ABSTRACT

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Traffic incidents on freeways cause a considerable loss of life and property. Therefore, some organizations provide freeway safety services to improve the roadway's safety condition by assisting in detecting and clearing incidents. Incidents generally require timely assistance in removing debris and disabled cars from roads and transferring injured persons to medical care places. However, these fast reactions require more resources such as professional staff and service vehicles from the service providers. Limited funding sources constrain these operations. Thus, it is essential to design appropriate service plans for the service providers to offer in-time assistance to road users at reasonable costs.

This research aims at providing appropriate freeway safety service plans based on historical traffic incident data and freeway road networks. First, clustering methods are applied to detect traffic incident hot spots. Second, with this hot spot knowledge integration, a standby service plan is formulated by configuring the whole freeway network and building a coverage model. Experiments are conducted to assess the performances of the designed plan by several proposed metrics. The data used in these experiments is from the patrol service provided by the Coordinated Highways Action Response Team (CHART) in Maryland in 2016. The proposed service plans are compared and evaluated by several metrics that are computed from evaluation experiments. The data used in the evaluation experiments are provided by the platform of PeMS in California from the incidents they assisted in 2017 due to the lack of vehicle dispatch timestamps in the CHART data. The evaluation experiment scenarios are built based on parts of road networks served by the California Highway Patrol (CHP). The experiment results indicate that the proposed model has the potential to improve upon the current operations by reducing the total response time and using the available service vehicles efficiently.

FREEWAY SAFETY SERVICE PLAN DESIGNING AND OPTIMIZATION MODELING

by

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Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Background and Motivation

Incidents on freeways cause a considerable loss of life and property. Therefore, some organizations provide freeway safety services to assist in detecting and clearing those incidents to improve the roadway's safety condition. These services can provide plenty of benefits to the roadway network and traffic system. For example, these services can reduce traffic congestion and increase travel time reliability on the road network by cleaning the debris and broken-down vehicles from the roadway. Besides, these services can instantly pass the real-time information regarding the incidents to the Traffic Management Centers (TMC) so that the operating staff can update the alert system in time.

Services provided by different organizations can vary widely since there is no standardization on their operation scope. The operation scope may refer to the incident detection methods, operating hours, the number of vehicles in service, and the physical service range, and it may be influenced by funding resources. Based on the features of their service scope, there exist different nomenclature among those programs, such as Freeway Service Patrols (FSP), Emergency Response Units (ERU), Motorist Assistance Patrols (MAP), and Courtesy Patrols (Virginia Department of Transportation 2017). FSP programs serve the freeway as their primary responsibility, and they are mainly operated by state-level government transportation agencies, such as the Department of Transportation (DOT) in the states. The ERU programs usually aim at clearing the incidents on the road network promptly. The MAP and Courtesy

Patrols focus more on towing and removing disabled vehicles from roads to keep a safe network environment, and contracted agencies usually provide these services. The examples of the above programs are listed in Table 1 by different types.

Table 1 Examples of road safety service programs

Program Name	Location	Operated by
Emergency Patrol	Maryland	CHART in partnership with the Maryland State Highway Administration (SHA), Maryland Department of Transportation (MDOT), Maryland Transportation Authority (MDTA), and the Maryland State Police (MSP) (W. Kim and Chang 2012)
FSP program	Monterey County, California	California Highway Patrol in coordination with Caltrans and Monterey County (California Highway Patrol, 2019)
H.E.L.P. (Highway Emergency Local Patrol)	New York	New York Department of Transportation (NYDOT) (New York State Department of Transportation, n.d.)
Safety Services	West Virginia Turnpike	West Virginia Parkways Authority (West Virginia Parkways Authority, 2019)
HEROs (Highway Emergency Response Operators)	Atlanta, Georgia	Georgia Department of Transportation (Georgia Department of Transportation, 2019)
Courtesy Patrol	Tarrant County, Texas	Texas Department of Transportation and the North Central Texas Council of Governments (Tarrant County, 2019)

Road Rangers Service Patrol	Florida	Florida Department of Transportation (Florida Department of Transportation, 2019)
Hoosier Helper Program	Indiana	Indiana Department of Transportation (Indiana Department of Transportation, 2006)
State Farm Assist Patrol Program	Multi-states	StateFarm ® (SateFarm, n.d.)

Many essential factors need to be considered when implementing safety service programs. These factors include operation hours, operation areas, historical event statistics, patrol route choosing, staff ability, equipment types and numbers, and the number of fully equipped vehicles. Different combinations of factors can form different service levels. Regarding the operation hours, some programs offer service only during rush hours, but some programs provide 24/7 service every week. Regarding the operation areas, some of the programs serve selected road segments, but some other programs can patrol on the network of all main freeways within certain boundaries. Based on different essential factors, the patrol services were grouped into three levels (Virginia Department of Transportation, 2017):

Level 1: Baseline level services. The service program at this level mainly consists of offering assistance to disabled motorists. One example of the baseline level service is the Highway Assistance Patrol operated by the Massachusetts Department of Transportation. This program only patrols in Massachusetts’s metropolitan areas during peak hours in the morning and evening five days per week. Another example is the FSP in Dallas. It also operates only on weekday peak hours.

Level 2: Mid-level services. In addition to the baseline level, the mid-level services have longer operation time intervals beyond the peak hours. Some may even be available 24/7 per week for special events and emergency calls. At this level, some examples are the FSP in Iowa state, the FSP in Springfield, Missouri, and the Florida Road Ranger program.

Level 3: Full-function services. These programs offer full-functioning patrols 24/7 every week. These functions include various services such as assisting with the incidents, clearing the incident resources, and assisting disabled motorists. Example programs in this full-function level are the Emergency Patrol provided by CHART in Maryland and the Emergency Response Operations operated by the Kansas City Scout and the Missouri DOT.

The first element that the organizations need to decide is determining which level of services to implement is the operation hours. Longer operation hours are considered if remarkable numbers of incidents arise beyond the peak hours and weekdays. Full-function service level will be preferred if it can save cost by assisting incidents by patrolling instead of dispatching on-call service. Unusual incident rates on specific road segments during off-operation hours may also be considered as a factor.

The second element to be considered is to decide the priorities of routes to operate. Based on the programs’ targets and funding situations, some agencies only patrol freeways, but others may serve both freeway and main arterial road segments.

The third element to be considered relates to selecting the best-fit type and number of vehicles to dispatch. The types involved with traffic management include but are not limited to regular responder vehicles, heavy-duty responder vehicles, incident command vehicles, and TMC response vehicles.

The fourth consideration is communication among TMCs and patrolling vehicles. The TMCs manage incidents remotely, so they need real-time information from the patrolling vehicles and other field personnel and facilities. The data collected by the field staff can contain weather data, incident location, the time of the incident, the number of vehicles and people involved, and the number of blocked lanes. The TMCs can utilize this data to predict potential incident severity and clearance time durations; furthermore, they can decide the most appropriate type and the number of vehicles to support the incidents consistent with their nature.

The safety service programs keep evolving since the funding sources, organization modes, program tasks, and new technologies change. It is essential to design an effective service plan so that the agencies can keep a safer driving environment for road users and improve the cost and benefit balance for the serving agencies themselves.

1.2 Problem Statement

This research aims at studying the freeway safety services operating at the full-functional level. One example program at this level is the CHART program in Maryland. It effectively improves the prevailing traffic condition, helps relieve road congestion, and reduces the chances of further secondary-incident. The current CHART operation provides patrolling services for incidents on freeways 24/7 by keeping the service vehicles traveling on the freeway network. Meanwhile, the patrolling services also require continuous funding and efforts to maintain their operation with the vehicle fees, personnel expenditure, patrolling and fuel costs, etc. Finding the best plan for this patrolling service with the minimum cost and maximum benefits is necessary. Hence, the service plan is better to be economical, efficient, and capable of boosting the operation plans' effectiveness. To stay closer to the above tasks, two problems need to be solved. The first problem is to design proper service plans, and the second one is to choose the plan that fits most based on the evaluation of benefit and cost.

Three types of service plans can be considered for the first problem (Zhu, Kim, and Chang 2012). The first one is to let a fleet of patrol vehicles cruising on the assigned service area. Those cruising vehicles head to the incidents and clean them as soon as they detect them by themselves, or they receive an incident report from the control center. The second one is to set service vehicles stand-by on some pre-selected locations where the risk of having an incident is higher than in other locations. The closest stand-by service vehicle is dispatched to the incident location after receiving notifications from the operation center or calls from other report sources. The third plan is a mixture of both cruising and stand-by vehicles in a service fleet. Under this arrangement, some vehicles are cruising on the road network, and at the same time, other vehicles in this service fleet will stay at the high-risk locations.

For the second problem, it is better to have an index as a quantitative tool to measure the service effects to evaluate the benefits of this patrolling service. In this research, both the benefit and cost methods were applied to this problem. The service cost comprises several parts: fuel cost and gas emission, travel time, and labor costs. The benefit may refer to the reduction of travel time and incident clearance time. It's necessary to propose several detailed evaluation metrics with considerations of both benefits and cost factors.

1.3 Research Objective

This research aims to design an appropriate freeway safety service plan to offer a service that can cover more high-risk road segments, take a shorter response time to the incident locations, and cost fewer recourses. To achieve this purpose, a standby vehicle service plan to implement the FSP based on the optimization model is needed to be created. It's also necessary to configure the freeway into several network links based on the length and risk levels. Besides, the service vehicle placement in each standby location is also an important problem to solve in this plan. Therefore, this research finds the most appropriately designed freeway safety service plan based on solving the above problems. Specified assessment methods are designed to evaluate the performances of different service plans. The evaluation of these candidate methods is considered from the angle of benefit and cost, which can be calculated as the delay time and the operation cost.

1.4 Research Contribution

This research first introduces the background of the freeway safety service programs, including the current operating programs, different service levels, and the considerations when choosing service levels for programs. Then a comprehensive literature review is presented to introduce the current research approaches, findings, and applications. The contributions of the methodologies are as follows.

First, this research develops the service plans by integrating both the time and spatial distribution of incidents on the entire road network as opposed to the existing methodologies that have only been applied to freeway services.

Second, a risk-based network configuration method is developed for each service plan, which can help to assign service vehicles more efficiently.

Third, an optimization model is formulated with multiple objectives to select the vehicle station locations and decide the number of vehicles housed in each station simultaneously. The assumption that each site can have at most two vehicles in the previous studies is relaxed. Instead, this number can be unlimited theoretically and flexibly adjustable based on the actual conditions.

Fourth, a heuristic algorithm is developed to solve the problems of freeway safety services in large-scale scenarios.

Fifth, multiple metrics are created to evaluate the model performance under different real-world conditions.

Lastly, several scenarios are built based on real-world data to evaluate the proposed service plan.

1.5 Dissertation Organization

The dissertation proposal is organized as follows. Chapter 1 introduced the background and motivation of this research. The problem and research objective were also stated in this chapter. Chapter 2 provides a comprehensive review of the literature related to the content of this research. Chapter 3 conducts the incident hot spot analysis by applying the clustering methods followed by the spatial autocorrelation estimation procedure. A case study is also included to examine the practicality of these introduced methodologies. Chapter 4 proposes the standby service problem by designing a risk-based road network configuration method and building a location optimization model. Two sample experiments are conducted to check the model's capability. In Chapter 5, a heuristic method to solve the optimization model is presented. Chapter 6 describes five evaluation scenarios to compare the model's performance to real-world data with multiple evaluation metrics. Chapter 7 presents the results of the sensitivity analysis conducted to check the impacts of different parameters. Chapter 8 summarizes the main work and contributions of this research. The main findings are presented, and future research directions are suggested at the end of this chapter.

Chapter 2 Literature Review

2.1 High-Risk Area Detection on Road Networks

2.1.1 Methodologies

Detecting the high-risk areas of incidents in a road network can provide road operators with a better understanding of safety conditions and crash patterns (Mohaymany et al., 2013). Researchers have applied various methodologies by utilizing knowledge from different domains to detect high-risk segments and areas in the road network. To be specific, this problem can be broken down into the following segments.

The first problem is how to define the "area," which is referred to as the study unit. The research conducted by Aguero-Valverde (Aguero-Valverde & Jovanis, 2006)and Jovanis Steenberghen et al. (Steenberghen et al., 2010), and Eckley (Eckley & Curtin, 2013) set the whole study region as several small areas. The shapes of these pre-defined areas can either be rectangular, circular, or nature-based (Aguero-Valverde & Jovanis, 2006). The boundaries of these small areas can also be selected from the road segment, zip code, main corridors, etc. (Songchitruksa & Zeng, 2010). The advantages of using this method to define the study unit are that it's easy to separate different regions based on the known information. However, this method sometimes fails to capture the road network's line-shape nature (Xie & Yan, 2013). Therefore, some researchers define the study unit as the line segments of the whole road network, which means that instead of small areas, the network is abstracted into connected line-shape arcs (Prasannakumar et al., 2011; Xie & Yan, 2013). The incident duration may also influence the area of the incident hot spots (Li et al., 2018). Considering the influences of the incidents durations, Valenti summarized some models commonly used in incident duration prediction (Valenti et al., 2010).

The second problem is how to choose the appropriate incident hot spot detection methods. Songchitruksa and Zeng (Songchitruksa & Zeng, 2010) found that most studies in detecting hot spots analyzed the incident data after aggregating them. In his research, Norden (Norden, Orlansky, and Jacobs, 1956) proposed that locations with incident frequencies significantly higher than expected can be recognized as incident hot spots. These incident hot spots were traditionally studied by incident counts based on locations (Hauer et al., 2002). However, spatial analysis has been proved as a more appropriate alternative approach (Songchitruksa and Zeng, 2010; De Oña et al., 2013)

M.G. Karlaftis (Karlaftis and Vlahogianni, 2011) summarized two main approaches currently applied in the transportation spatial data analysis area: the statistical method and the neural network (NN). Even though they have some differences in terminology and model-building processes, there are still similarities among them. For example, the probabilistic NN can be considered an equivalent component to the kernel discriminant analysis, which is similar to the relationship that the competitive learning networks can be regarded as equivalent to the k-means clustering. Among the family of spatial data analysis methods, the clustering method is one of the most widely used techniques. Clustering methods can be classified into the following categories: distance-based methods, model-based methods, hierarchical methods, and density-based methods (Saxena et al., 2017).

Among the distance-based clustering methods, the k-means clustering described by Karlaftis (Karlaftis and Vlahogianni, 2011) is widely used due to its efficiency and extendibility (Saxena et al., 2017). An excellent review of the model-based clustering methods is conducted by Bouveyron and Brunet-Saumard (Bouveyron and Brunet-Saumard, 2014). In one research by Juan de Oña et al. (De Oña et al., 2013), the Latent Class Cluster (LCC) and Bayesian Networks were integrated for accident segmentation and factor identification, and this integrated method was proved capable in revealing further information than the methods without prior segmentation. For the hierarchical clustering, the hierarchical methods, a traditional clustering algorithm family, were compared to some non-hierarchical clustering methods by Mingoti and Lima (Mingoti and Lima, 2006). The results didn't show significant differences in their performances. Regarding the density-based model, the KDE method was presented as an efficient way to investigate the traffic incidents' spatial distribution (Xie and Yan, 2013).

The third problem is to check if these clusters are significant or not after detecting them (Eckley and Curtin, 2013). Moran's I is one of the common indices for determining the spatial concentration of incidents with both global and local versions (Soltani and Askari, 2017). Another popular method for analyzing the location-related trend is the Getis-Ord spatial statistic (Getis and Ord, 1992). This statistic, which is usually denoted as ${G_i}^*$, is a relatively new way to check the spatial autocorrelations in point pattern analysis and it is capable to capture the event frequency and spatial correlation values at the same time (Songchitruksa and Zeng, 2010). The Monte Carlo simulation can be applied to test the statistical significance of the above statistics, especially for the clusters calculated based on points events on a network (Steenberghen, Aerts, and Thomas, 2010). In the research of Eckley and Curtin, the spatial clustering of traffic incidents was evaluated by the network-based Know statistics (Eckley and Curtin, 2013).

2.1.2 Applications

Rodrigo Mesa-Arango (Mesa-Arango and Ukkusuri, 2015) studied the demand clustering of truckload freight logistics networks by proposing a novel clustering framework to take the interactions among lanes into account. The lane volumes and prices are changeable and interrelated in this model. Besides, when forming up clustering, both the contemporaneous bilateral utility of the logistics network and the geographic nearness contribute to cluster the demand. Xie and Yan (Xie and Yan, 2013) improved the traditional KDE by integrating it into a real-world road network and applied the model together with the Moran's *I* to detect traffic accident hot spots. Bahir Dar (W/Yohannes and Minale, 2015) also applied the KDE in transportation accident analysis, and a total of 25 incident hot spot sites were detected. A similar study was also conducted in Mashhad, Iran, by Shafabakhsh et al. (Shafabakhsh, Famili, and Bahadori, 2017) with an additional-function analysis as a supplement. The Spatial Getis-Ord statistics was also used as a reference to identify the concentrated areas for traffic crashes (Songchitruksa and Zeng, 2010). Furthermore, the Monte Carlo simulation method was applied in Brussels in Belgium to detect dangerous locations for traffic incidents in a road network (Steenberghen, Aerts, and Thomas, 2010).

2.2 Road Incident Services

2.2.1 Service plan modeling

It can be found from the literature that mathematical programming models are the most widely applied methods in the road incident service area. Among the variety of mathematical programming models, both the family of vehicle routing models (Lenstra and Kan, 1975) and the family of location-allocation models (Farahan and Hekmatfar, 2009), including the covering models (H. Kim et al., 2014), were utilized widely in the accident service field.

2.2.2.1 Models for vehicle routing problems

I. Stochastic Vehicle Routing Problems

The classical VRP model usually fails to capture the nature of the real world's transportation system (Kumar and Panneerselvam, 2012). One reason is that parameters associated with the real transportation systems are uncertain and non-deterministic, mainly involving customer presence, demand, and travel time. So many variants to the traditional VRP are generated to deal with the uncertainties in the problems, and these variants are categorized as the stochastic vehicle routing problem (SVRP) (Berhan et al., 2014).

The SVRP problems can be classified into four types based on different stochastic components. First, the VRP associated with stochastic demand is the most studied topic among all the SVRP problems based on current literature surveys (Kořenář, 2003). The second type is the VRP with random service object occurrences. This problem can be viewed as a direct transformation from the traveling salesman problem (TSP) with the stochastic customer. Each service object has deterministic demand but presents some probability distribution (Lei, Lin, and Miao, 2015). The combination of the previous two types forms the third type, which has random service object occurrences and random demand (Mukhopadhyay et al., 2017). The fourth type is the VRP with stochastic travel time. Both the service time and travel times can be set as stochastic components (Laporte, Louveaux, and Mercure, 1992). In this case, vehicles carry a penalty having a proportional relationship to the cost of driving through the corresponding route. The cost here is usually stated as travel time. Mathematical programming models applied to formulate this problem are the chance-constrained model, the three-index simple recourse model, and the two-index recourse model.

II. Time-dependent Vehicle Routing Problems

The travel time in the road networks is a time-varying quantity, and the most suitable way to depict it is to describe it a priori in a probabilistic way. The leading causes of its randomness include traffic jams, road incidents, road construction works, severe weather, etc.

Time-dependent routing amounts to designing the “best” routes in a graph in which arc traversal times may vary over the planning horizon (Ichoua, Gendreau, and Potvin, 2003). Gendreau (Gendreau, Ghiani, and Guerriero, 2015) reviewed the time-dependent routing problems by classifying them into the following categories: travel time and speed models (deterministic and stochastic), point-to-point route planning, time-dependent TSP and its variants, time-dependent VRP, and time-dependent ARP. Figliozzi (Andres Figliozzi, 2012) proposed benchmark problems such as time-dependent VRP with hard time windows and soft time windows, respectively. The research of (Gao and Chabini, 2006) pointed out that the travel times are commonly correlated arc-wise and time-wise. In a large network, arc travel times interact with each other over a given period if the randomness is caused by the weather, while they are correlated subsequently if the randomness is attributed to incidents. In the paper of (Jung and Haghani, 2001), a formulation for dynamic VRP with time-dependent travel times together with a genetic algorithm was proposed.

2.2.2.2 Models for coverage problems

Coverage models are a family of models that are usually applied in solving the location-allocation problems.

Leknes (Leknes et al., 2017) constructed a problem of locating and allocating emergency medical vehicles among stations and demands based on the Maximum Expected Performance Location Problem by taking the regions with hierarchical demands in a format of mixed-integer linear programming modeling. Instead of linear mathematical models, Mukhopadhyay proposed a non-linear mathematical program that can seek the maximum expected incident coverage results by taking the incident prediction mechanism into account (Mukhopadhyay et al., 2017). Kaan Ozbay built mathematical programming models with probabilistic constraints to describe the incident management and service vehicle dispatch problem (Ozbay and D, 2004). In the research of Lou (Lou, Yin, and Lawphongpanich, 2011), this problem was studied with a focus on congestion mitigation and the objective of minimizing the total average incident response time by assigning service vehicles to each designed group of freeway segments. Daneshgar studied the patrol deployment planning problem in a similar 2-steps way after dividing the whole network into several parts for patrolling and defining each part as a beat. Then road segments are assigned to different beats in the network. In the end, the number of vehicles of each beat is determined (Daneshgar, 2018).

2.2.2.3 Models for Integrated Problems

Some researchers constructed VRP models with different constraints to meet the requirements of real-world problems. Yang et al. (Saini Yang, Hamedi, and Haghani, 2005) developed an optimization model that integrated the VRP to the online dispatching scenarios considering real-time traffic information. This research accounted for the concerns of service area coverage by relocation and redistribution of idle standby vehicles. The integrated model can also be formulated by joining the coverage and the median objectives of demand area supplies (Yao, Zhang, and Murray, 2019). In Keskin's (Keskin et al., 2012) research, the integration of maximum coverage and patrol routing problem was studied based on the scenario of patrolling of state troopers on highways and was named Maximum Covering Patrol Routing Problem (MCPRP). The objective of this model was to maximize the total amount of service time, and the service time was defined as the time that falls into the time window of a traffic accident hot spot with a mixed-integer linear programming model. Sorensen and Church formulated a hybrid model combining the expected coverage and local reliability to solve emergency health support location problems (Sorensen and Church, 2010). The local reliability was quantified by solving the Maximum Availability Location Problem (MALP).

