpoint

Table B2: Links for the 2016 Network

Link	Old ID	Between Nodes		On Road	Link	Old ID	Between Nodes		On Road
1	1	112	111	US-15	**41**	41	36	37	I-495
2	2	111	81	US-15	**42**	42	37	109	I-495
3	3	79	1	I-70	**43**	43	109	24	I-495
4	4	1	2	I-70	**44**	44	24	25	I-495
5	5	2	3	I-70	**45**	45	25	26	I-495
6	6	3	111	I-70	**46**	46	26	28	I-495
7	7	80	112	US-15	**47**	47	28	86	I-495
8	8	111	101	I-70	**48**	48	86	27	I-495
9	9	101	4	I-70	**49**	49	27	29	I-495
10	10	4	5	I-70	**50**	50	29	30	I-495
11	11	5	6	I-70	**51**	51	30	31	I-495
12	12	6	7	I-70	**52**	52	31	33	I-495
13	13	7	8	I-70	**53**	53	33	32	I-495
14	14	8	9	I-70	**54**	54	32	34	I-495
15	15	9	10	I-70	**55**	55	34	100	I-495
16	16	10	107	I-70	**56**	56	55	56	US-50
17	17	107	11	I-70	**57**	57	56	57	US-50
18	18	101	12	I-270	**58**	58	57	86	US-50
19	19	12	13	I-270	**59**	59	86	58	US-50
20	20	13	14	I-270	**60**	60	58	59	US-50
21	21	14	15	I-270	**61**	61	59	60	US-50
22	22	15	98	I-270	**62**	62	60	76	US-50
23	23	98	16	I-270	**63**	63	55	61	MD-295
24	24	16	17	I-270	**64**	64	61	26	MD-295
25	25	17	18	I-270	**65**	65	26	75	MD-295
26	26	18	19	I-270	**66**	66	75	62	MD-295
27	27	19	20	I-270	**67**	67	62	63	MD-295
28	28	20	21	I-270	**68**	68	92	106	I-195
29	29	21	102	I-270	**69**	69	106	108	I-195
30	30	102	22	I-270	**70**	70	108	91	I-195
31	31	22	85	I-270	**71**	71	64	65	MD-295
32	32	103	102	I-270 spur	**72**	72	65	108	MD-295
33	33	73	97	I-495	**73**	73	108	51	MD-295
34	34	97	103	I-495	**74**	74	51	72	MD-295
35	35	103	96	I-495	**75**	75	109	38	I-95
36	36	96	85	I-495	**76**	76	38	39	I-95
37	37	85	95	I-495	**77**	77	39	40	I-95
38	38	95	35	I-495	**78**	78	40	94	I-95
39	39	35	23	I-495	**79**	79	94	41	I-95
40	40	23	36	I-495	**80**	80	41	106	I-95

Link	Old ID	Between Nodes		On Road	Link	Old ID	Between Nodes		On Road
81	81	106	110	I-95	**99**	103	43	44	I-695
82	82	110	71	I-95	**100**	104	44	89	I-695
83	83	74	70	US-29	**101**	105	89	45	I-695
84	84	70	69	US-29	**102**	106	45	99	I-695
85	85	69	68	US-29	**103**	107	99	46	I-695
86	86	68	67	US-29	**104**	108	46	47	I-695
87	87	67	66	US-29	**105**	109	47	48	I-695
88	88	66	10	US-29	**106**	110	48	49	I-695
89	NA	63	64	MD-295	**107**	111	49	50	I-695
90	94	52	110	I-695	**108**	112	88	53	I-83
91	95	110	87	I-695	**109**	113	53	54	I-83
92	96	87	107	I-695	**110**	114	54	105	I-83
93	97	107	84	I-695	**111**	115	42	78	I-83
94	98	84	104	I-695	**112**	116	82	1	I-81
95	99	104	42	I-695	**113**	117	1	83	I-81
96	100	42	105	I-695	**114**	118	93	97	Cabin J Pkwy
97	101	105	90	I-695	**115**	119	77	104	I-795
98	102	90	43	I-695					

APPENDIX C: NON-PATROLLING DETECTION: NUMBER OF INCIDENTS 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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