2.2.2 Solution methods

The general branch and cut algorithm can be utilized to solve the chance-constrained model, the three-index simple recourse model, and the two-index recourse model in the VRP with stochastic travel time problems (Laporte, Louveaux, and Mercure, 1992).

Traditional constant time VRPs with time windows can be solved successfully by the local search methods and metaheuristics. However, as Figliozzi (Andres Figliozzi, 2012) stated, a significant degree of adjustments to those methods is needed for solving the VRPs with time-dependent travel times.

In solving the integrated VRP problem, Yang et al. addressed the issues based on two scenarios to get the optimal route. In essence, one used a static shortest path algorithm, and another one used the time-dependent shortest path algorithm (Saini Yang, Hamedi, and Haghani, 2005). Keskin et al. chose a heuristic method based on local and tabu search for solving the integrated coverage and routing problem (Keskin et al., 2012). The constraint-based solution procedure was also applied in Yao's research (Yao, Zhang, and Murray, 2019).

For the mixed-integer linear programming coverage models, the iterative procedure is a common method in past studies. Meanwhile, the standard methods, such as the branch-and-bound method, are also applicable to solve these models with a deterministic theoretical convergence (Leknes et al., 2017).

Mukhopadhyay proposed a framework by improving the greedy random adaptive search (GRASP) to solve the issue generated by the non-linear and nonconvex constraints for the non-linear maximum coverage models (Mukhopadhyay et al., 2017).

Heuristic algorithms have been proved as an effective way of problem-solving in past literature for deployment problems. Lou (Lou, Yin, and Lawphongpanich, 2011) applied the dual-based greedy algorithm to decide how many vehicles should be assigned to each beat by using the dual information and then producing an improved plan in a greedy manner. Large scale problems can be solved by the neighborhood search algorithms that include the variable-depth method, the network flow method, the restricted polynomial-time solvable sub-problem method, and methods that integrate some or all of them (Ahuja et al., 2002). Besides, the meta-heuristic approaches, such as simulated annealing and its derived probabilistic search algorithms, are also applicable to solving problems (Lou, Yin, and Lawphongpanich, 2011).

2.2.3 Service evaluation studies

Constructing scenarios to simulate the real world is widely used by researchers to generate meaningful metrics to evaluate the performances of proposed models. Some simulation scenarios generate traffic flow and accident events as the time stamp moves (Saini Yang, Hamedi, and Haghani, 2005).

The B/C ratio is utilized in many studies related to the performance of the freeway service program evaluation. Chou and Miller-Hooks (Chou, Miller-Hooks, and Promisel, 2010) presented a simulation-based methodology to assess the influences on cost savings of travel delay, gas consumption and emissions, and secondary accidents. This methodology was applied in the H.E.L.P. program, and the B/C ratio was utilized to assess the results. Yang et al. (Shu Yang, Lu, and Wu, 2013) identified the accidents' economic cost by utilizing the techniques based on the geographic information system (GIS). The investment return on freeway service programs was also studied based on the economic and environmental cost of freeway incidents and service operations. Dougald and Demetsky (Dougald and Demetsky, 2008) assessed the investment return on the safety patrol programs in Northern Virginia and Hampton Roads based on their B/C ratios. In their research, the benefits included both total annual delay and fuel benefits, and the cost was considered as the total annual cost.

Another index that can be applied in performance checking for the freeway service programs is the duration of the incident detection process. The H.E.L.P. program was found to have a significant influence on the incident detection procedure by reducing the total incident duration to 20 minutes (Haghani, 2006).

2.4 Summary and Research Gaps

The methodologies for both high-risk area detection on road networks and incidents services were reviewed in this chapter. Some research gaps are found after summarizing this literature. First, efficient integration of the spatial data analysis methods and the road incident planning problems does not exist adequately. Few studies designed service plans to sufficiently take into account the incidents' unbalanced distribution on both time and location. Second, the service plans for freeway incident assistance need to be improved and properly evaluated in a large-scale network. Finally, the demands for solving large-scale problems are increasing, and the algorithms designed specifically for solving freeway service planning problems need to be developed.

Chapter 3 Traffic Incident Clusters Detection

The traffic incidents occur randomly on the road network. However, the spatial distribution of incidents' occurrence may have specific patterns and features within a given time horizon. These patterns can be identified as incident hot spots on the road networks indicating higher risks of incident events at these locations. Therefore, it is essential to have a further understanding of the characteristics of incident hot spots. In this chapter, clustering methods are introduced to detect the locations of incident hot spots. These locations' spatial autocorrelations are then further measured by the Moran's *I* and Getis-Ord GI* statistics. A case study at the end of this chapter is conducted to check the performance of detecting incident hot spots.

3.1 Methodologies for Incident Spatial Cluster Identification

3.1.1 The single variate kernel density estimation (single KDE)

The KDE method usually requires two parts of input: point data and network data. Specifically, in traffic incidents, they are 1) incident location data logged by latitude and longitude coordinates, and 2) the road network data recorded as separated road segments with geographical information. Hotspot analysis uses vectors instead of rasters to identify the locations of statistically significant hot spots. For general hotspot analysis, points are usually aggregated to polygons. However, it makes more sense for the freeway patrol service to aggregate traffic incidents into line segments than polygons due to the characteristics of the road network.

To conduct the KDE analysis, the first step is data pre-processing. This step is to make the given raw data sets compatible with the KDE model's requirements. This model needs two data sources: the data of points and the data of the segmented network. Here the data of point refers to the incident locations, and the segmented network is the abstraction of the freeway network. Each incident point needs to be assigned to its closest road segment, and the distance of the point to its corresponding segments is also calculated. Here the “closest” is measured by the Euclidean distance. Each road segment has another attribute added, indicating how many incident points are aggregated to this segment.

The second step is to choose a suitable kernel function. This study adopts the Epanechnikov kernel. Even though other shapes of kernels like a triangle kernel or a Gaussian kernel may also work, the Epanechinikov kernel is still the most adaptable one (Bíl, Andrášik, and Janoška, 2013). The reason is that it can reflect the extent of the uncertainty of the incident’s actual location, and also it has the minimum asymptotic mean integrated squared error. The definition of the Epanechnikov kernel is shown in equation (1).

$$K_h(\boldsymbol{x}) = 0.75 * \left(\frac{\left(1-\left({}^{x}/_{h}\right)^2\right)}{h}\right) * I_{(-h,h)}(\boldsymbol{x}) \tag{1}$$

where h stands for the bandwidth, and $I_{(-h,h)}(x)$ is an indicator function with values of $(1, 0)$.

The third step is to choose a value of the kernel’s bandwidth parameter h. Generally, the bandwidth value in the highway area is larger than in the urban area, and this value could range from 0.03 miles to 0.3 miles [15][57]. Since the kernel value is non-negative, the largest distance of incident points to their assigned segments is selected as the candidate bandwidth value so that each incident point can be associated with a kernel value by calculating from the equation (1).

The fourth step is to calculate the KDE value for each road segment. The KDE function is a summation value of a series of kernel functions (Bíl, Andrášik, and Janoška, 2013). Its function is shown in equation (2).

$$\hat{f}(\boldsymbol{x}) = \frac{\sum_{i=1}^{n} K_h(x - X_i)}{n}, \qquad i = 1, \ldots, n \tag{2}$$

The incident points within their assigned road section are expressed as $(X_1, X_2, \ldots, X_n)$.

3.1.2 The multivariate kernel density estimations (multivariate KDE)

The traditional single KDE can consider only one feature when calculating the density. For instance, only the distance feature can be taken into account in the single KDE method. However, other features such as the incident durations are also not neglectable when considering the incidents' influences on the whole road network. The incident durations closely relate with the incidents' type and severity condition based on 2016 CHART data. The detailed incident durations with different incident types are listed in Figure 1. Using the multivariate KDE method, the influences of incident severity can be taken into account by using the incidents' durations.

Therefore, the multivariate KDE method, which can carry the information of both distance features and incident durations, may fit this problem better (Zhang et al., 2011). As a variate and extension of the single KDE, the multivariate KDE can be expressed in equation (3).

$$\hat{f}(\boldsymbol{x}) = \frac{\sum_{i=1}^{n} \left(\prod_{k=1}^{d} K_{h_k}(x - X_i)\right)}{n}, \qquad i = 1, \ldots, n; k = 1, \ldots, d \tag{3}$$

where d stands for the number of considered features, and the other parameters and variables are the same as equation (2).

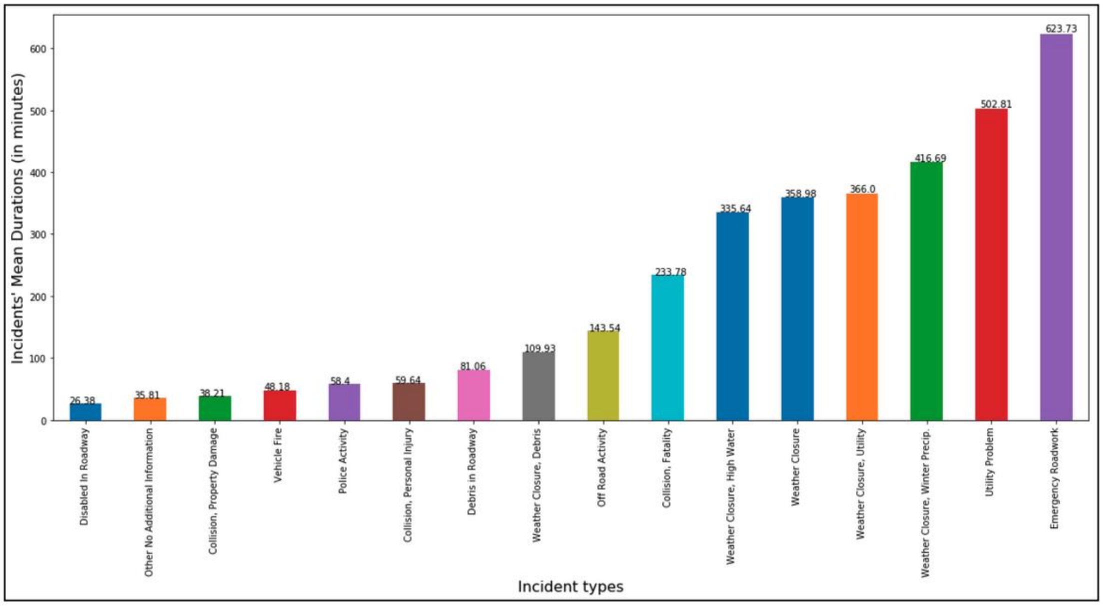


Figure 1 Durations of different incident types (minutes)

3.2 Methodologies for Spatial Autocorrelation Analysis

3.2.1 Spatial autocorrelation concept configuration

Spatial clustering is a process to identify consistent groups of observations based upon their features and attributes (Eckley and Curtin, 2013), and spatial autocorrelation is a concept in the geographic information system that measures the degree of similarity between nearby observations (Liu and Sharma, 2017). Spatial autocorrelation analysis has two components: testing and visualizing the statistic of correlation (Anselin, Syabri, and Kho, 2006). The Moran's *I* is a most commonly used statistic to check if the value of a variable (e.g., one road segment's KDE value) has any correlation with the value of the same variable but in another neighboring location (Prasannakumar et al., 2011). The hotspot function Getis-Ord GI* is also applied to test whether the values of variables have significant relationships with their locations or not.

I. The Moran's *I* statistic

The Moran's I statistic can check if there is a spatial concentration of traffic incidents. This statistic can be presented as equation **Error! Reference source not found.** (Blazquez and Celis, 2013).

$$I = \frac{N}{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}} * \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{N}(x_i-\bar{x})^2}, i = 1, \ldots, N; j = 1, \ldots, N \quad (4)$$

In equation **Error! Reference source not found.**, w_{ij} stands for the spatial weight between location i and j, N is the total number of locations, x_i and x_j are attribute of incident points at location i and j separately, and $\bar{x}$ is the average of the incident points' attributes.

The Moran's I statistic ranges within $[-1, +1]$. Higher degrees of spatial clustering of analogous values in the dataset brings out larger positive values; on the opposite, higher degrees of spatial spreading are indicated by larger negative values. If Moran's *I* is equal to zero, it means the distribution pattern of this feature is stochastic.

II. The spatial Getis-Ord GI* statistic

The application of Getis-Ord GI* here is to check if the incidents' occurrences have any relationship with their location information. This statistic is shown with the notation G_i^* is computed as equation (4).

$$G_i^* = \frac{\sum_{j=1}^{N} w_{ij}x_j}{\sum_{j=1}^{N} x_j} \quad (4)$$

where x_j refers to the attribute value for feature j, w_{ij} is the spatial weight between locations i and j, and N is the total number of locations.

In the ideal condition, if the distribution of variable $\boldsymbol{x}$ is normal, the G_i^* statistic is also normally distributed. However, when $\boldsymbol{x}$ is not a normally distributed variable (e.g., the KDE value of incidents), G_i^* will not be normal any longer. In this condition, we can standardize the G_i^* by following the equation (5) (Soltani and Askari, 2017). This equation changes the G_i^* into a Z score, and hence a statistically significant analysis can be applied to this problem.

$$Z(G_i^*) = \frac{\sum_{j=1}^{N} w_{ij}x_j - \bar{x} - \sum_{j=1}^{N}(w_{ij})^2}{s\sqrt{\frac{N\sum_{j=1}^{N} w_{ij}^2 - (\sum_{j=1}^{N} w_{ij})^2}{N-1}}} \tag{5}$$

3.2.2 Key node selection and adjustment

After finding out the high-risk road segments, the mid-points of these segments are selected as key nodes for further network abstraction. Choosing these key nodes makes building network models convenient, and it can help determine the standby location for cars more appropriately. However, in real-world practice, it is not suggested that service vehicles be placed at locations where they may influence the regular traffic flows. Putting vehicles in some selected road segment mid-points may block the lanes and cause congestions. In this case, manual adjustments for key nodes based on the actual roads are necessary after automated detections.

3.3 Case Study: Preliminary Analysis

In this section, a case study was conducted to explore the performance of the introduced methodologies for detecting traffic incident clusters on the road network. The incident clusters were first detected by utilizing the multivariate KDE method, and then their stability was evaluated by calculating the specific spatial statistics.

3.3.1 Data description

The data applied in this case is from one region that is served by CHART in Maryland. There are two types of data included to conduct this analysis. One is the traffic incident data, and another is the corresponding road network data. The traffic incident data was recorded in two separate files named “Event” and “Location,” respectively. The Event file contains each incident’s basic description and the timestamps of the event opening and closing. The “Location” file includes each incident’s location description and geographic coordinates. Both files share a common column of “Event_ID” as the primary key that links them together.

In the incident data, there are a total of 35881 recorded incidents in 2016 spread in the entire state of Maryland. The number of incidents located within 10 miles (Haversine distance) of the freeways is 29042. Based on the primary key mentioned above, this data can provide each incident’s type, location, duration, timestamps of each step in incident cleaning, and so on. The total length of the served freeways is 805.79 miles. The locations of these incidents and the freeways are shown in Figure 2.

A subset of the whole freeway network is used in this case analysis. In this sub-network, there are a total of 424.28 miles of roads covered. For further study purposes, the whole network was divided into several small segments, each with a length of approximately one mile. The incidents located within 10 miles of the freeway and lasting no longer than one day (1440 minutes) were considered as involved incidents. After processing, the whole network was divided into 364 small road segments, with 23680 traffic incidents involved. The segmented road network is shown in Figure 3.

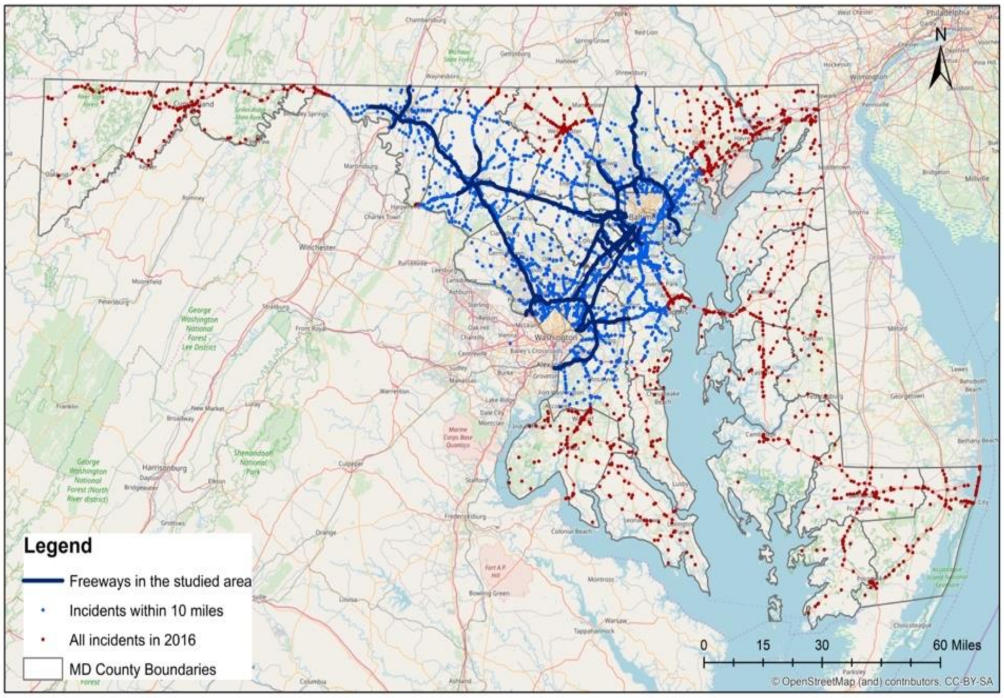


Figure 2 The incidents within 10 miles of freeway in the studied area in 2016

Figure 3 The segmented road network in the study area

The longest segment is 3.15 miles, and the shortest one is 0.41 miles. The histogram of the length distribution of all road segments is presented in Figure 4.

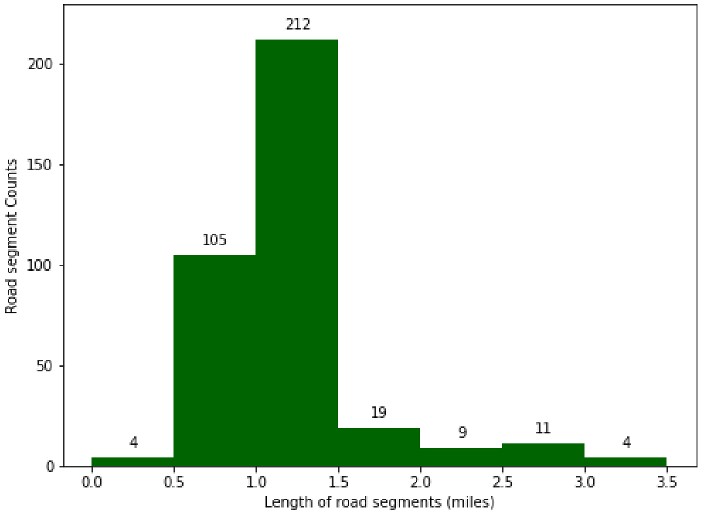


Figure 4 The distribution of the lengths of road segments

3.3.2 Incident clusters detection by the multivariate KDE method

The KDE method introduced in the previous section was applied to the sample data described above.

Step 1: Data pre-processing

The incident data and the road network were spatially joined based on the Euclidean distance between each incident to its closest road segment. The outputs shown in Table 2 can be generated by this spatial joining step and utilized in further processes.

Table 2 Useful outputs generated by joining data spatially

1) The ID of the nearest road segment to which each incident was assigned;

2) The incident counts on each road segment;

3) The distance between each incident and its assigned road segment.

The distribution of the number of incidents assigned to each road segment after spatially joining the data is shown in Figure 5.

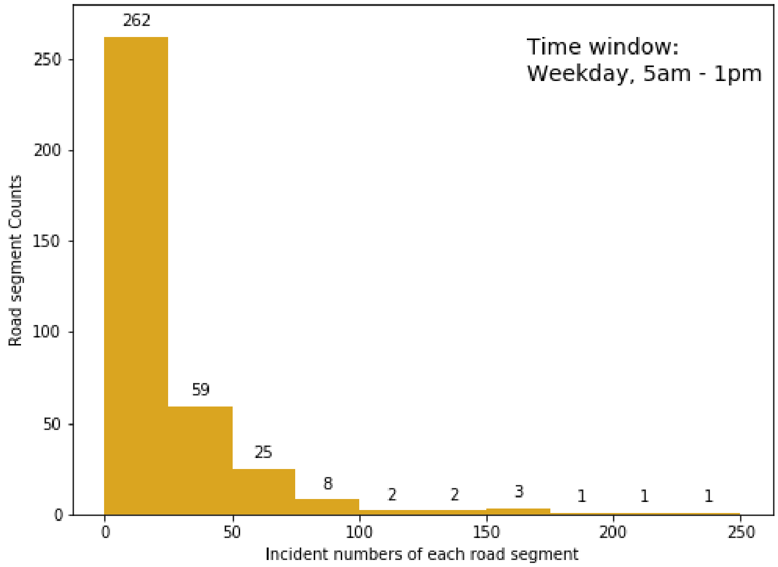


Figure 5 Distribution of the number of incidents per road segment after spatial joining

Step 2: Kernel function selection

Based on the methodologies introduced in the previous sections, the Epanechinikov kernel was selected to be the kernel function for further density estimation.

Step 3: Bandwidth selection

The nature of the Epanechnikov kernel function requires that all the kernel values computed from this function should be non-negative. Two bandwidth values, h_1 and h_2, are needed for taking into account both distances and durations of incidents accordingly.

For deciding h_1 , the maximum distance between incidents to their corresponding road segment is $w = 9.8053$ miles. A series of candidate values were tested to find out the bandwidth h_1. The series of candidate values are:

$$c = 0.05 * \theta * w, \quad \theta = 0,1, \dots ,40$$

The minimum kernel values of each bandwidth are shown in Figure 6. The computation result shows that the first non-negative value appears when $\theta = 20$. It indicates that all bandwidth values larger than the longest distance from incidents to closest road segments are eligible for the Epanechnikov kernel.

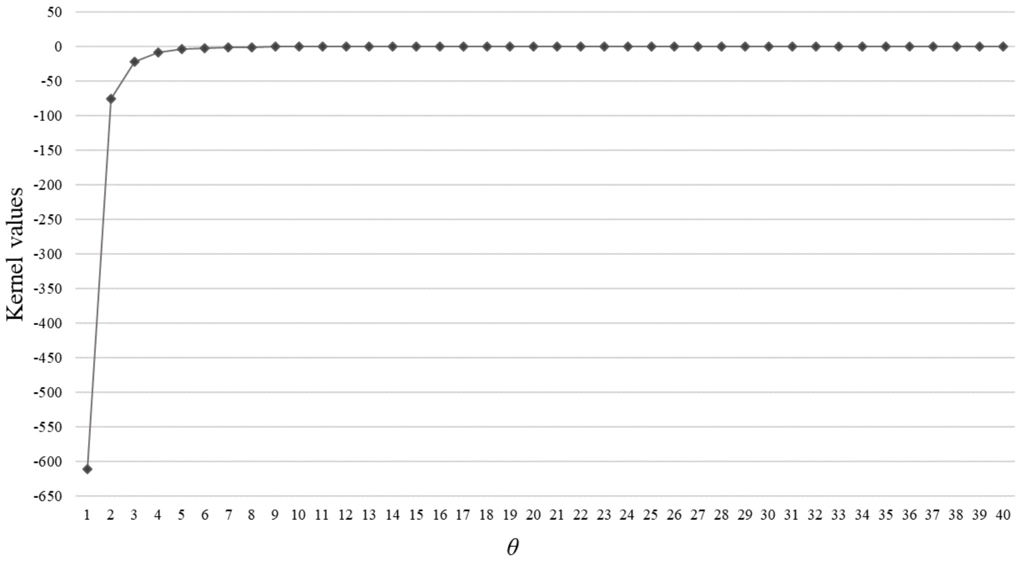


Figure 6 Minimum kernel values computed from different bandwidths

Further checks were also made to select the appropriate bandwidth. The KDE values of some sample distance bandwidth values are plotted in Figure 7. These results present that the bandwidths smaller than the longest distance result in negative kernel values, and larger bandwidth values dismiss the value differences between road segments. Therefore, $\theta = 20$ was selected for computing the bandwidth h_1.

For h_2 the duration bandwidth is decided by the planning horizon. In practice, the planning horizon can be divided into five time windows: peak hours and non-peak hours on weekdays and weekends separately (Daneshgar, 2018). Specifically, the five time windows are listed in Table 3. The duration bandwidth for each time window is the percentage of the time window's length in minutes.

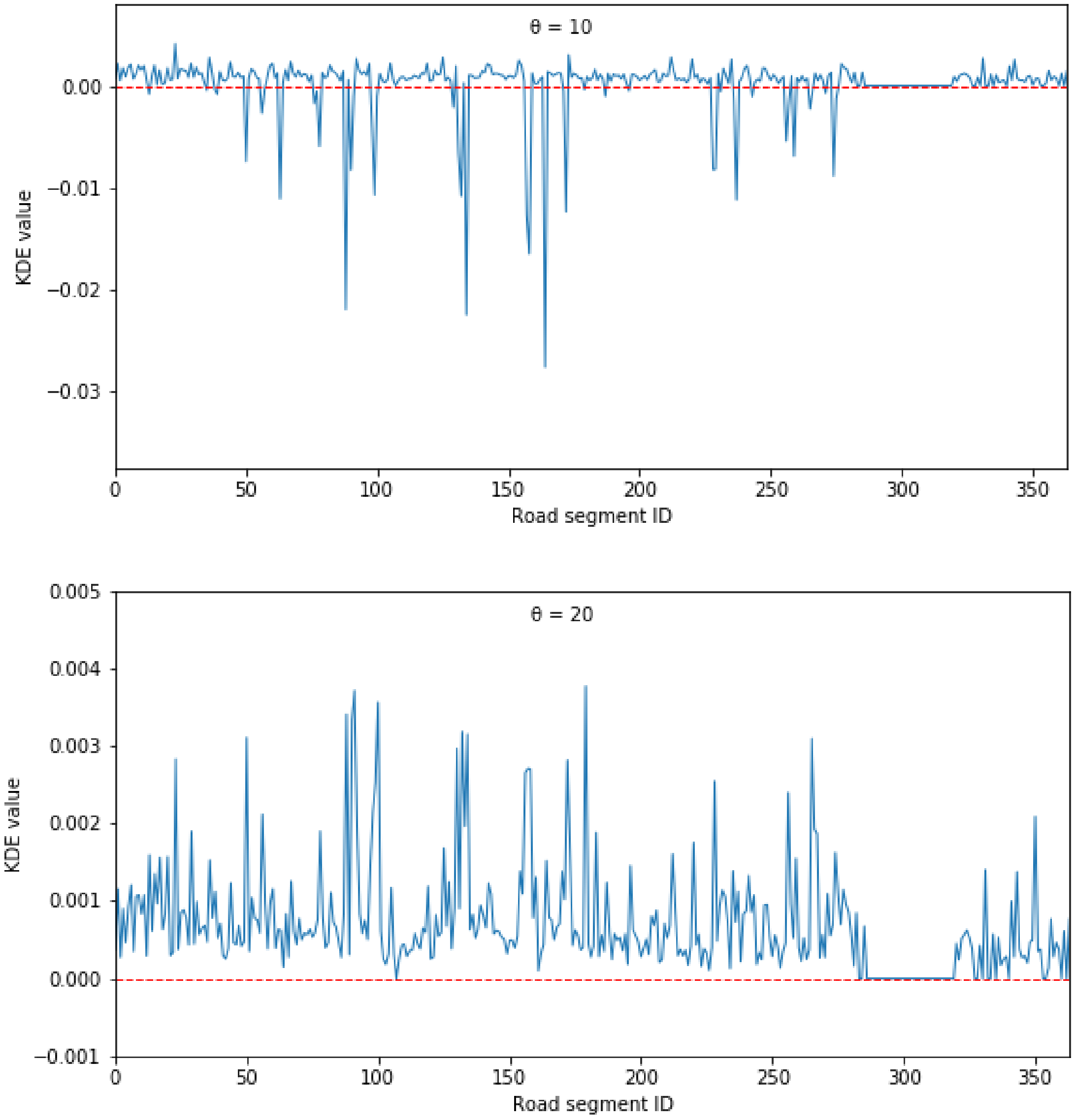


Figure 7 Single distance KDE values on sample bandwidths

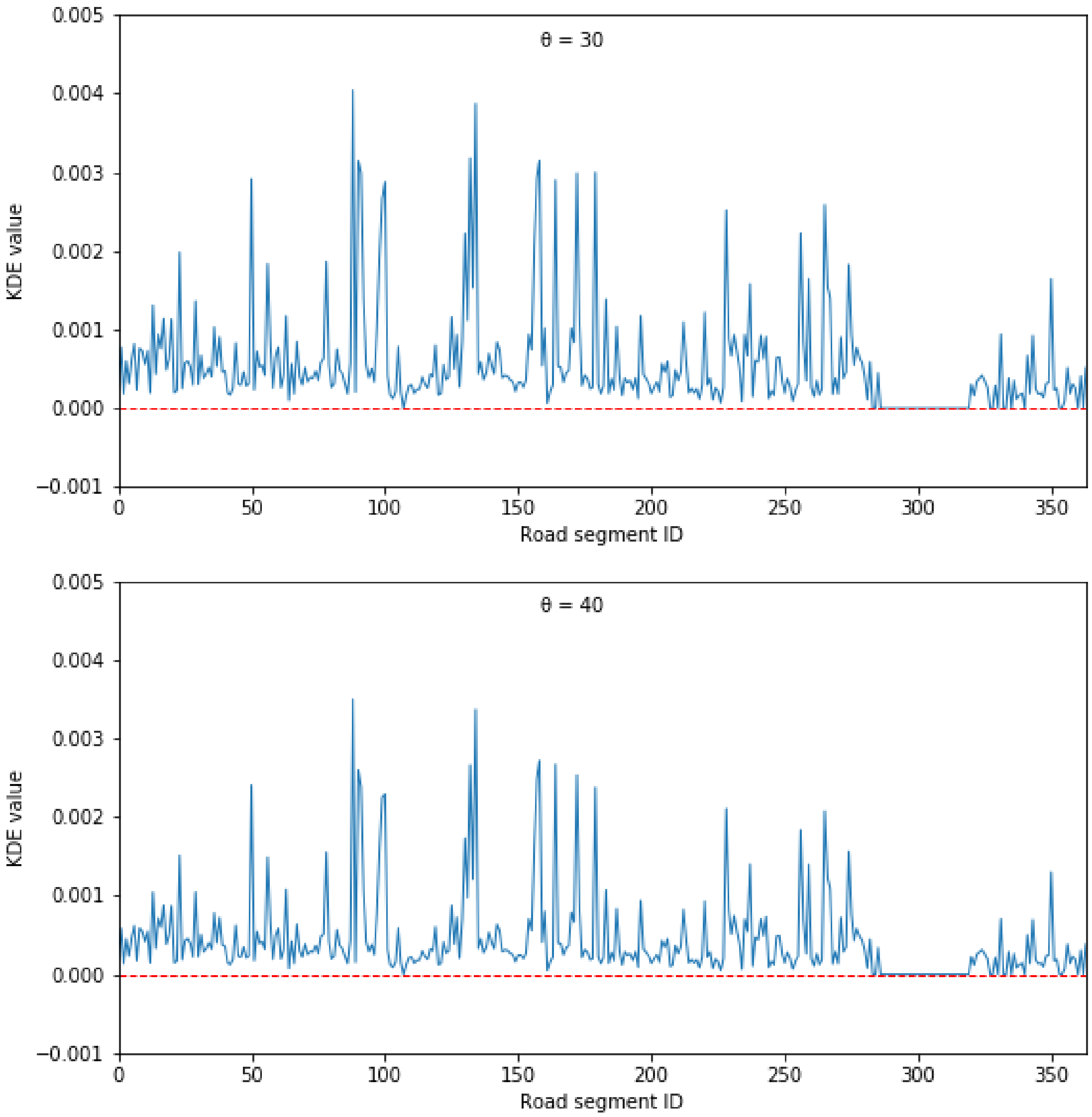


Figure 7 (Cont'd) Single distance KDE values on sample bandwidths

Table 3 Time windows for planning

Time window 1	Weekday	5 am – 1 pm
Time window 2	Weekday	1 pm – 9 pm
Time window 3	Weekday	9 pm – 5 am
Time window 4	Weekend	5 am – 5 pm
Time window 5	Weekend	5 pm – 5 am

Take the time window of morning peak 5 am – 1 pm on weekdays as an example. The duration of this time window is $tw = 480$ minutes. So the bandwidth is:

$$h_2 = \varepsilon * tw, \qquad \varepsilon = 0.01, 0.02, \ldots, 1$$

With the methods proposed in the previous sections, the bandwidth value when $\varepsilon = 0.66$ was found to not only meet the non-negative requirement but also reflect most differences among segments. So that $h_2 = 0.66 * 480 = 316.8$.

Step 4: Calculate the multivariate KDE value

The KDE values considering the features of both distances and durations were calculated in this step. The calculation results are presented in Figure 8 and Figure 9. Figure 8 illustrates the histogram of the KDE values' distribution for the road segments. The values and the map for road segments with different KDE values are shown in Figure 9 and Figure 10, respectively.

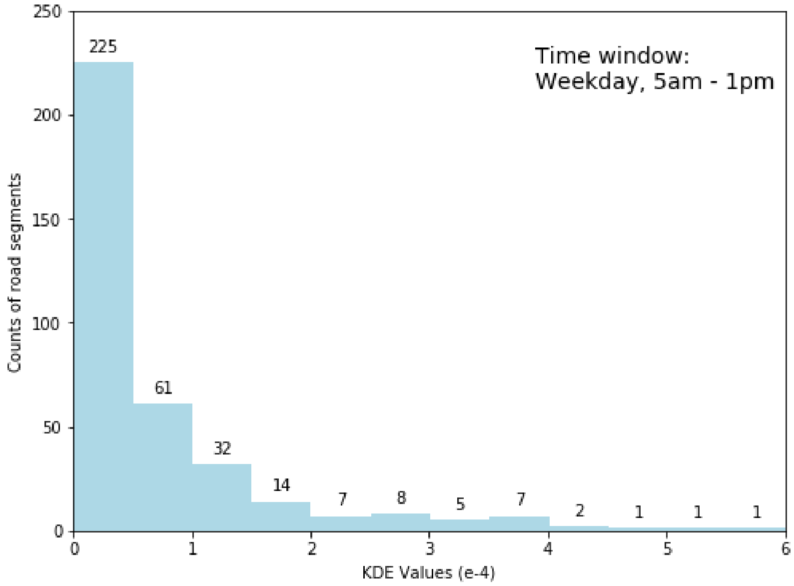


Figure 8 Distribution of the KDE values for road segments

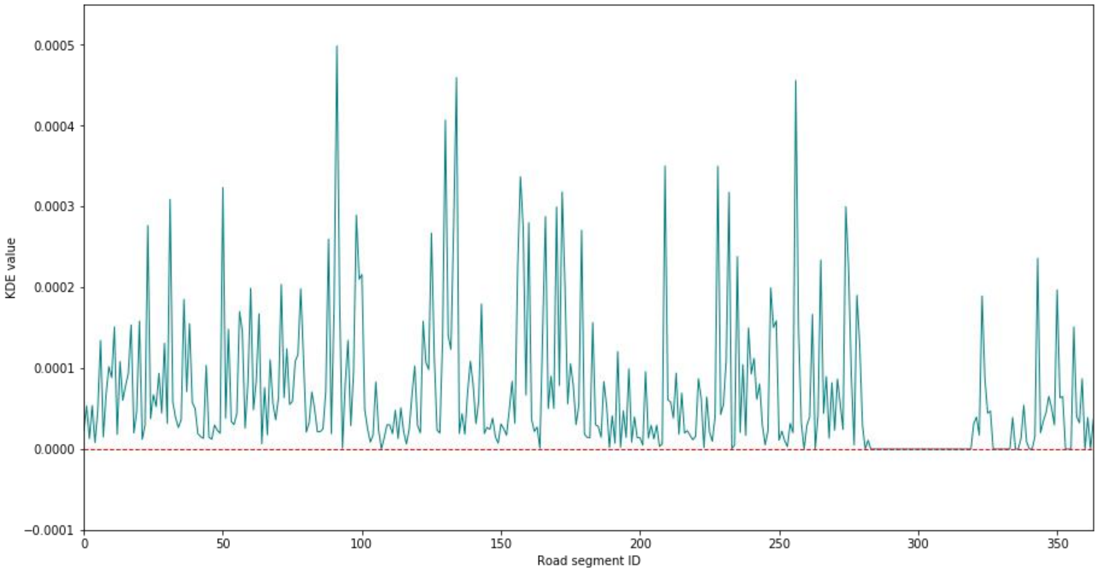
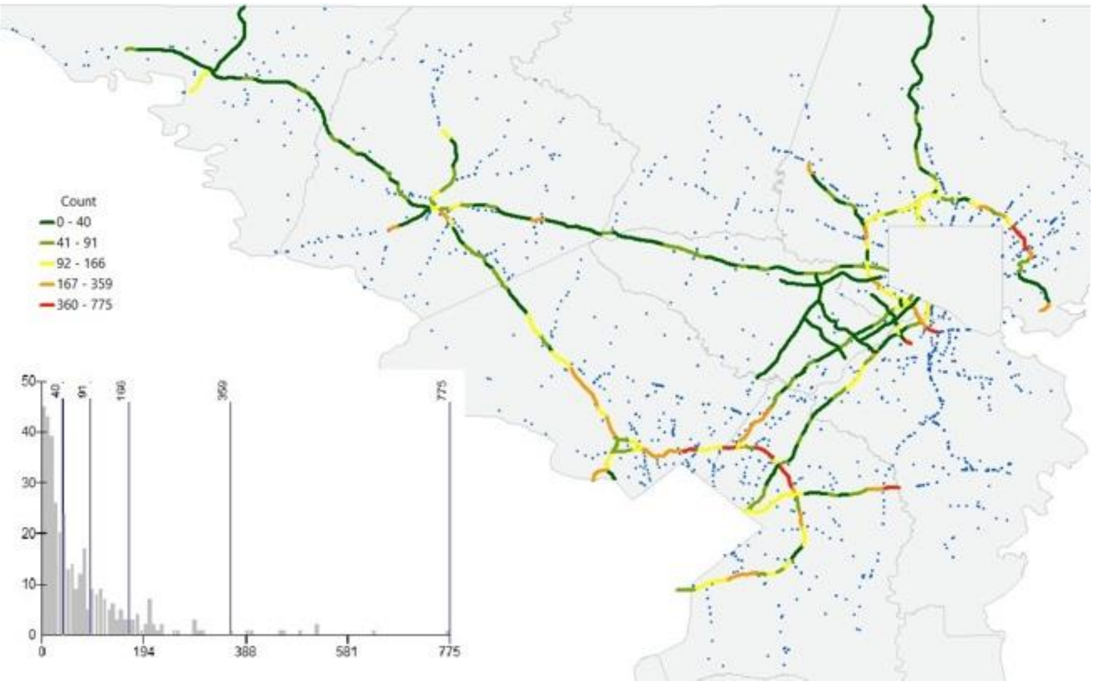
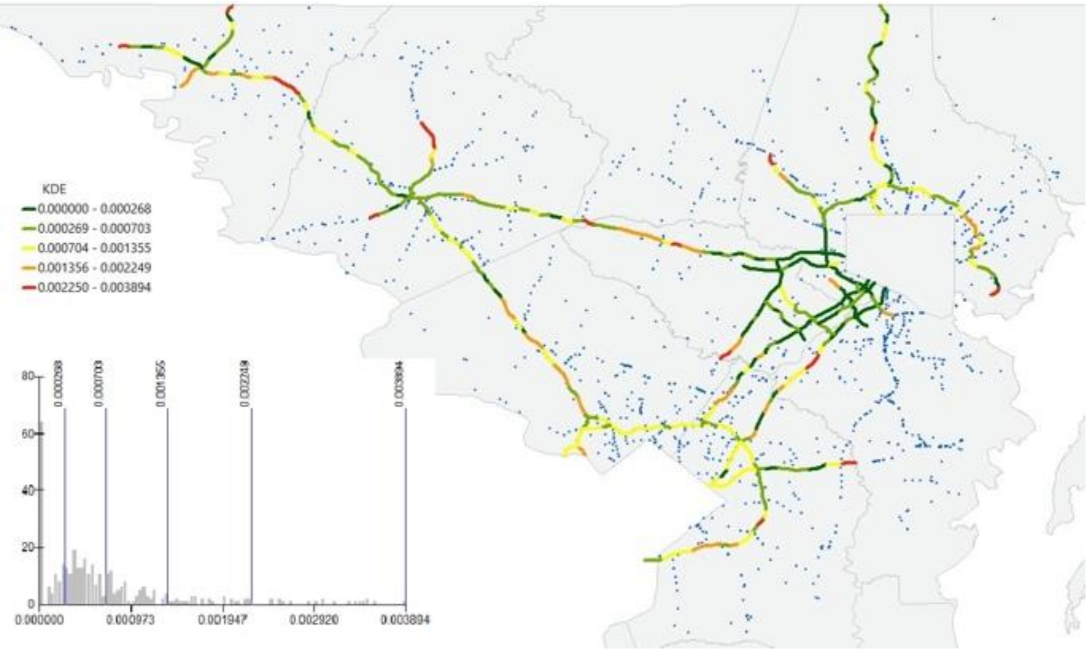


Figure 9 KDE values for each road segment

The four maps in Figure 10 display different styles of the spatial distribution of incidents under different evaluation indexes. By showing the road segments with different incident counts, Figure 10 (a) offers a reference to the detection results of the KDE methods. Figure 10 (b) shows that the single-distance KDE method displays more hot spot segments than the incident count only, and the hot spots are located widely on the whole network instead of a few regions. Figure 10 (c) shows that the high-risk segments detected by the single-duration KDE method provide a different spatial distribution style than other methods.

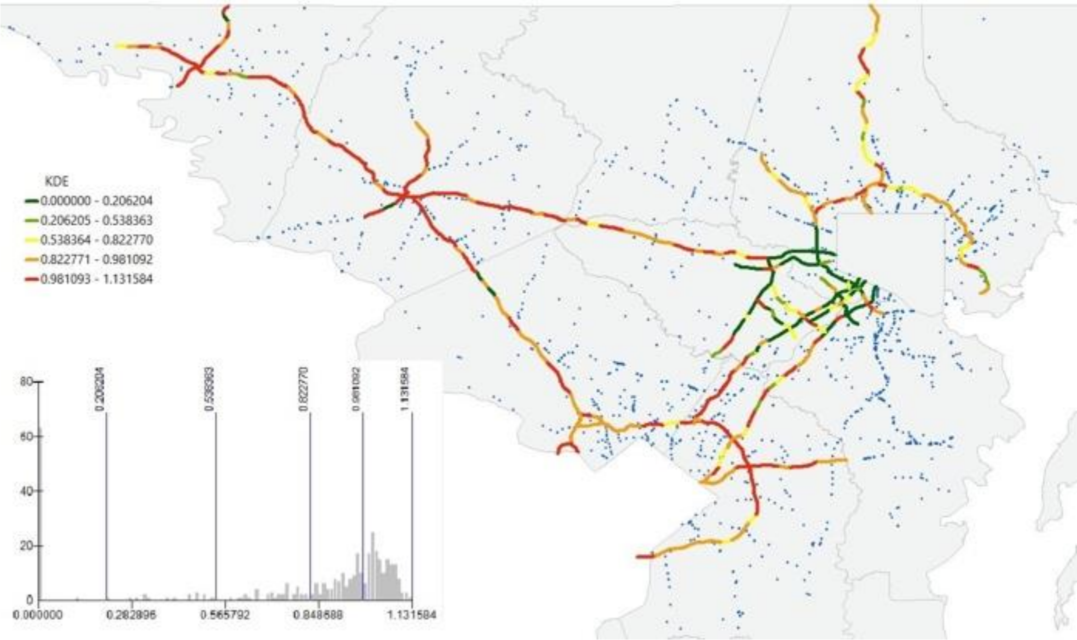


(a) Road segments with different incident counts

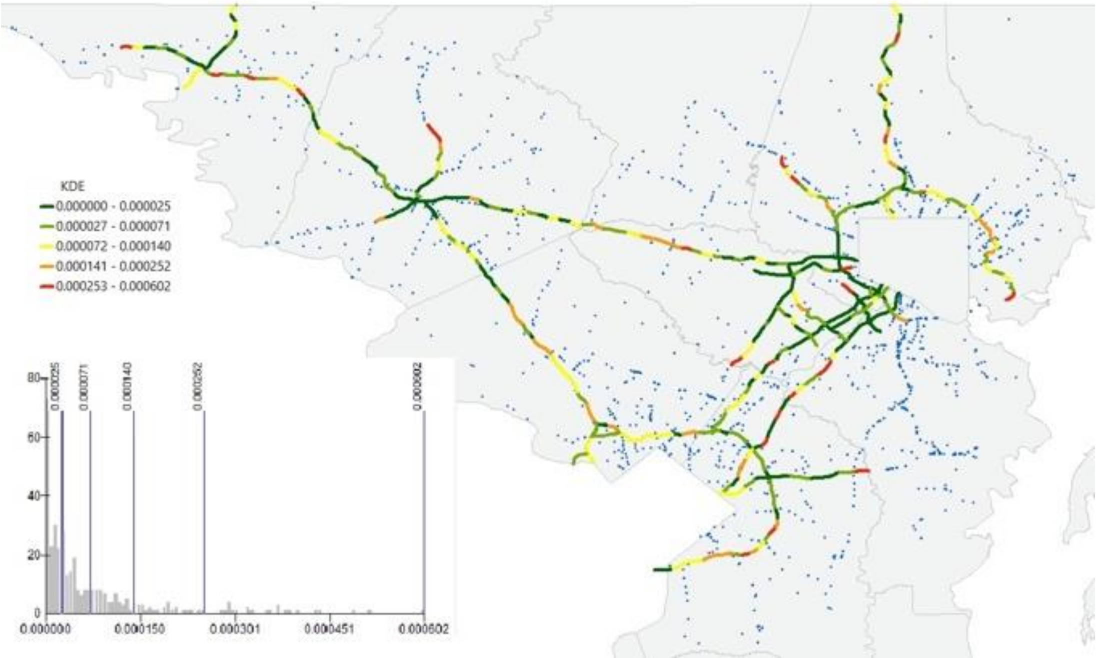


(b) Road segments with different single distance KDE values

Figure 10 The map of road segments with different KDE values



(c) Road segments with different single duration KDE values



(d) Road segments with different multivariate KDE values

Figure 10 (Cont'd) The map of road segments with different KDE values

More segments are recognized as medium or high-risk levels than other maps when taking the incident duration into account only. Figure 9 (d) has a similar spatial distribution style to

Figure (b), but the risk levels detected by the single distance KDE decrease to medium or low levels after changing the detection method to the multivariate KDE method. Though the multivariate KDE method considers the impacts from distance and duration factors, the spatial distance plays a more significant role than the incident durations in the hot spot detection.

3.3.3 Spatial autocorrelation analysis

The spatial correlation was checked by using Moran's I. The null hypothesis of no spatial correlation is tested by assuming normality of I under this hypothesis. If $I_{observed} > I_{expected}$ significantly, positive autocorrelation is indicated. Otherwise, negative autocorrelation is detected. The $I_{observed}$ that is computed from the data is 0.04540, and the $I_{expected}$ that is, the expected value of I under the null hypothesis is -0.00020, with a standard deviation of 0.00719. The $p - value$ is equal to 4.271e-11, which is smaller than 0.05. Based on the results of this analysis, we may reject the null hypothesis that zero spatial autocorrelation is presented among the incidents and road segments at the 0.05 significant level. Thus, the incidents have clustering patterns. The process was conducted for all five time windows. The calculation results for analyzing the spatial autocorrelation are shown in Table 4.

Table 4 Spatial autocorrelation analysis for different KDE applications

	Time Window		$I_{observed}$	$I_{expected}$	std*	$p - value$
single KDE - distance	Weekday	5 am - 1 pm	0.0634	-0.002755	0.006642	0
		1pm - 9 pm	0.0713		0.006625	0
		9 m - 5 am	0.0556		0.006605	0
	Weekend	5 am - 5 pm	0.0401		0.006594	7.97e-11
		5 pm - 5 am	0.0633		0.006623	0
single KDE - duration	Weekday	5 am - 1 pm	0.1581		0.006678	0
		1pm - 9 pm	0.1409		0.006667	0
		9 m - 5 am	0.0801		0.006691	0
	Weekend	5 am - 5 pm	0.1293		0.006687	0
		5 pm - 5 am	0.1355		0.006690	0
multivariate KDE	Weekday	5 am - 1 pm	0.0319		0.006618	1.62e-07
		1pm - 9 pm	0.0353		0.006432	3.22e-09
		9 m - 5 am	0.0431		0.006525	2.03e-12
	Weekend	5 am - 5 pm	0.0167		0.006210	1.75e-03
		5 pm - 5 am	0.0640		0.006572	0

All the p-values calculated from the Moran's I index are smaller than 0.05. We may reject the null hypothesis that zero spatial autocorrelation is presented among the incidents and road segments at a 0.05 significant level. This result shows that traffic accident does have spatial autocorrelations with each other. The estimated standard deviations were generated when the spatial autocorrelations of their adjacent area were having traffic incidents were ignored. Thus, the incidents have clustering patterns. Both the distance and duration factors significantly influence the formation of these incidents' hot spots on the road network.

3.4 Summary

This chapter introduced the methodologies of the KDE for clustering detection in both single variate and multivariate formats and the methods of checking the spatial correlations of clusters. This process is conducted using the kernel density estimation methodology to locate the incident clusters with historical traffic incident data and the road network of the study area, which indicates the high-risk areas on freeway networks. In the end, these clusters' spatial autocorrelation status can be examined by The Moran's *I* statistics. A case study was also included in this chapter to examine the practicality of these introduced methodologies.

Chapter 4 Standby Service Optimization Model

The freeway standby service plan aims at selecting several locations where the service vehicles can stay and wait for service requests. Each selected location can be placed with at least one service vehicle. Meanwhile, the total number of vehicles is fixed since the funding of these freeway service programs is generally pre-determined. The objective of this standby service plan can be chosen either as providing maximum coverage to the potential incident locations or as responding to the incident with the minimum response time or costs.

4.1 Problem Statement

The task at hand is to design an assistance plan to provide standby services for incidents that happen on freeways. In this process, service vehicles standby at several selected stations during the planning time windows. Once the operation centers receive the incident report, a service vehicle will be dispatched to the incident location to offer assistance.

The whole incident duration in this process includes the reporting time, the time that service vehicles travel from standby stations to incident locations, and the clearing time. The reporting time depends on when the operation center receives the call. The response time is defined as the time elapsed from the moment a vehicle is dispatched to its arrival at the incident scene. It depends on where the closest standby vehicle is when the incident happens and how long it takes for the vehicle to arrive at the incident. The clearing time is defined as the time elapsed from the moment the dispatched vehicle arrives at the incident scene to the time the incident is deemed cleared. It is decided based on the features of the incident itself, such as incident type, occurrence time, pavement condition, influenced number of lanes, etc. Reducing the total incident duration is a crucial task for the freeway safety service. It is also expected for the road assistant agency to help more incidents within the budget limitation. Since the service vehicles do not control the reporting time and the clearing time, we will focus on the response time when designing the standby service plan.

To design this plan, we need to answer four main questions.

1) Where to set the standby stations for the service vehicles?

The whole road network is segmented into short segments in the risk-level calculation step with the approximately one-mile length for each segment. However, the service radius of each vehicle ranges from 8 miles to 15 miles, which requests a larger scale for each service station. A smaller number of total candidate service sites is also necessary for the computation efficiency purpose. Therefore, an algorithm that can re-configure the whole freeway network is proposed in Section 4.2 to combine short segments into longer pieces. After the segment combination, the road shoulder of the middle point of each long segment can be selected as the standby location for the service vehicles. Because the standby vehicles should not influence the normal traffic flows, the exact locations of each segment will also be adjusted manually based on the actual traffic condition.

2) How many vehicles should be set to each station?

Each standby station has a limitation on the vehicle capacity. This limitation restricts the maximum number of vehicles that each station can have to standby. Under this cap, each station may also have different numbers of standby vehicles.

If multiple vehicles are assigned to one standby station, there are two ways of placing service vehicles. One is to put all the vehicles at the same location point; another is to place the vehicles separately and evenly along the road. However, placing vehicles separately along the freeway may cause extra impacts on the regular traffic flow. It is also difficult for the vehicle drivers to find the exact location when driving back to the origin after finishing the service to incidents. For practical purposes, the vehicles assigned to one standby station are located at the same point.

High-risk segments are expected to have more vehicles offering coverages, and low-risk segments may require fewer vehicles to reduce the total operation cost. To decide the exact number of vehicles in each station under different capacity limits, an integer programming model is developed in Section 4.3. A heuristic algorithm is also presented to solve this optimization model in Chapter 5.

3) Under different budget limitations, will the decisions be different?

The freeway safety service quality may vary under different budget limits of the agency. Considering this, experiments with different preliminary conditions were conducted to examine each limitation’s influences in Chapter 6.

4) How is the performance different based on different decisions?

To check the performances of each decision calculated under different experiment environments, several simulation scenarios were set up based on the ground-truth incident data in the freeway network in California in Chapter 6.

4.2 Road Network Configuration.

4.2.1 Problem Motivation

After conducting the spatial and clustering analysis for the data of incidents and road networks, each road segment can be associated with a calculated multivariate KDE value. This value contains the information on the incident counts of the road segment, the distances from the incident to the road segment, and the duration of the incidents. In the road network for computing the KDE values, the lengths of road segments in the network are relatively short to illustrate the spatial distribution more accurately. However, this design may not be compatible with further routing and coverage model building. This is because the routing and coverage model may require a fewer number of segments for computational efficiency. Therefore, longer segments in the network are necessary.

In this section, an algorithm for generating hierarchical zoning on freeway road segments is introduced. This hierarchical zoning algorithm is developed based on the Depth First Search algorithm. It divides the whole network into two levels of layers based on the pre-computed KDE values:

Level 1: high-risk sections;

Level 2: low-risk sections.

4.2.2 Algorithm Description

The objective of generating hierarchical zoning for road segments is to splice the small road segments into longer sections such that:

(1) each section has a reasonable length for one vehicle to clear all incidents within one time window;

(2) the total number of sections is reasonable such that too many standby vehicles are not employed.

The constraints on this zoning process are:

(1) Vehicles in each segment can clear all expected counts of incidents within one time window.

(2) Each vehicle has a finite service radius. In this study, the driving time is applied instead of the driving distance.

(3) Since this research focuses on freeways, we assume that the travel speed is the same in different segments, but it may be different in different time windows.

(4) There is a time limit for the vehicles to arrive at the incident locations. For example, after detecting an incident, a service vehicle should arrive at the incident within t_w minutes.

(9) The length for each section should fall in this interval: $(l_{min},\ l_{max})$

where

$$l_{min} = min(\frac{Total\ length\ of\ the\ road\ network}{Service\ vehicle\ number}, freeway\ speed\ * service\ time\ limit) \tag{6}$$

$$l_{max} = max(\frac{Total\ length\ of\ the\ road\ network}{Service\ vehicle\ number}, freeway\ speed\ * service\ time\ limit) \tag{7}$$

The upper bound of the segment length is to set up a limit on how long it should take for the vehicle to arrive at the incident in time to avoid extra loss. The lower bound of the segment length is set to prevent too many short segments on the network and the increase in resource investment. Therefore, the optimal length of the segments should fall into the interval bounded by the upper and lower limits.

From 2016 data, the service road network length is about 800 miles, and there are 43 service vehicles in total. The freeway speed is 55mph. We may assume the service time limit as 10 or 15 minutes. So the length interval can be

$$\left(55mph * \frac{10}{60} = 9.17\ miles,\quad \frac{800\ miles}{43\ vehicles} = 18.60\ miles\right)$$

Or

$$\left(55mph * \frac{15}{60} = 13.75\ miles,\quad \frac{800\ miles}{43\ vehicles} = 18.60\ miles\right).$$

The road network configuration algorithm was developed based on the Depth First Search algorithm (DFS). The original DFS requires a graph G and a node v on it as the input data. The output of DFS is a traversal of all nodes in this graph based on recursion. The workflow of the DFS algorithm is described in

Table 5.

Table 5 The DFS algorithm description

Input:	$DFS(G, v)$
Initialization:	Label node v as "searched."
Recursion:	For one node w belonging to the set W of all nodes that connected to the node v in G:
	If w has not been searched, then:
	Mark w as "searched" and repeat the recursion step;
	If w has been searched, then:
	Move to the next w and repeat the recursion step;
End:	All nodes are marked as "searched."

However, the classic DFS algorithm connects nodes without considering each node's feature. In the road network problem, among all the n segments, each segment has a label $r_i \in R,\ R = \{Low\_risk,\ High\_risk\}$ showing its risk level and a label $l_i \in L\ (i = 1, \dots, n)$ showing its length.

The updated DFS algorithm that takes the hierarchical zoning task into account (HZ-DFS) is illustrated in Table 6.

4.2.3 Experiments on Different Scenarios

Three experiment scenarios were built up based on different freeway conditions to examine the performance of this algorithm. These experiment scenarios considered the situation of the freeway segments without intersections, freeway segments with multiple intersections, and freeway segments in the real world.

4.2.3.1 Line-shape freeway network

The first scenario is the line-shaped freeway network, which stands for the most straightforward freeway shape. It has only one start node and one end node. There are no intersections in the whole network. This scenario is illustrated in Figure 11 (a). This piece of freeway has a total of 21 demand segments with an entire length of 23.74 miles. The shortest demand segment is 0.92 miles, and the longest one is 3.15 miles. The average length of the 21 segments is 1.13 miles. Their risk levels are displayed in Figure 11 (b). The high-risk segments are plotted in red, and the low-risk segments are plotted in green. The assumption of a 10-minute limit for the service time was adopted in this experiment. Therefore, the lower bound of the serving distance is 9.17 miles, and the upper bound is 18.6 miles.

Table 6 The HZ-DFS algorithm description

```
Input:          $\boldsymbol{HZ-DFS(G, v, L, R)}$
Initialization: Label node $v$ as "searched."
                List $S$ for long segment storage.
                List $R_L$ for saving the risk levels of the long segments.
Recursion:      For one node $w_k$ belongs to the set $W$ of all nodes that connected to the node $v$ in $G$:
                  If $w$ has not been searched, then:
                    If the risk level $r_i$ on the node $w_k$ is same as the risk level on $v$:
                      If the length of the link between $v$ and $w_k \in (l_{min}, l_{max})$ :
                          Mark $w_k$ as "searched";
                          Save the link between $w_k$ and $v$ to $S$;
                          $k = k + 1$;
                          Repeat the recursion step till reaching $l_{max}$;
                      Save the links' average risk level into $R_L$.
                      If the length of the link between $v$ and $w_k > l_{max}$:
                          Save the link between $w_k$ and $v$ to $S$;
                          Save the links' average risk level into $R_L$;
                          Take $w_k$ as the new search start point $v$.
                    If the risk level $r_i$ on the node $w_k$ $are$ not same as $v$:
                      If the length of the link between $v$ and $w_k < l_{min}$:
                          Mark $w_k$ as "searched;"
                          Save the link between $w_k$ and $v$ to $S$;
                          $k = k + 1$;
                          Repeat the recursion step till reaching $l_{max}$
                      Save the links' average risk level into $R_L$.
                      If the length of the link between $v$ and $w_k \in (l_{min}, l_{max})$ :
                          Save the link between $w_k$ and $v$ to $S$;
                          Take $w_k$ as the new search start point $v$;
```

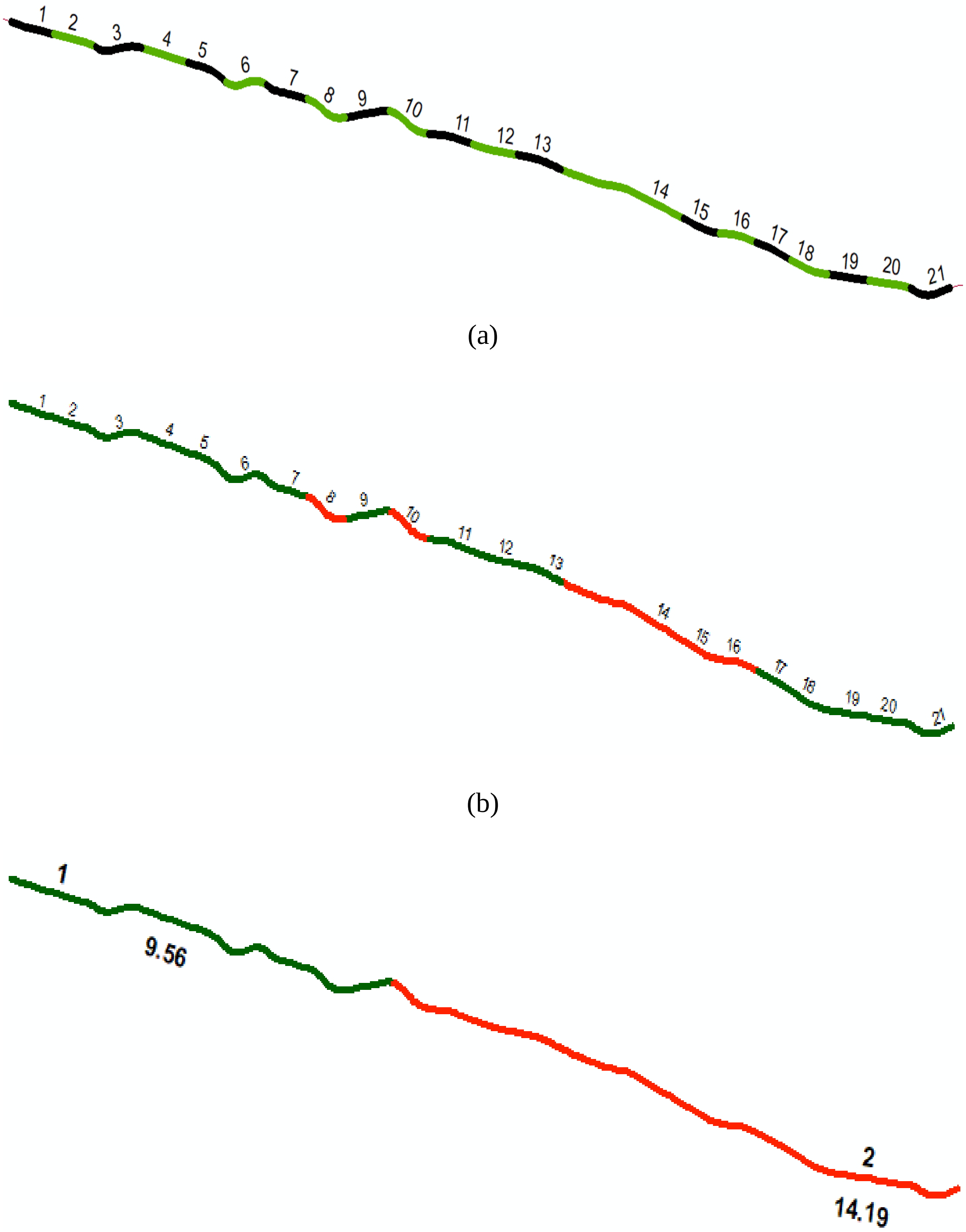
```
            Repeat the recursion step till reaching $l_{max}$;
        Save the links' average risk level into $R_L$.
End:   All nodes are marked as "searched."
```

The experiment result of conducting the HZ-DFS algorithm is displayed in Figure 11 (c). The whole road was reshaped into two long segments with lengths of 9.56 miles and 14.19 miles, respectively. The long segment with ID 1 is marked as low risk and plotted in green, and the other long segment with ID 2 is marked as high risk and plotted in red. Both of the two long segments meet the requirement on service time limits.

4.2.3.2 Network with multi-lines and intersections

The second scenario is the freeway network with multiple lines and two intersections. It has five nodes that can be taken as the start nodes. Two intersections exist on the whole network. This scenario is illustrated in Figure 12 (a). This piece of freeway has a total of 73 demand segments with an entire length of 80.72 miles. The shortest demand segment is 0.52 miles, and the longest one is 3.15 miles. The average length of the 21 segments is 1.11 miles. The assumption of a 10-minute limit for the service time was adopted in this experiment. Therefore, the lower and upper bounds of the serving distance are the same as in the first scenario.

The experiment result of conducting the HZ-DFS algorithm is displayed in Figure 12 (b). The whole road was reshaped into seven long segments with the shortest length of 9.21 miles and the longest length of 14.84 miles. All long segments meet the requirement on service time limits.

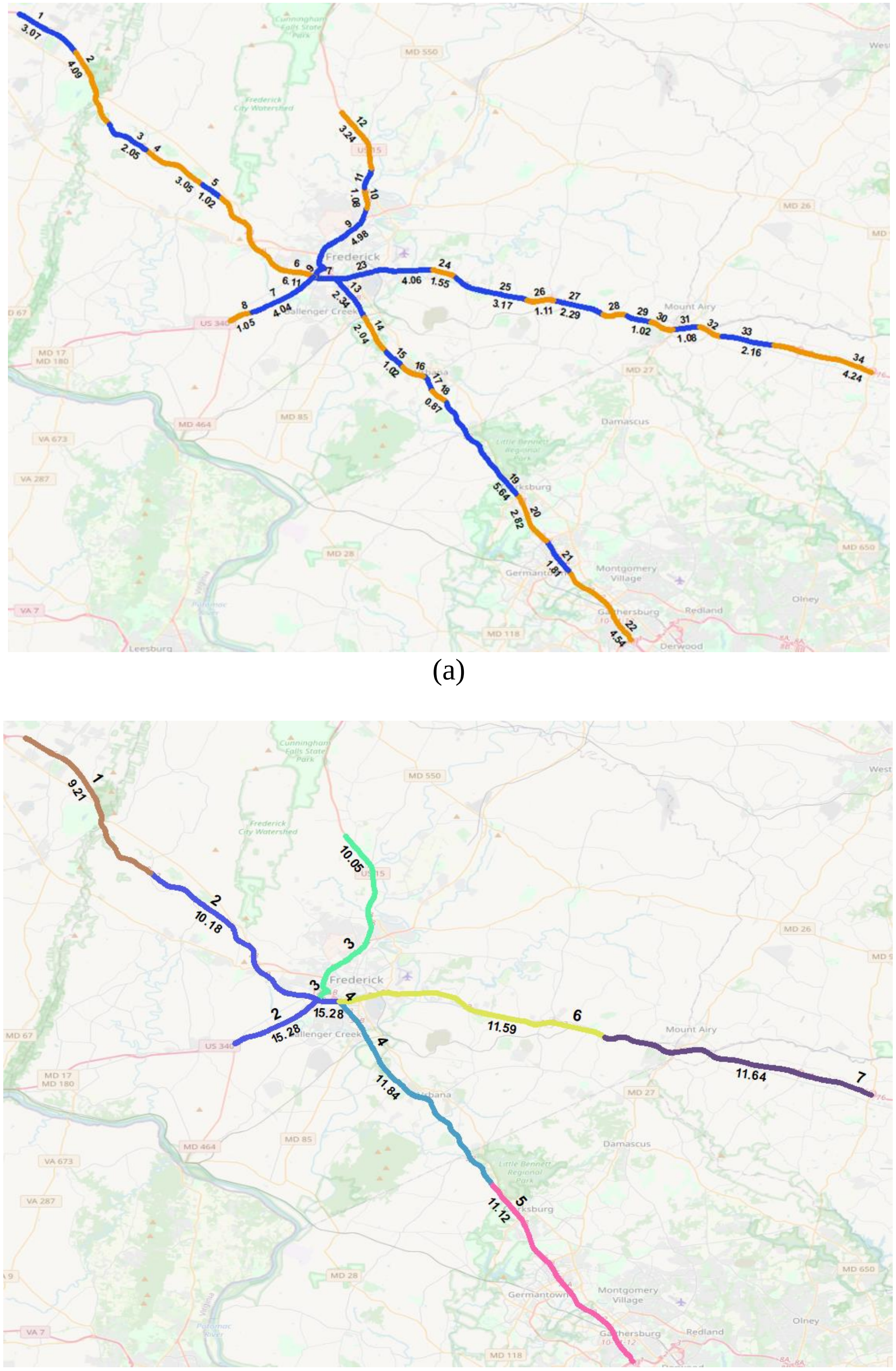


(a)

(b)

(c)

Figure 11 The line-shaped freeway network configuration



(a)

(b)

Figure 12 The multi-line freeway network configuration

4.2.3.3 Freeway Network in Maryland

The third scenario is built upon the real freeway network in Maryland. It was divided into 323 short demand segments, each having an approximate length of one mile. The network is displayed in Figure 14 (a).

The experiment result of conducting the HZ-DFS algorithm on the third scenario is displayed in Figure 14 (b). The whole road was reshaped into 26 long segments with the shortest length of 10.74 miles and the longest length of 18.57 miles. All 26 long segments meet the requirement on service time limits.

4.2.3.4 Initial searching node selection

In the initialization step, it’s recommended that the initial node be located at the ends of the network edges instead of intersections. This is because the algorithm takes all the nodes being searched as a first priority and the restrictions of lengths and risk levels as the second. Therefore, searching from an end node of an edge initially may reduce the risk of generating uncombined segments. The comparison of different results starting from different initial nodes in Figure 13 is listed in Table 7. The length of each short segment in Figure 13 is the same as the data displayed in Figure 12 (a).

4.3 Standby Service Optimization Model

An optimization model is proposed in this section to solve two problems: (1) finding the optimal locations for vehicles to standby, (2) deciding how many vehicles to be placed in each selected location. This model is formulated based on the hierarchical-zoned network built by the HZ-DFS algorithm. Under the same assumptions and constraints, the solutions are obtained under different budget limitations and objective functions within a planning time window.

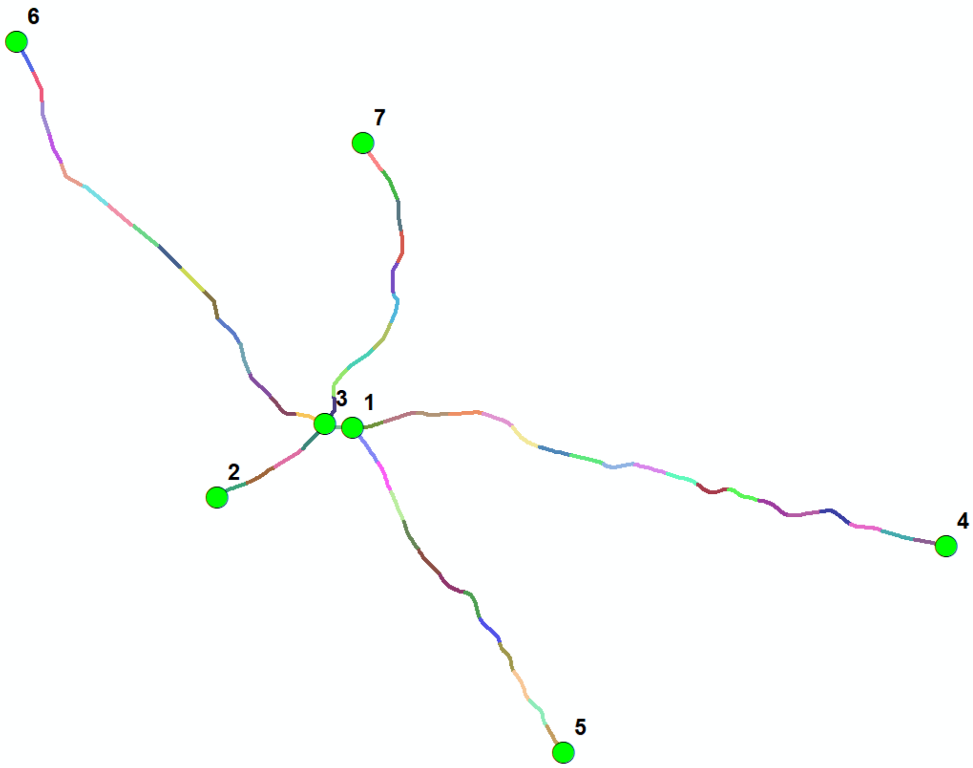
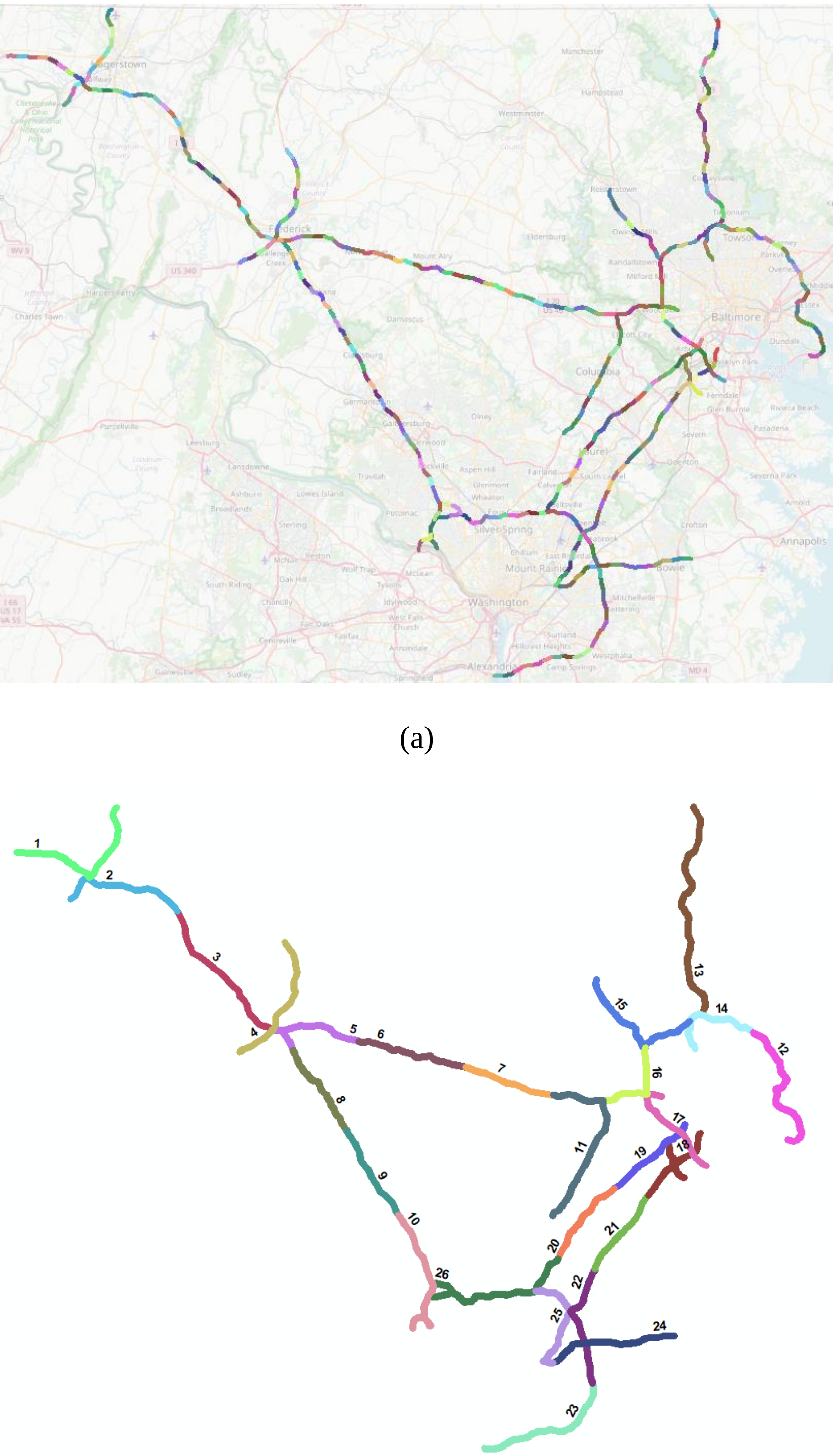


Figure 13 Starting nodes in a sample network

Table 7 The comparison of different segmentation results by searching from different initial nodes

Initial node ID	Node location	Segment length after combination (miles)		Total Number of segments	Number of short segments that failed to fall in the length boundaries
		Min	Max		
1	Intersection	4.95	19.56	5	2
2	Edge	9.20	16.04	6	0
3	Intersection	10.52	17.03	6	0
4	Edge	9.21	14.81	7	0
5	Edge	11.03	18.20	6	0
6	Edge	9.21	14.81	7	0
7	Edge	10.17	14.81	6	0



(a)

(b)

Figure 14 The Maryland freeway network configuration

4.3.1 Sets and Parameters

The response time is calculated from when traffic operation centers receive the incident report to when the support vehicle arrives at the incident location. This time includes the time for the operation centers deciding from which station to dispatch a service vehicle plus the time for the service vehicle traveling on the roads.

This research assumes that the time for operation centers to make decisions is negligible. Therefore, the response time depends only on the vehicle's travel time from its standby station to the incident location. The sets and parameters related to this problem are shown in Table 8.

4.3.2 Decision Variables

For the sake of answering the two questions listed in the problem statement, two decision variables are employed in this model. The first variable X_{ij} is a binary variable. It decides if a demand segment i can be assisted by candidate station j. The second variable q_j is an integer variable. Its value ranges from zero to the maximum vehicle number that each station can have. The decision variables used in this problem are shown in Table 9.

Table 8 Sets and parameters in the model

$\boldsymbol{I}$	The set of all demand segments, $\boldsymbol{I} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{n}\}$, $\boldsymbol{n} = \mathbf{323}$
$\boldsymbol{I_H}$	The set of high-risk demand segments, $I_H \in I$
$\boldsymbol{J}$	The set of standby stations, $J = \{1,2, \dots, m\}$, m = 26
$\boldsymbol{T}$	The set of time windows, $T = \{1, 2, 3, 4, 5\}$
$\boldsymbol{K}$	The set of daily incident numbers on each demand segment within a time window, $K = \{1, 2, 3, 4\}$
$\boldsymbol{i}$	The index of a demand segment, $i \in I$
$\boldsymbol{i_H}$	The index of a high-risk demand segment, $i_H \in I_H$
$\boldsymbol{j}$	The index of a candidate station, $j \in J$
$\boldsymbol{t}$	The index of a time window, $t \in T$
$\boldsymbol{k}$	The index of the daily incident number on each demand segment within a time window, $k \in K$
$\boldsymbol{Q}$	The total vehicle number
$\boldsymbol{tw_t}$	The length of time window t, $t \in T$
$\boldsymbol{h_i}$	The incident number of demand segment i
$\boldsymbol{d_{ij}}$	Driving distance between demand segment i and station j, miles
$\boldsymbol{dt_{ijt}}$	Driving time between demand segment i and station j at the time window t, minutes
$\boldsymbol{gdt_{wt}}$	Ground-truth response time of a service vehicle arriving at a collision w in the historical data, minutes
$\boldsymbol{sdt_{wt}}$	Saved response time for an incident w when using the dispatched response time dt_{ijt} to replace the ground-truth response time gdt_{wt}, minutes
$\boldsymbol{R}$	service radius, miles
$\boldsymbol{a_{ij}}$	$= 1\ if\ d_{ij} \leq R$ and demand segment i is within the coverage zone of station j, otherwise $= 0$
$\boldsymbol{S}$	Total number of standby stations

$\boldsymbol{V}$	The set of maximum capacities for the vehicle number that each station can have. $V = \{1, 2, 3, 4\}$
$\boldsymbol{v}$	The index of maximum capacities for the vehicle number that each station can have. $v \in V$
$\boldsymbol{W}$	The set of incidents in the historical data
$\boldsymbol{w}$	The index of an incident in W
$\boldsymbol{KDE_i}$	The KDE value of segment i
$\boldsymbol{R}$	The set of risk levels for each demand segment, $R = \{Low\_risk,\ High\_risk\}$
$\boldsymbol{r_i}$	The risk level of segment i, $r_i \in R$
$\boldsymbol{p_{ikt}}$	The probability of demand segment i having k incidents at the time window t
$\boldsymbol{E_{it}}$	The expectation of the incident number of the demand segment i at the time window t
$\boldsymbol{dur_{it}}$	The expected duration for an incident occurred on the demand segment i at the time window t
$\boldsymbol{dur_t}$	The duration for the time window t
$\boldsymbol{c_{drv}}$	The driving cost per minute for a service vehicle
$\boldsymbol{c_f}$	fixed cost per hour for a service vehicle in work
$\boldsymbol{c_l}$	The financial loss per minute for an incident not being served

Table 9 Decision variables in the model

$\boldsymbol{Y_j}$	$= \boldsymbol{1\ if}$ station $\boldsymbol{j}$ is selected from candidate sites $\boldsymbol{J}$, otherwise 0
$\boldsymbol{X_{ij}}$	$= 1\ if$ demand segment i is assisted by station j, otherwise 0
$\boldsymbol{q_j}$	$= \{0, 2, \ldots, V\}$ The number of vehicles at station j

4.3.3 Objective functions

The objective of this standby service model is to generate the best possible service based on a set of selected performance measures. The performance measures for this model include three parts: coverage measurements, travel time, and operation costs. For the purpose of finding the best solutions, an objective function is proposed by combining the above measures by converting them into evaluative costs.

(1) Costs

The cost has three parts: the driving cost, the fixed cost, and the financial loss for delayed assistance.

The driving cost c_{drv} is defined as the cost of a service vehicle driving from station j to the demand location i when a collision occurs at i. This cost is mainly generated by the gasoline consumption of the service vehicles, and it can be shown in expression (8).

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} k \times p_{ikt}\, c_{drv} dt_{ijt} a_{ij} X_{ij} q_j\, , t \in \{1,2,3,4,5\} \tag{8}$$

The fixed cost c_f stands for the cost of maintaining the freeway assistant plan with service vehicles standby in the service system. This cost is mainly generated by wages of the vehicle drivers, and it's shown in expression (9).

$$\sum_{j\in J} c_f q_j\, dur_t, \qquad t \in \{1,2,3,4,5\} \tag{9}$$

The financial loss $\boldsymbol{c_l}$ indicates the monetized penalty for the delayed assistance for a traffic collision. This cost contains the information of the loss from traffic congestion and the loss from potential additional medical fees caused by the collision, and it's shown in expression (10).

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} k \times p_{ikt}\, c_l dt_{ijt} a_{ij} X_{ij}\,, t \in \{1,2,3,4,5\}$$

(10)

(2) Benefits

The benefits of operating this standby service model instead of the vehicle patrol service model are expressed as the monetized benefits on the saved response time. For an incident w that happened on the demand segment i during the time window t, the saved response time sdt_{wt} is measured as the difference between the ground-truth response time gdt_{wt} and the response time dt_{ijt} calculated by dispatching a vehicle from station j to the same demand segment i. The ground-truth response time gdt_{wt} for the incident w can be found from the records of the historical data. The benefits can be shown as the expression (11).

$$\sum_{i\in I}\sum_{j\in J}\sum_{w\in W} c_{drv} sdt_{wt} a_{ij} X_{ij} q_j\,, t \in \{1,2,3,4,5\}$$

(11)

Therefore, the objective function can be expressed in equation (12).

$$\text{Min Z} = \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} k \times p_{ikt}\, c_{drv} dt_{ijt} a_{ij} X_{ij} q_j + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} k \times p_{ikt}\, c_l dt_{ijt} a_{ij} X_{ij}$$
$$+ \sum_{j\in J} c_f q_j\, dur_t - \sum_{i\in I}\sum_{j\in J}\sum_{w\in W} c_{drv} sdt_{wt} a_{ij} X_{ij} q_j\,, \qquad t \in \{1,2,3,4,5\}$$

(12)

4.3.4 Constraints

It is assumed that the centroid of each long segment is considered a candidate station when formulating the model. This is due to the actual shape of each long segment that can be either a single line or a line with branches (examples shown in Figure 14 (b)). When the segment has several branches, a centroid has a better representation than a geometric middle point for abstracting the segment. It is also assumed that all the candidate stations have the same maximum capacity for service vehicles to standby. However, the actual number of standby vehicles for each station can be different.

If a demand segment is covered by one vehicle from one station, this demand segment is considered as being covered once. A demand segment can be covered by different service sites with multiple vehicles.

The constraints associated with this model in each planning time horizon are as follows.

1) Based on incident cluster analysis results, each demand segment has a label of the risk level. Each high-risk level segment is denoted as $i_H \in I_H$.
2) All demand segments must be covered at least once, which is expressed in equation (13).

$$\sum_{j=1}^{m} a_{ij} X_{ij} q_j \geq 1, \forall i \in I \tag{13}$$

3) The number of times that high-risk segments are covered should not be smaller than the low-risk segments, either by single vehicles in different stations or by multiple vehicles in the same station. This constraint is shown in equation (14).

$$a_{i_H j} q_j \geq a_{ij} q_j, \quad \forall i_H \in I_H, \forall i \in I, \forall j \in J$$

(14)

4) The total number of vehicles Q is given and fixed. The sum of the number of vehicles in all stations should be no larger than the total number Q, and this constraint is expressed in equation (15).

$$\sum_{j=1}^{m} q_j \leq Q$$

(15)

5) The maximum capacity for each station V is pre-decided and fixed.

6) A demand segment has only two statuses: either covered or not covered by station j. The two statuses are expressed by the binary variable X_{ij} shown in equation (16).

$$X_{ij} = 0, 1, \forall i \in I, \forall j \in J$$

(16)

7) The number of vehicles assigned to each station is represented by an integer variable q_j shown in equation (17). This number ranges from 0 to the maximum capacity V of a single station.

$$q_j = 0, \dots, v,\ \forall j \in J, \forall v \in V$$

(17)

The above constraints are summarized in Table 10.

4.4 Numerical Examples

4.4.1 Network description

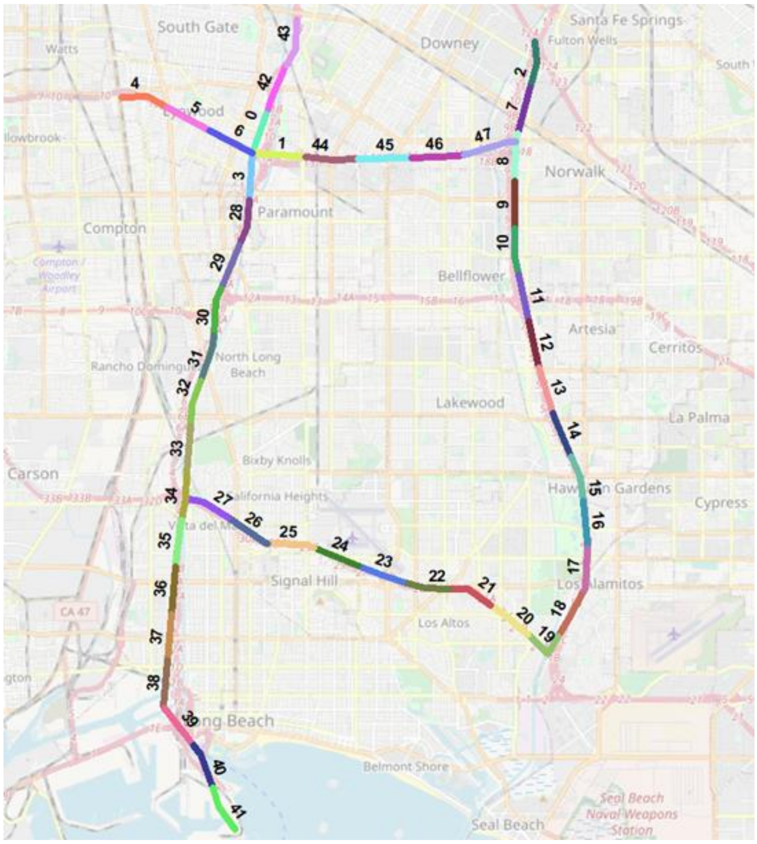
Two sample scenarios displayed in Figure 15 are used to examine the model's capability. Different demand segments with their segment IDs in sample scenarios I and II are shown in Figure 15 (a) and (b), respectively. The networks in both sample scenarios are extracted from Southern California. Different time windows and network sizes are used to check the capability of the model. Sample scenario I stands for a larger network in the weekday morning period, and Sample scenario II represents a smaller network during the weekend daytime period with fewer collisions occurring.

The counts of incidents on each demand segment i in the two sample scenarios are shown in Table 11.

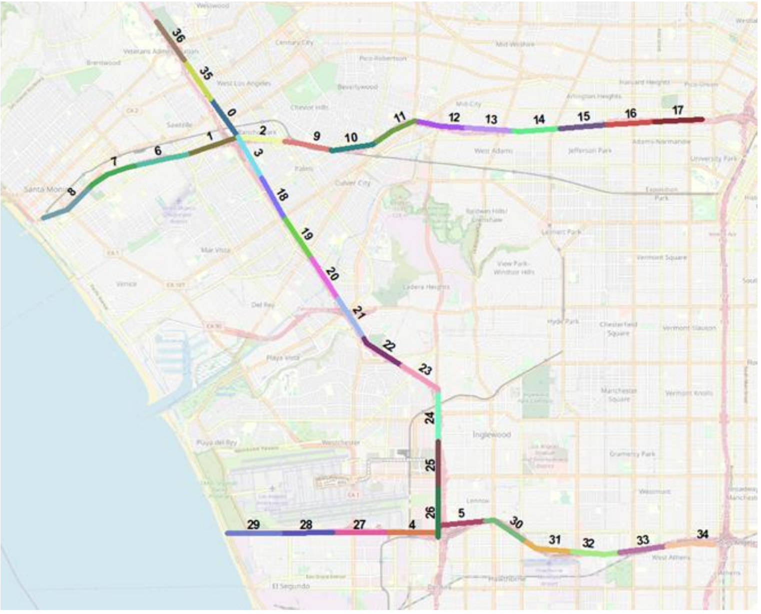
The road networks for these two scenarios with related parameters are described in Table 12. The locations of candidate standby stations configured by the HZ-DFS and their corresponding buffer zones are illustrated in Figure 16.

Table 10 Model constraints

$\boldsymbol{\sum_{j=1}^{m} a_{ij} X_{ij} q_j \geq 1}$,	$\forall \boldsymbol{i} \in \boldsymbol{I}$
$\boldsymbol{a_{i_H j} X_{i_H j} q_j \geq a_{ij} X_{ij} q_j}$,	$\forall i_H \in I_H, \forall i \in I, \forall j \in J$
$\boldsymbol{\sum_{j=1}^{m} q_j \leq Q}$	
$\boldsymbol{\sum_{i=1}^{n} a_{ij} X_{ij} \leq V}$	$\forall i \in J$
$\boldsymbol{q_j = 0, \dots, v}$	$\forall j \in J, \forall v \in V$
$\boldsymbol{X_{ij} = 0, 1}$	$\forall i \in I, \forall j \in J$



(a) Demand segments in Scenario I



(b) Demand segments in Scenario II

Figure 15 Demand segments in sample scenarios I and II

Table 11 Counts of incidents on each demand segment

Sample scenario I				**Sample scenario II**			
i	**Incident counts**	i	**Incident counts**	i	**Incident counts**	i	**Incident counts**
0	2	23	3	0	6	30	4
1	14	24	2	1	4	31	1
2	70	25	8	3	4	32	1
3	3	26	6	4	2	34	24
4	41	27	2	5	2	35	2
5	4	28	12	7	2	36	8
6	2	29	24	8	4		
7	16	30	24	9	6		
8	6	31	16	11	2		
9	10	32	15	13	6		
10	3	33	12	14	6		
11	63	34	36	16	8		
12	15	35	8	17	37		
13	8	36	6	18	4		
14	12	38	10	19	2		
15	12	42	10	20	6		
17	26	43	54	21	6		
18	6	44	4	22	6		
19	12	45	8	23	3		
21	9	46	2	24	6		
22	6	47	6	26	22		

4.4.2 Parameter calculation

4.4.2.1 Driving durations between demand segment i and candidate station j in time window t: dt_{ijt}

The parameter dt_{ijt} measures the traveling time of a service vehicle driving from a candidate station j to a demand segment i that is located within its buffer zone during the time window t. The data was retrieved from the Google Map API, and it is listed in Table 13.

Table 12 Descriptions of the two sample networks

	Sample scenario I	Sample scenario II
Total length	49.01 miles	38.82 miles
Number of demand segments	48	37
Number of high-risk demand segments	13	13
Number of candidate stations	4	3
Studied time window	$t = 1$	$t = 4$
Time window range	Weekday 5 am – 1 pm	Weekend 9 am – 9 pm
Time window duration	8 hours	12 hours
Number of days	23 days	8 days
Number of collisions	291	119
Number of total available vehicles $\boldsymbol{Q}$	10	10
Maximum number of vehicles in each location $\boldsymbol{V}$	3	2
Fixed cost $\boldsymbol{c_f}$	\$12/hour	\$12/hour
Financial loss $\boldsymbol{c_l}$	\$20/hour	
Driving cost $\boldsymbol{c_{drv}}$	\$1.9/hour	

(a) Sample scenario I (b) Sample scenario II

Figure 16 Candidate stations for sample scenarios I and II

4.4.2 2 The probability of demand segment i having k incidents at the time window t: p_{ikt}

Based on the historical data of the incidents in the California freeway, the distribution of incident numbers in each time window for every demand segment can be calculated. For example, Time Window 1, which stands for the weekday morning peak period, has an 8-hour duration. There were 23 weekdays in August of the year 2017 in total. The probability of demand segment i having k incidents at the time window t for a single day is shown in Table 14.

Table 13 Driving duration in minutes between demand segments i and candidate stations j in time window t

Sample scenario I, t =1									**Sample scenario II, t =4**					
j	i	dt_{ijt}	j	i	dt_{ijt}	j	i	dt_{ijt}	j	i	dt_{ijt}	j	i	dt_{ijt}
0	43	5.5	1	22	13.7	2	29	10.1	0	0	9.13	1	8	8.47
0	0	7.65	1	46	6.95	2	30	8.32	0	1	8.25	1	9	5.33
0	6	9.4	1	47	10.9	2	34	4.63	0	2	8.05	1	10	1.35
0	12	11.2	1	13	7.92	3	40	18.3	0	3	6.07	1	11	2.32
0	4	9.73	1	23	14.5	3	41	19.1	0	4	8.08	1	12	6.28
0	2	7.43	1	8	7.08	3	16	10.1	0	5	11.2	1	13	7.6
0	3	8.08	1	31	15.4	3	39	14.6	0	6	8.55	1	14	5.17
0	44	3.55	1	45	11.3	3	24	4.75	0	7	11.2	1	15	6
0	28	7.02	1	17	9.73	3	12	13.6	0	8	9.87	1	16	7.1
0	46	9.13	1	9	6.62	3	21	3.42	0	9	11.3	1	17	9.73
0	47	9.33	1	42	14.8	3	35	8.82	0	10	11.4	1	18	7.72
0	8	6.22	1	10	4.42	3	15	7.15	0	11	8.38	1	19	8.08
0	33	13.4	1	7	10	3	14	10.3	0	12	9.9	1	20	9.13
0	31	10.9	1	1	14.4	3	22	2.7	0	13	13.2	1	21	11
0	45	2.55	1	29	11.6	3	27	10.5	0	14	10.8	1	22	11.9
0	9	7.35	1	18	16.3	3	26	7.12	0	15	11.6	1	23	13.5
0	42	6.98	1	30	13.3	3	20	5.27	0	16	12.7	1	24	12.2
0	5	8.25	1	11	9.72	3	13	11.6	0	18	6.97	1	25	11.4
0	10	8.55	2	40	11.3	3	23	3.5	0	19	3.73	1	35	7.55
0	7	9.43	2	41	12.1	3	33	14	0	20	0.07	1	36	6.43
0	32	11.7	2	39	7.6	3	37	12	0	21	6.4	2	4	9.33
0	1	6	2	24	8.6	3	36	10.7	0	22	7.98	2	5	2.02
0	29	6.95	2	21	8.62	3	31	12.9	0	23	8.9	2	20	12.2
0	30	9.03	2	35	1.82	3	17	10.2	0	24	7.55	2	21	7.93
0	34	13.8	2	3	12.3	3	25	7.93	0	25	6.85	2	22	10.6
0	11	11.4	2	28	11.3	3	38	13.2	0	26	8.4	2	23	6.15
1	43	12.2	2	22	9.95	3	10	11.9	0	27	10.4	2	24	7.25
1	16	16.2	2	27	6.23	3	32	11.6	0	28	12.4	2	25	5.82
1	0	14.3	2	26	4.62	3	18	4.28	0	29	14	2	26	4.07
1	6	16.7	2	20	9.13	3	34	7.02	0	30	14.5	2	27	8.53
1	12	5.33	2	23	7.35	3	11	10.3	0	35	8.72	2	28	11.5
1	21	16	2	33	6.97	3	19	8.22	0	36	7.58	2	29	13.2
1	15	12.3	2	37	5				1	0	8.95	2	30	3.57
1	2	8.33	2	36	3.65				1	1	8.1	2	31	8.02
1	3	15.8	2	31	8.9				1	2	5.93	2	32	5.4
1	44	9.33	2	25	3.58				1	3	6.37	2	33	9.32
1	14	10.3	2	38	6.22				1	6	7.17	2	34	7.52
1	28	14.8	2	32	7.57				1	7	9.78			

Table 14 The probability of demand segment i having k incidents at time window t

	Sample scenario I, t =1						Sample scenario II, t =4				
i	k =0	k =1	k =2	k =3	k =4+	i	k =0	k =1	k =2	k =3	k =4+
0	0.938	0.062	0	0	0	**0**	0.889	0.055	0.055	0	0
1	0.813	0.062	0.062	0	0.062	**1**	0.945	0	0.055	0	0
2	0.5	0.062	0	0.189	0.249	**2**	1	0	0	0	0
3	0.906	0.094	0	0	0	**3**	0.889	0.111	0	0	0
4	0.748	0	0.032	0.062	0.158	**4**	0.945	0.055	0	0	0
5	0.876	0.124	0	0	0	**5**	0.945	0.055	0	0	0
6	0.938	0.062	0	0	0	**6**	1	0	0	0	0
7	0.687	0.251	0	0	0.062	**7**	0.945	0.055	0	0	0
8	0.876	0.062	0.062	0	0	**8**	0.945	0	0.055	0	0
9	0.749	0.189	0.062	0	0	**9**	0.889	0.055	0.055	0	0
10	0.906	0.094	0	0	0	**10**	1	0	0	0	0
11	0.342	0.188	0.094	0.188	0.188	**11**	0.945	0.055	0	0	0
12	0.625	0.28	0.094	0	0	**12**	1	0	0	0	0
13	0.749	0.251	0	0	0	**13**	0.834	0.166	0	0	0
14	0.751	0.124	0.124	0	0	**14**	0.889	0.055	0.055	0	0
15	0.751	0.124	0.124	0	0	**15**	1	0	0	0	0
16	1	0	0	0	0	**16**	0.889	0.111	0	0	0
17	0.563	0.189	0.124	0.124	0	**17**	0.778	0.055	0.028	0.028	0.111
18	0.876	0.062	0.062	0	0	**18**	0.889	0.111	0	0	0
19	0.813	0.062	0.062	0.062	0	**19**	0.945	0.055	0	0	0
20	1	0	0	0	0	**20**	0.834	0.166	0	0	0
21	0.719	0.281	0	0	0	**21**	0.834	0.166	0	0	0
22	0.906	0	0.094	0	0	**22**	0.917	0	0.083	0	0
23	0.906	0.094	0	0	0	**23**	0.917	0.083	0	0	0
24	0.938	0.062	0	0	0	**24**	0.917	0	0.083	0	0
25	0.813	0.124	0.062	0	0	**25**	1	0	0	0	0
26	0.811	0.189	0	0	0	**26**	0.723	0.111	0.111	0.055	0
27	0.938	0.062	0	0	0	**27**	1	0	0	0	0
28	0.717	0.189	0.094	0	0	**28**	1	0	0	0	0
29	0.437	0.375	0.189	0	0	**29**	1	0	0	0	0
30	0.437	0.375	0.189	0	0	**30**	0.889	0.111	0	0	0
31	0.751	0.124	0	0.124	0	**31**	0.972	0.028	0	0	0
32	0.531	0.469	0	0	0	**32**	0.972	0.028	0	0	0
33	0.811	0	0.189	0	0	**33**	1	0	0	0	0
34	0.25	0.562	0	0.188	0	**34**	0.778	0.083	0	0.111	0.028
35	0.813	0.124	0.062	0	0	**35**	0.945	0.055	0	0	0
36	0.811	0.189	0	0	0	**36**	0.889	0.055	0.055	0	0
37	1	0	0	0	0						
38	0.749	0.189	0.062	0	0						
39	1	0	0	0	0						
40	1	0	0	0	0						
41	1	0	0	0	0						
42	0.876	0	0.062	0.062	0						
43	0.501	0.062	0.062	0.125	0.249						
44	0.876	0.124	0	0	0						
45	0.813	0.124	0.062	0	0						
46	0.938	0.062	0	0	0						
47	0.876	0.062	0.062	0	0						

4.4.2.3 Costs

(1) Driving cost: c_{drv}

The driving cost is based on gasoline consumption. The primary type of service vehicle is the tow trucks that use diesel as the fuel. In California, the diesel price is currently about \$4.205 per gallon, and one tow truck consumes 0.59 gallons per hour. Therefore, the driving cost c_{drv} for a service vehicle is:

$$(\$4.205\ /gallon) \times 0.59\ (gallon/hour) = 2.48\ (\$/\text{hour}).$$

(2) Fixed cost for one service vehicle in work: c_f

The vehicle driver's salary determines the fixed cost for one service vehicle in work. Since the standby service only uses the available vehicles in the service agencies, the capital cost of buying vehicles is not included. The fixed cost exists when the vehicle is at work, either in the standby status or in the driving status. Based on the data in (Daneshgar, 2018), the fixed fee c_f is \$20/hour.

(3) Financial loss for an incident not being served c_l:

An incident also causes financial loss that includes property damages and health impacts. Although it is crucial to provide timely assistance to the incidents, there may be cases where the service vehicle fails to arrive at the incident location in time. This situation will result in a financial loss that ranges from \$10/hour to \$15/hour (Daneshgar, 2018). In this study, the value for c_l is taken as \$12/hour.

4.4.3 Experiment results and analysis

The parameters applied in the experiments are listed in Table 12. The problems were solved using the commercial software Gurobi. The solutions representing the coverage condition and the vehicle assignment at each standby station of the two experiment scenarios are listed in Table 15 and Table 16, respectively.

All the high-risk segments are being covered multiple times. The details of how many times that each high-risk segment is being covered are listed in Table 17. For Scenario I, five high-risk segments can be double covered. For Scenario II, eight high-risk segments can be covered double covered by the service vehicles.

Table 15 The coverage conditions and the vehicle assignments at each standby station of Scenario I

Scenario I									
x_{ij}									
i	***j* = 0**	***j* = 1**	***j* = 2**	***j* = 3**	***i***	***j* = 0**	***j* = 1**	***j* = 2**	***j* = 3**
0	1	0	0	0	**26**	0	0	1	1
1	1	0	0	0	**27**	0	0	1	1
2	1	0	0	0	**28**	1	0	1	0
3	1	0	0	0	**29**	1	0	1	0
4	1	0	0	0	**30**	1	0	1	0
5	1	0	0	0	**31**	1	0	1	0
6	1	0	0	0	**32**	0	0	1	0
7	1	0	0	0	**33**	1	0	1	0
8	1	0	0	0	**34**	0	0	1	0
9	0	1	0	0	**35**	0	0	1	1
10	0	1	0	0	**36**	0	0	1	1
11	0	1	0	0	**37**	0	0	0	1
12	0	1	0	0	**38**	0	0	1	1
13	0	1	0	0	**39**	0	0	0	1
14	0	1	0	0	**40**	0	0	0	1
15	0	0	0	1	**41**	0	0	0	1
16	0	0	0	1	**42**	1	0	0	0
17	0	1	0	0	**43**	1	0	0	0
18	0	0	0	1	**44**	1	0	0	0
19	0	0	0	1	**45**	1	0	0	0
20	0	0	0	1	**46**	0	1	0	0
21	0	0	1	1	**47**	1	0	0	0
22	0	0	1	1	q_j	$q_0 = 1$	$q_1 = 1$	$q_2 = 0$	$q_3 = 1$
23	0	0	0	1					
24	0	0	1	1					
25	0	0	1	1					

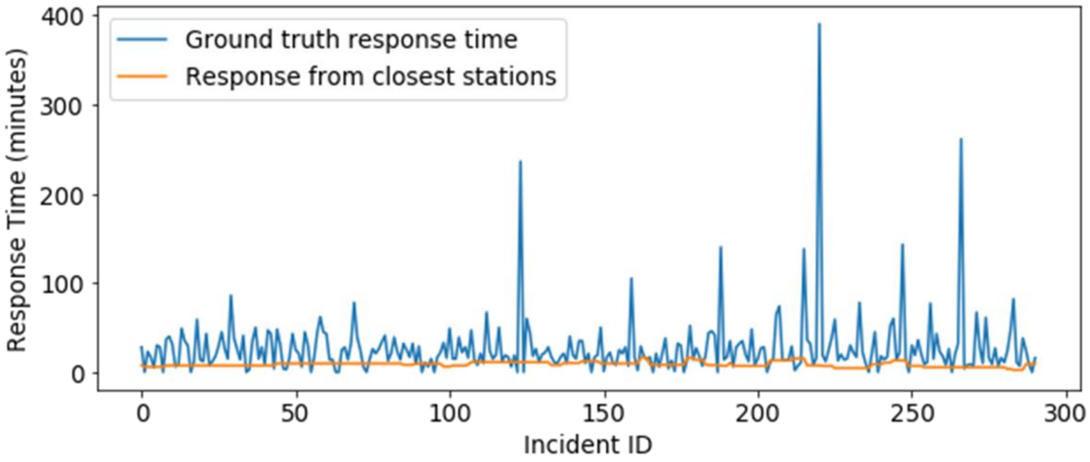
Table 16 The coverage conditions and the vehicle assignments at each standby station of the Scenario II

Scenario II							
x_{ij}							
i	$j=0$	$j=1$	$j=2$	i	$j=0$	$j=1$	$j=2$
0	1	1	0	**26**	1	0	1
1	1	1	0	**27**	0	0	1
2	0	1	0	**28**	0	0	1
3	1	1	0	**29**	0	0	1
4	1	0	1	**30**	1	0	1
5	1	0	1	**31**	0	0	1
6	0	1	0	**32**	0	0	1
7	0	1	0	**33**	0	0	1
8	1	1	0	**34**	0	0	1
9	1	1	0	**35**	0	1	0
10	0	1	0	**36**	1	1	0
11	1	1	0	q_j	$q_0=0$	$q_1=1$	$q_2=1$
12	0	1	0				
13	1	1	0				
14	1	1	0				
15	0	1	0				
16	1	1	0				
17	0	1	0				
18	1	1	0				
19	1	1	0				
20	1	1	0				
21	1	0	1				
22	1	0	1				
23	1	0	1				
24	1	0	1				
25	0	1	0				

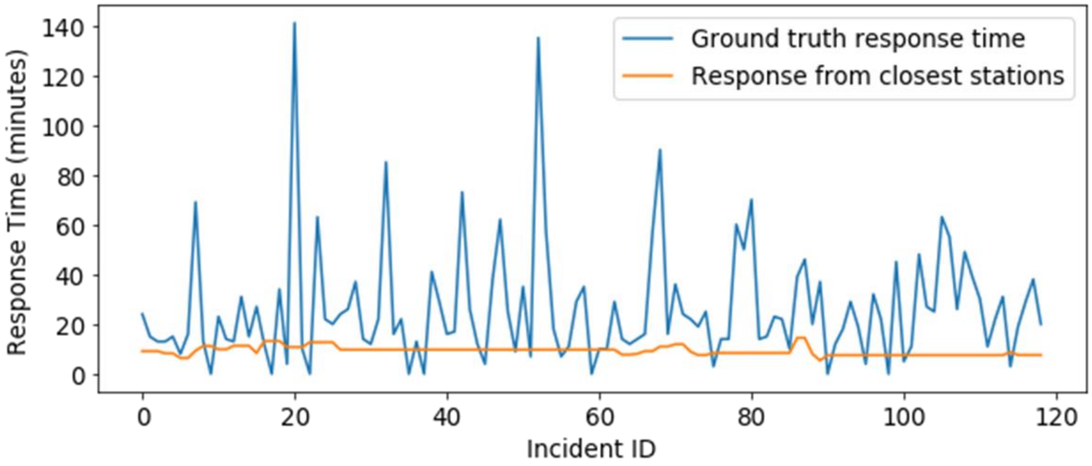
Table 17 The number of times that high-risk segments are covered

Scenario I		**Scenario II**	
High-risk Segment ID	**Times of coverages**	**High-risk Segment ID**	**Times of coverages**
1	1	0	2
5	1	3	2
7	1	13	2
10	1	14	2
11	1	18	2
18	1	21	2
19	1	23	2
29	2	24	2
30	2	26	1
32	2	31	1
34	2	32	1
38	2	33	1
42	1	34	1

The response time can also be saved by applying this model compared to the previous methods. The total ground-truth response time of previous methods provided in the historical data is 7868 minutes for Scenario I and 3136 minutes for Scenario II, but the response time by applying this method is 2540 minutes and 1099 minutes for Scenario I and II, respectively. The response times for serving each collision in the two scenarios are shown in Figure 17 (a) and (b), respectively. The figures show that for most of the incidents, the proposed model can reduce the response time.



(a) Scenario I



(b) Scenario II

Figure 17 The response time for serving an incident using different service methods

Chapter 5 Heuristic Method for solving the Optimization Model

The proposed optimization model is designed to answer two questions: which candidate station should be selected and how many vehicles should be placed at each station chosen. The proposed model was applicable in solving problems in small networks listed in Section 4.4 using the commercial solver Gurobi. For the highway networks on a larger scale, a heuristic method is proposed by decomposing the solution procedure into two steps for solving this model.

5.1 Problem decomposition

Heuristic Method for solving the Optimization Model

The heuristic method solves this model by decomposing the solution procedure into three steps: (1) buffer zone creation, (2) preselection for the possible feasible solutions, (2) vehicle number calculation based on the preselected solutions. The optimization problem is separated into two parts by employing the problem decomposition, and the complexity of the problem can be reduced.

5.2 Steps

5.2.1 Step 1: Buffer zone creation

To determine the exact demand segments covered by each candidate station, buffer zones are created to describe the coverage relationships between the candidate stations and the demand segments. The centroids are used as the center of the buffer circles, and the service radius is utilized as the radius of the buffer circles. In this experiment, a buffer radius of 8 miles is adopted so that (1) all the centroids of the demand segments can be covered by the service stations; (2) the diameter of the whole service buffer can be 16 miles and satisfy the upper bound of the service time limits. The buffer zones and their coverage ranges are illustrated in Figure 18.

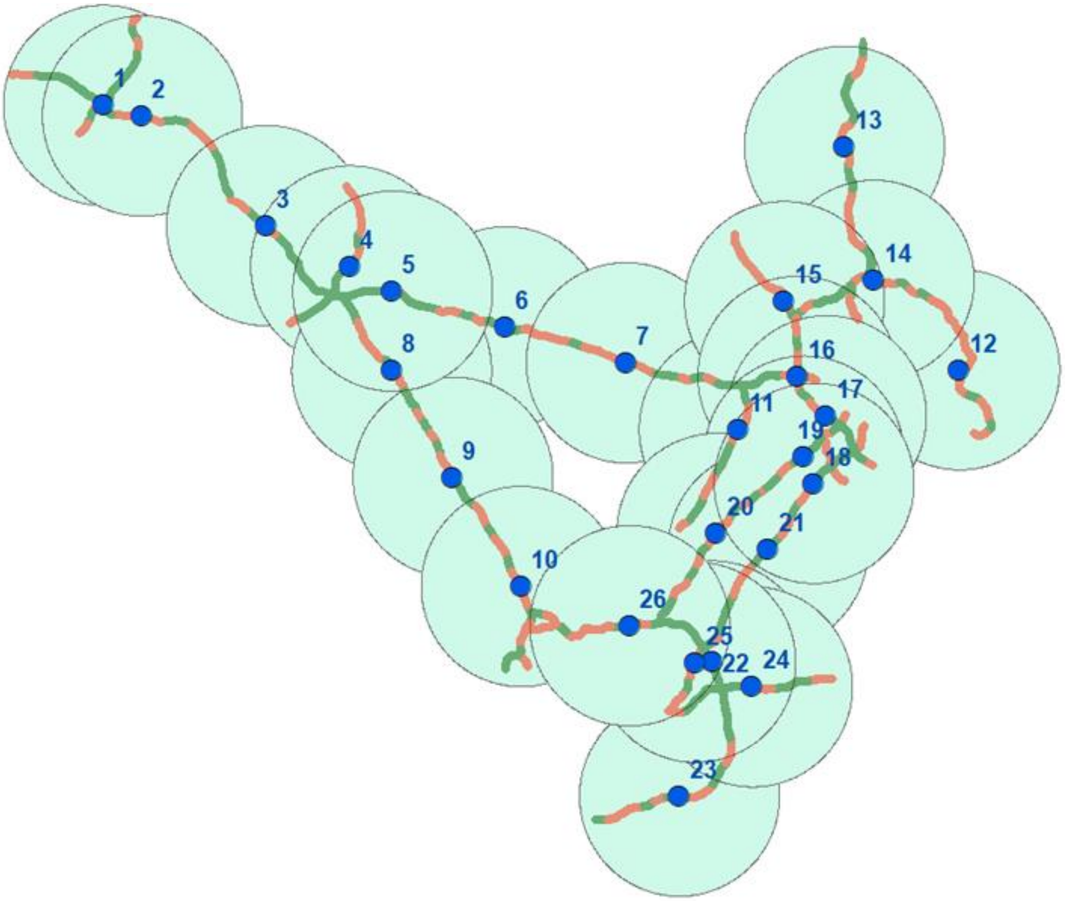


Figure 18 Buffer zones with service radius as 8 miles

5.2.2 Step 2: Preselection for the possible feasible solutions

The preselection part also has three substeps. The first substep is to select the must-have stations from all the candidate stations to cover all the demand segments. In this substep, the number of times each demand segment is covered is calculated based on the buffer zone generated from the service stations. Since all the demand segments need to be covered at least once, the candidate stations that cover those demand segments that are covered only once are considered the must-have stations. These must-have stations are saved to the set J_M. Based on the Maryland freeway network data, the must-have stations are displayed in Figure 19.

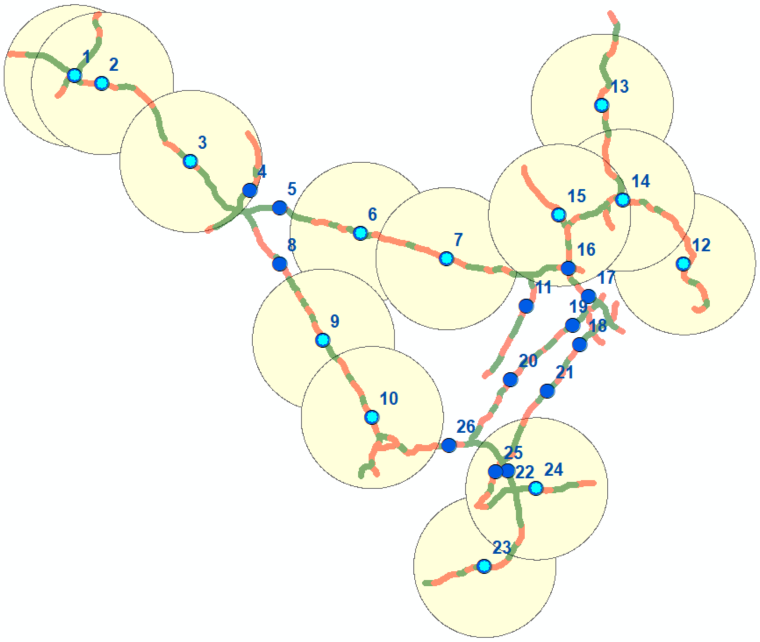


Figure 19 The must-have stations and their buffer zones

The second substep is to generate a list of all combinations of the rest of the candidate stations, denoted as J_R. There are m total candidate stations, and m_{MH} of them are selected as the must-have stations. The number of the rest of the candidate stations m_R is equal to $(m - m_{MH})$. Therefore, the number of combinations that the elements in J_R can generate is: $\sum_{u=0}^{m_R} C_{m_R}^{u}$.

The third substep is to filter out the supplement station set J_S from the combinations of the un-selected candidate stations list J_R ($J_S \in J_R$) such that the union set $J_U = J_M \cup J_S$ can cover all the demand segments. A dummy binary variable Y_j is utilized to record the selection conditions, and $Y_j = 1$ for all the stations in J_U, else $Y_j = 0$. It's remarkable that the supplement station set J_S is not unique. Multiple combinations of the unused candidate stations can provide full coverage to the network.

Two samples are displayed in Figure 20. The yellow buffers are generated from the must-have stations in J_M. The green and purple buffers are generated from two sample sets of J_S. By uniting the must-have stations J_M and the supplement stations J_S together, all the solutions in the set J_U can satisfy the full coverage constraints. Therefore, when taking all the $Y_j = 1$ for $j \in J_U$ and $Y_j = 0$ for $j \in (J \setminus J_U)$, each list in the set J_U is a feasible solution for the decision variable Y_j. All the possible feasible solution sets of J_U are saved in the list $[Solu]$.

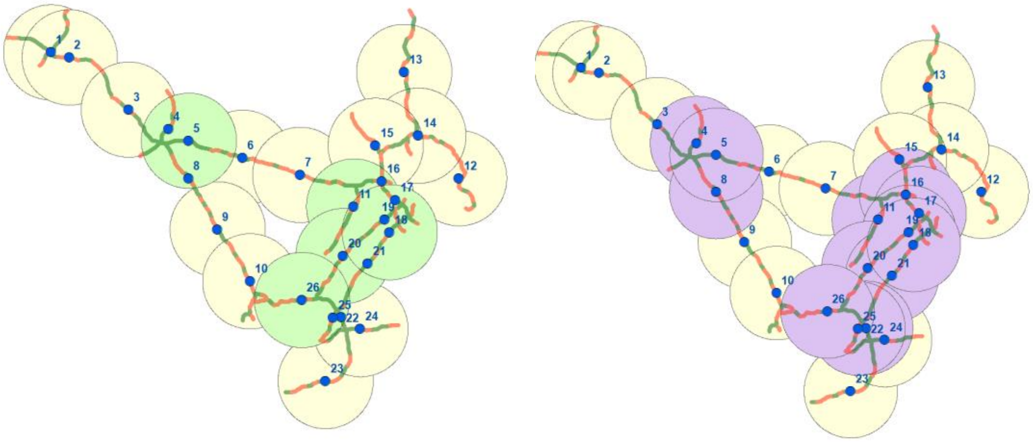


Figure 20 Examples of feasible solutions generated based on the must-have stations

5.2.3 Step 3: Vehicle assignment to the candidate stations

All the solutions should be subject to the constraints that all the demand segments should be covered at least once. All lists in the set of J_U can meet this requirement due to the preselection step. All the candidate stations with the corresponding value 1 should be selected in each list, otherwise not. Hence, the problem in this step is to decide the vehicle number q_j of each candidate station for each list in the set of J_U and it can be simplified to the optimization model with objective functions. The complete procedure of the heuristic method is summarized in Table 18.

5.3 Numerical Examples

The numerical examples based on two sample scenarios are used to check the performance of the proposed heuristic method. The data of road networks and incidents used in these scenarios are the same as the data described in Section 4.4.

Step 1: Buffer zone creation

The created buffer zones are the same as the outputs shown in Figure 16 since the same scenarios were used.

Step 2: Preselection for the possible feasible solutions

Based on the coverage constraints, the must-have stations of the two scenarios are found out. Their coverage conditions are shown in Figure 21. The must-have stations J_M are listed in Table 19.

Based on the must-have stations, all possible combinations of the candidate stations $\boldsymbol{J_U}$ can be listed. Therefore, all possible feasible solutions $\boldsymbol{Y_j}$ corresponding the $\boldsymbol{J_U}$ can be generated. These solutions are listed in Table 20.

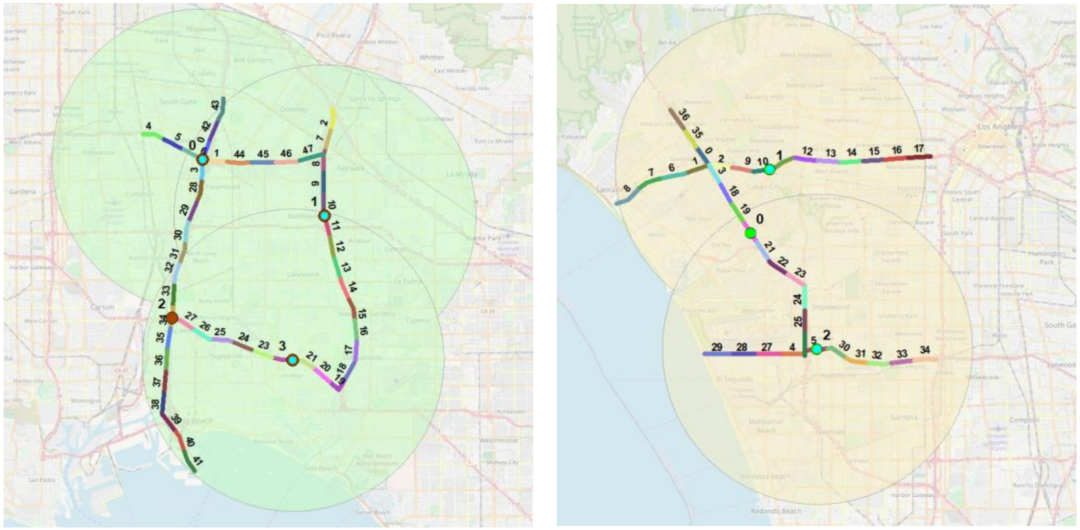
Table 18 The summary of the steps of the heuristic method

Step 1: Buffer zone creation	
1)	Based on the connectivity of the road network configuration results, create buffer zones for each candidate station.
2)	Generate a table a_{ij} having service station and demand segment pairs based on the connectivities and the coverage radius R.
Step 2: Preselection for the possible feasible solutions	
1)	Calculate the times that each demand segment $i \in I$ is covered by all $j \in J$ based on the buffer zones.
2)	For the demand segments being covered only once, label their corresponding service stations as “must-have.”
3)	Save all the candidate stations with the “must-have” label to the set J_M. J_M has total m_{MH} stations in it.
4)	The number of the rest candidate stations is $m_R = m - m_{MH}$.
5)	Denote the set of all the rest candidate stations as J_R, $J_R = \{J \setminus J_M\}$. The number of combinations that the elements in J_R can generate is: $\sum_{u=0}^{m_R} C_{m_R}^{u}$.
6)	Filter out the supplement station set J_S from the combinations of the un-selected candidate stations list J_R ($J_S \in J_R$)
7)	Create the union set $J_U = J_M \cup J_S$ such that J_U can cover all the demand segments.
8)	Create a dummy binary variable Y_j to record the selection conditions
9)	$Y_j = 1$ for $j \in J_U$, and $Y_j = 0$ for $j \in (J \setminus J_U)$
10)	Create a solution list $Solu$ to save all the different J_U sets
Step 3: Vehicle assignment to the candidate stations	

1) Simplify the problem to the optimization model with a single decision variable q_j

2) For each J_U set in the list $[Solu]$, solve the optimization model using Gurobi for all the six objective functions

3) Save the q_j that can produce the best objective values



(a) Scenario I

(b) Scenario II

Figure 21 The coverage conditions of the must-have stations of the two scenarios

Table 19 The must-have stations of the two scenarios

Scenario ID	J	J_M
Scenario I	$[0, 1, 2, 3]$	$[0, 1, 3]$
Scenario II	$[0, 1, 2]$	$[1, 2]$

Step 3: Vehicle assignment to the candidate stations

The problems were simplified into solving for the integer variable of q_j, which is the number of vehicles residing at each candidate station having $Y_j = \mathbf{1}$. Hence, this problem can be solved using the commercial software Gurobi. The solutions representing the selected stations and the vehicle assignment at each standby station of the two experiment scenarios are listed in Table 21. The vehicle assignment result for each scenario can be decided by the solution with the smallest objective value. Based on the data in Table 21, the final vehicle assignment results are $q_j = [1, 1, 0, 1]$ for Scenario I and $q_j = [0, 1, 1]$ for Scenario II.

Table 20 All the possible feasible solutions

Scenario ID	J_U	Y_j
Scenario I	$[0, 1, 3]$	$[1, 1, 0, 1]$
	$[0, 1, 2, 3]$	$[1, 1, 1, 1]$
Scenario II	$[1, 2]$	$[0, 1, 1]$
	$[0, 1, 2]$	$[1, 1, 1]$

Table 21 Solutions and vehicle assignment results

Scenario ID	q_j	**Objective value**
Scenario I	$[1, 1, 0, 1]$	1577.5798
	$[1, 1, 1, 1]$	1744.0382
Scenario II	$[0, 1, 1]$	503.3850
	$[1, 1, 1]$	742.4717

These results calculated from the heuristic method are the same as the results generated by the Gurobi in Chapter 4. Therefore, it is reasonable to assume that the proposed heuristic method produces good results for the large-scale optimization model in this problem.

Chapter 6 Scenario Experiments and Analysis

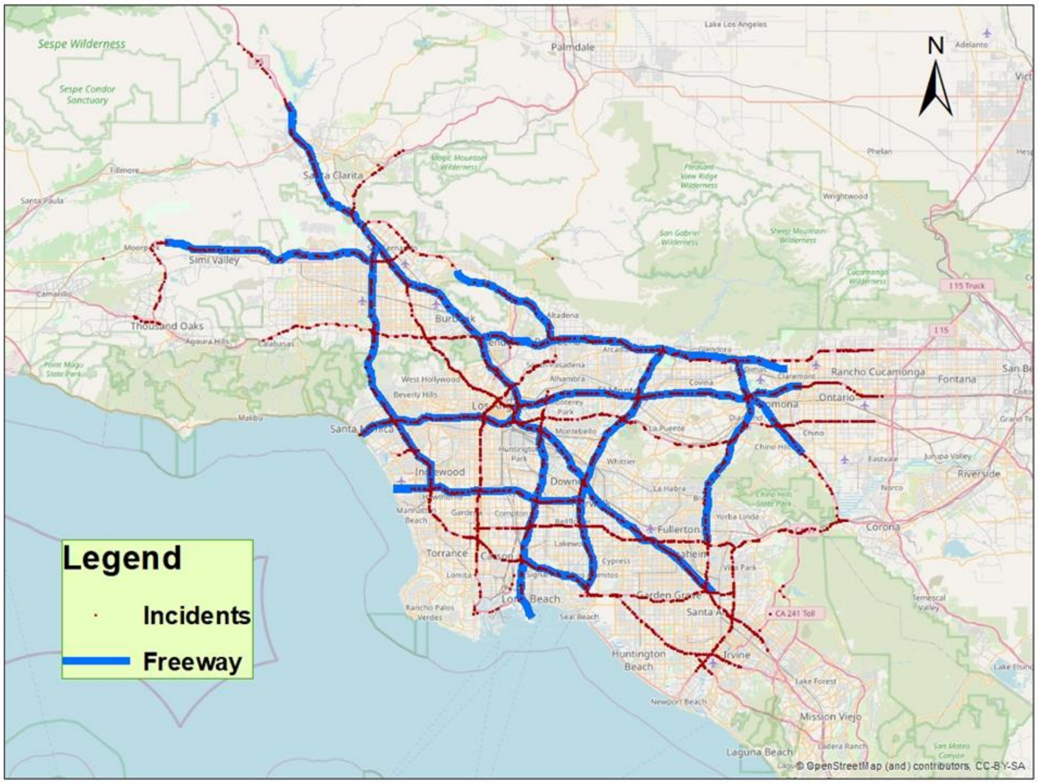
6.1 Data Descriptions

6.1.1 The freeway network in the experiment scenarios

To evaluate the performances of the solutions, it's necessary to compare the data generated from the evaluation experiments to the ground truth data. This comparison requires three types of timestamps: the time when receiving the incident reports, the time when dispatching a service vehicle, and the time when the service vehicle arrives at the incidents. However, the dataset provided by CHART does not have the timestamp of vehicle dispatching. Due to the lack of vehicle dispatch timestamps in the CHART data, the experiment scenarios for solution evaluation are built based on the freeway network in Southern California instead of Maryland.

The work of Daneshgar (Daneshgar, 2018) utilized CHART data, which did not include the timestamps of vehicle arriving, either. Therefore, the result of this research is not compared to his work but compared to the ground truth data directly.

This freeway network has a total length of 378.11 miles. The organization of California Highway Patrol (CHP) provides a patrol service on the freeways in this area. Their service data is recorded and can be achieved through the Caltrans Performance Measurement System (PeMS) platform. The freeway network and the collisions that happened in this area are displayed in Figure 22.



© OpenStreetMap (and) contributors, CC-BY-SA

Figure 22 Freeway network in Southern California

6.1.2 The collisions in the experiment scenarios

Based on the PeMS records, there were 2180 collisions served by the CHP during August 2017 in total on the freeway in this area. Each collision was recorded as an event with multiple timestamps. These timestamps include the time of the incident occurrence, the time of a service vehicle being dispatched, the time of the service vehicle arriving at the collision location, and the time of the collision being fully cleared from the highway.

The distribution of the numbers of collisions varies in different time windows. The counts of collisions of each date by five different time windows in August 2017 are shown in Figure 23. It can be found that the time window of weekday afternoon (1 pm – 9 pm) generally has a higher number of collisions than other time windows. The number of collisions in weekday evenings is the lowest among all the five time windows. The two time windows on weekend days have a longer length than the others on weekdays. Their daily collision counts are at a similar level to the time window of weekday mornings (5 am – 1 pm).

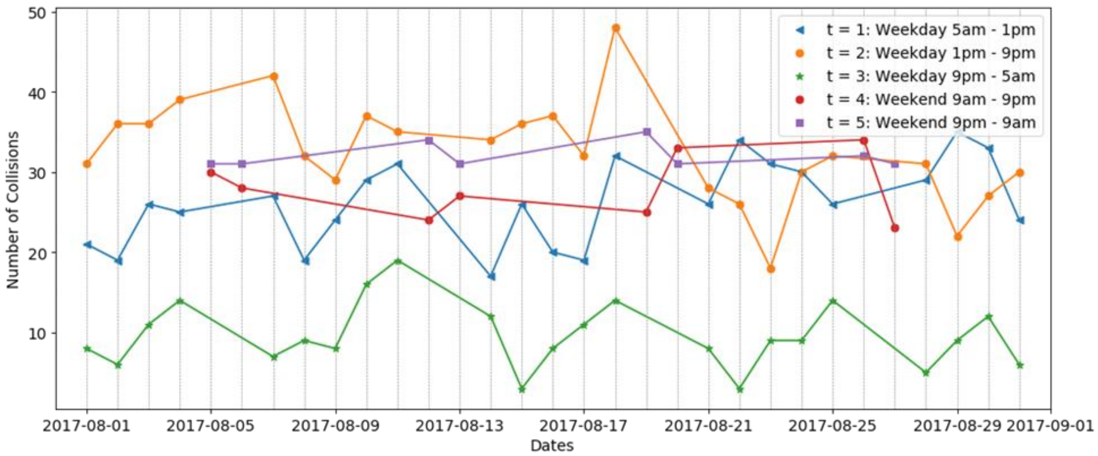


Figure 23 Number of collisions on the freeway network of Southern California

To check the model's performance under different distributions of counts of collisions, the evaluation experiment scenarios are designed as one time window. The experiments focused on checking the performances for the first four time windows since the weekend nighttime has a similar lower incident frequency as the weekday nighttime. Therefore, four scenarios were examined based on the solutions calculated from the optimization model, and each of them stands for a single time window, which is defined in Table 3. The duration of each scenario is the length of the time window of a single day. The date selection is based upon the incident numbers. Three dates were chosen to build up the scenarios for the evaluation experiments, and each of them has either the least or the most collision number among the month. The selection of scenarios also considered the situation of incident overlaps. Both of the situations with and without incident overlaps are included in the experiments.

6.2 Road Network Configuration

The length of the whole freeway network is 378.11 miles. Based on the method introduced in the previous chapters, the network was divided into 366 demand segments. The minimum, average, and maximum length of the demand segments are 0.9954, 1.03 miles, and 1.2763 miles, respectively. The demand segments and their corresponding ID in the network are shown in Figure 24.

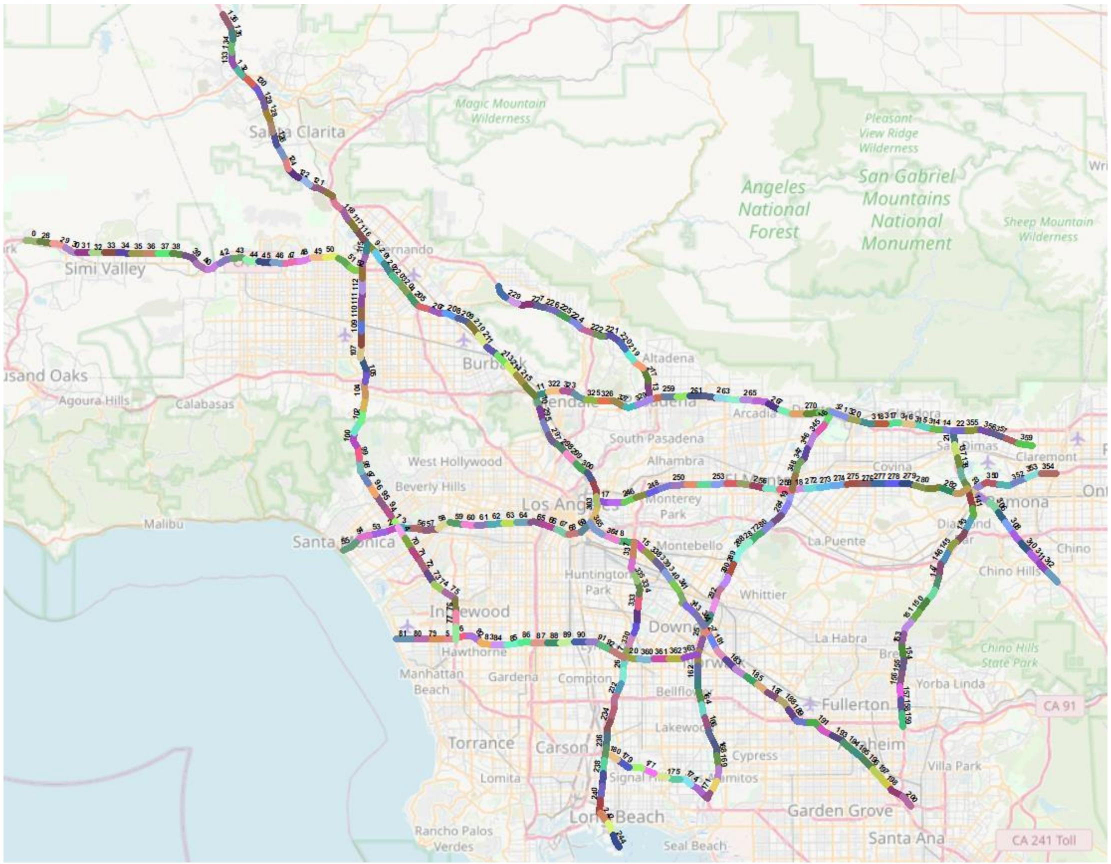


Figure 24 Demand segments in the freeway network in Southern California

For each demand segment, the incident levels and KDE values were calculated. The HZ-DFS algorithm was applied to this network to transform the short segments into longer ones based on their lengths. The result is shown in Figure 23 (a). The service time limit was set as 10 minutes so that the lower bound of the interval length is 9.17 miles, calculated in equation (18) when the speed limit of the freeway is 55 mph.

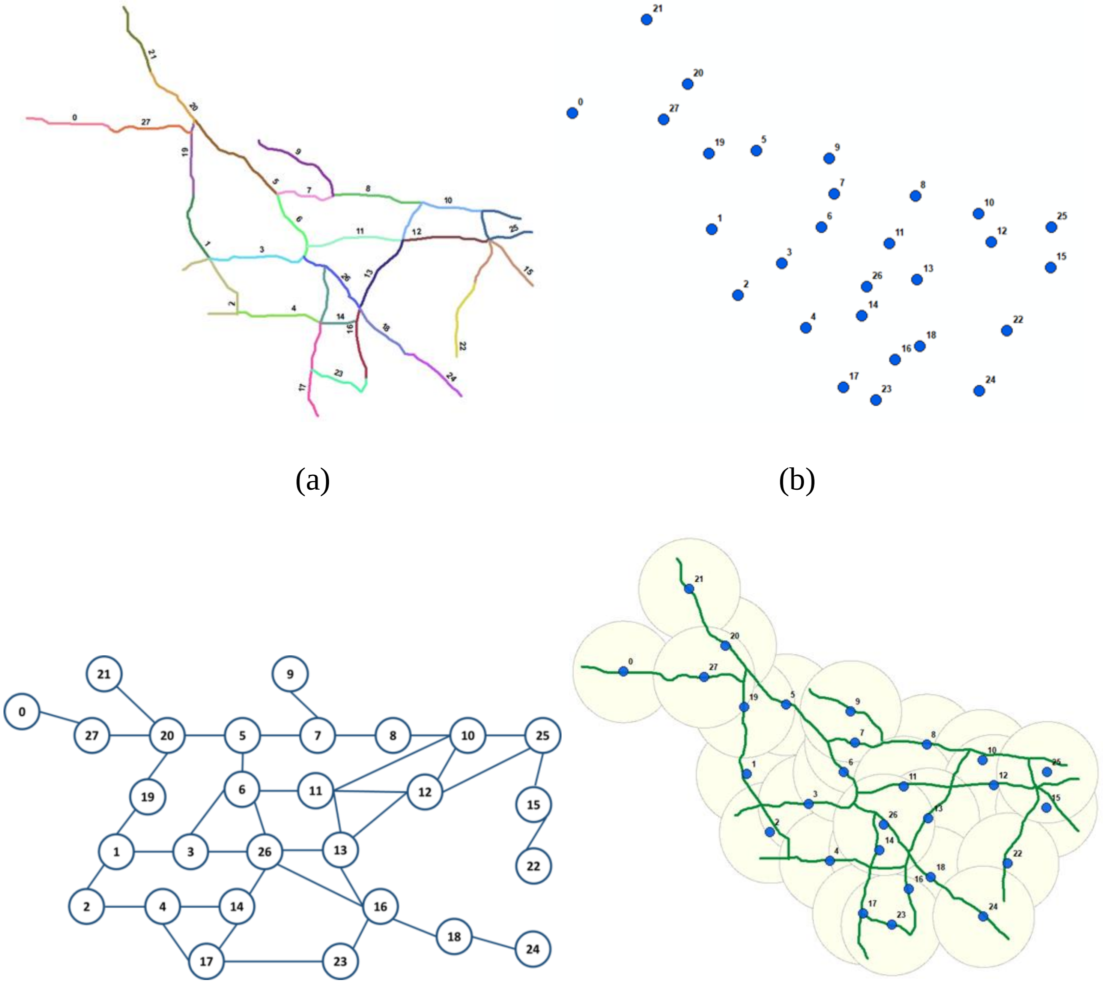
$$55mph * \frac{10}{60} = 9.17\ miles \tag{18}$$

The first step to building the experiment environment is producing the abstracted road network based on an existing freeway network. The freeways in Southern California are adopted as the network data in this experiment.

For each spliced long segment, its centroid, shown in Figure 25 (b), represents the segment. After extracting the centroids (Figure 25 (c)), new edges are created to connect the centroids based on the road network structure. All the edges are associated with a length value that stands for the distances between each centroid pair. The final abstracted network is shown in Figure 25 (d). The driving distances between each pair of service stations and their covered demand segments in the network are shown in Appendix B. The driving distance and the driving time data are shown in Appendix B were retrieved from Google Maps API based on the ground-truth data.

6.3 Vehicle Assignments based on the Standby Service Optimization Model

The vehicle assignments in the examined scenarios are based on the solutions of the optimization model, which was solved by the heuristic method introduced in Chapter 5. The must-have stations to offer the full coverage to all the demand segments for the solutions and their buffer zones J_M are plotted in Figure 26. The figure shows that 11 stations should have at least one service vehicle standby so that all the demand segments can be covered at least once.



(a) (b)

(c) (d)

Figure 25 Freeway network abstraction

Different preliminary conditions were set to conduct the experiments. These preliminary conditions include the limit on the number of vehicles in a single station V and the total number of vehicles in the system, Q that stands for the entire available service vehicles of the agency. Under each initial condition, the best solutions were calculated based on the objective function.

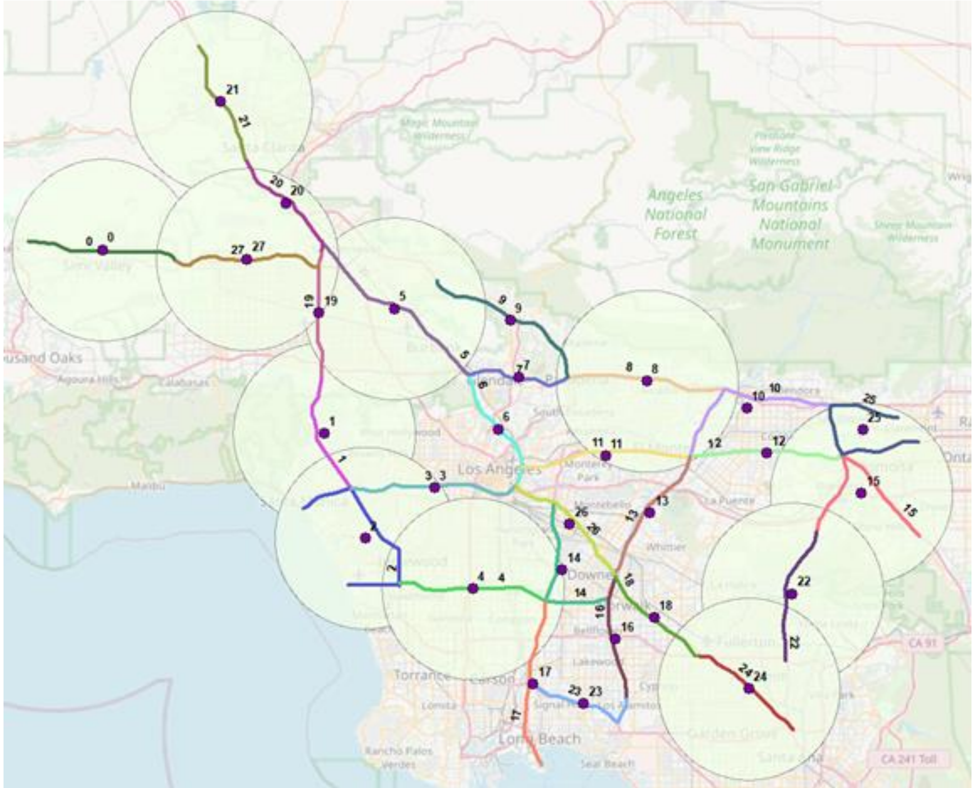


Figure 26 The must-have stations for the solutions and their buffer zones

One base condition for these experiment scenarios was set as 30 vehicles in the system in total, and at most, two vehicles allowed in each standby station. The vehicle assignments under different scenarios are shown in Table 22.

Five scenarios were created to evaluate the five time windows. The data in the five scenarios are from August 20, August 28, and August 29 in 2017. Scenarios I and II stand for the weekday time windows of morning and afternoon, respectively, on Aug 29. Scenario III stands for the weekday time window of midnight between Aug 28 and Aug 29. The time windows of daytime and nighttime on weekends are shown in

Scenario IV and V correspondingly. Detailed descriptions of the five scenarios are described in Table 23.

6.4 Evaluation Experiment Scenarios

The overlap conditions of these incidents of the five scenarios in the time dimension are illustrated in Figure 27 (a), (b), (c), (d), and (e), respectively. In Figure 27, the x-axis shows the time elapsed in the morning peak period, and the y-axis shows the ID of each collision. The blue dots stand for the time the incidents occur, and the red dot stands for the cleared time of the corresponding incident. The length of the blue lines indicates the duration of the incidents. Longer blue lines indicate that the incident lasts for a longer time.

6.5 Evaluation Experiment Settings

The experiments are conducted with the time step as one minute. The predefined condition for the experiment scenarios is that the pre-assigned vehicles on the road network are listed in Table 22, and each station can have most two vehicles, and there are 30 vehicles available in the system in total. For each solution, the experiment scenario was searched by the minute. Three lists of labels were also created to record the event that happened during the experiments. The three lists are (1) event assistant status, (2) the station ID that offers the assistance, and (3) the traveling time that the vehicle drives from the station to the incident.

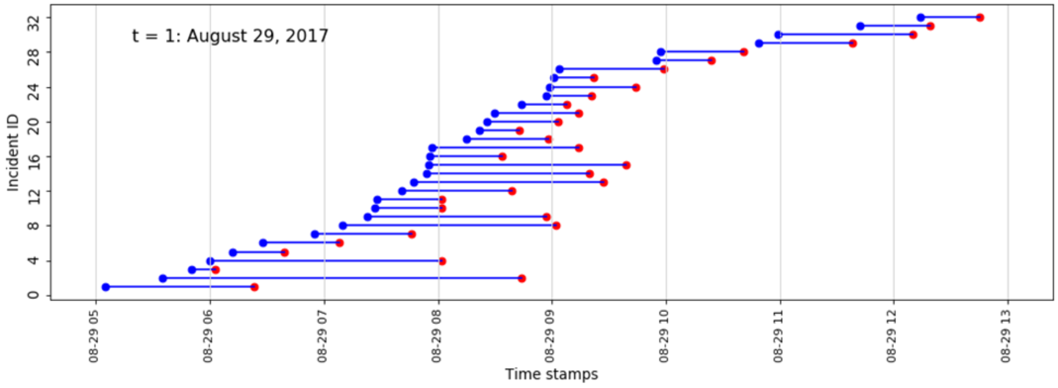
Table 22 Vehicle assignments in the five time windows

	q_j				
j	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
0	1	1	1	1	1
1	1	1	1	1	1
2	1	1	1	1	1
3	0	0	0	0	0
4	1	1	1	1	1
5	1	1	1	1	1
6	1	1	1	1	1
7	1	0	1	1	1
8	1	1	1	1	1
9	0	1	0	0	0
10	0	1	1	1	0
11	1	1	1	0	0
12	1	0	0	0	1
13	0	0	0	1	1
14	1	1	0	1	1
15	1	1	1	1	1
16	1	1	0	0	0
17	2	0	0	0	0
18	0	0	1	1	1
19	0	2	2	0	0
20	0	0	0	0	0
21	2	1	2	1	1
22	1	1	2	1	2
23	2	1	1	1	1
24	1	1	1	1	1
25	0	0	0	0	0

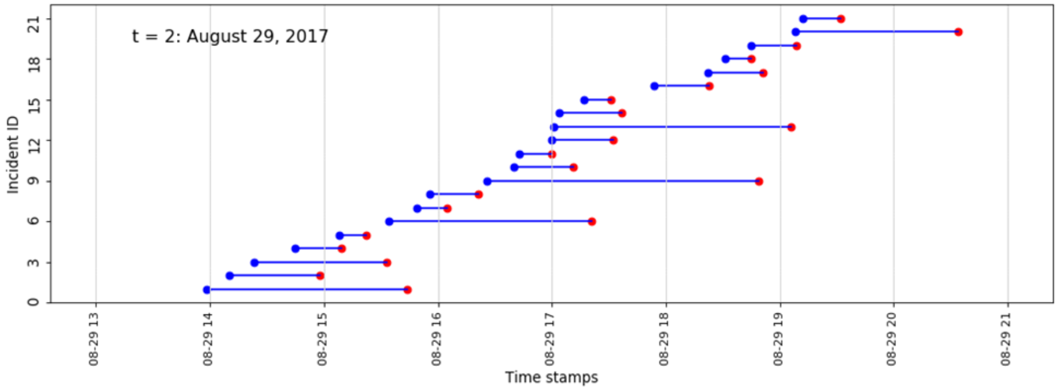
26	0	0	2	0	0
27	1	1	1	1	1

Table 23 Experiment scenario descriptions

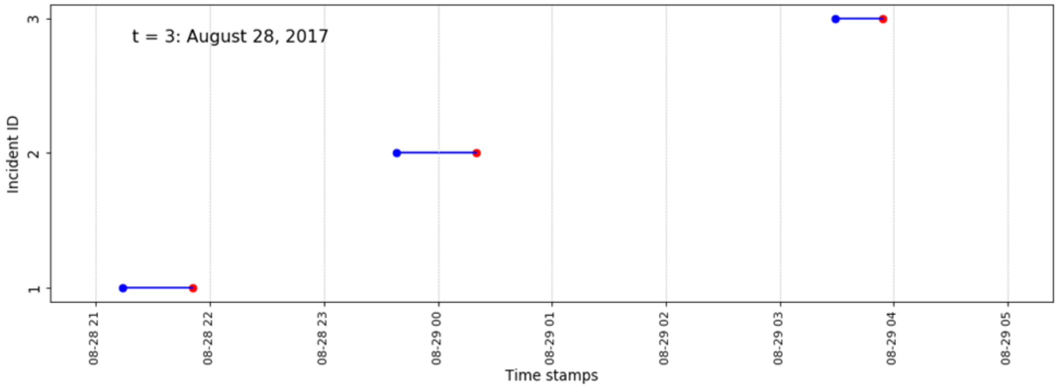
	Scenario I	**Scenario II**	**Scenario III**	**Scenario IV**	**Scenario V**
Date	Aug 29, 2017	Aug 29, 2017	Aug 28, 2017	Aug 20, 2017	Aug 20, 2017
Time Window	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
Experiment Duration	8 hours	8 hours	8 hours	12 hours	12 hours
Collision Number	33	22	3	26	8
Scenario Characters	High level of collision frequency	Mid-level of collision frequency	Low level of collision frequency	Mid-level of collision frequency in a longer time window	Low level of collision frequency
Incident Overlaps	Yes	Yes	No	Yes	Yes



(a) Scenario I: Weekday morning

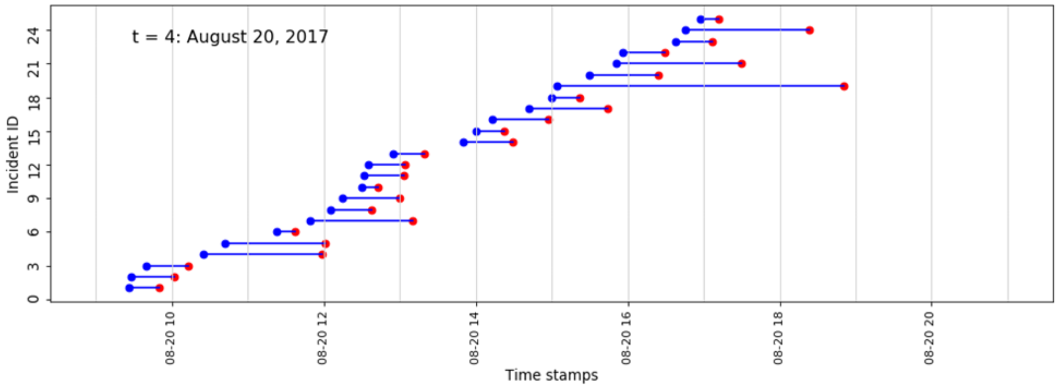


(b) Scenario II: Weekday afternoon

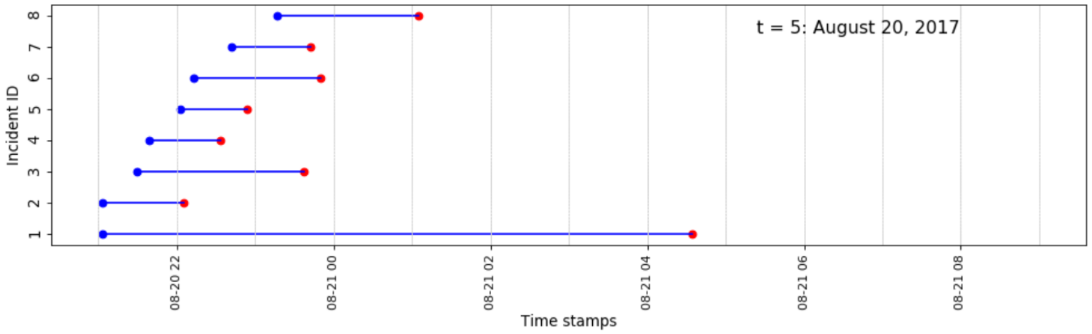


(c) Scenario III: Weekday evening

Figure 27 The overlap conditions of incidents in the time domain



(d) Scenario IV: Weekend daytime



(e) Scenario V: Weekend nighttime

Figure 27 (Cont'd)The overlap conditions of incidents in the time domain

The list of event assistant status has two types of elements: “incident assisted” and “incident missed.” If an incident is successfully served by a vehicle from a station that offers coverage to its demand segment, the incident will be labeled as “incident assisted.” If there are not enough vehicles in all stations that can cover the demand segment when an incident occurs, the incident will be labeled as “incident missed.”

The *Collision_ID* list records from which candidate station the service vehicle is dispatched to the incident if the incident is assisted in time.

The *Response_Time* list records how long it takes when the service vehicle arrives at the incident location.

If multiple stations cover a demand segment in the experiment, service vehicles will be assigned from the closest station. The sequence for station selection is based on their distances to the demand segment. Vehicles from the closer station will be first considered during the assignment. After assisting the assigned incident, the service vehicle will return to its original standby location if the vehicle number in the original location has not reached the maximum capacity based on the solution. Otherwise, the vehicle will be allocated to the closest standby station that has not reached its maximum capacity. The detailed experiment processes are summarized in Table 24.

6.5 Evaluation Experiment Results

The evaluation experiment results and logs of the five scenarios of different time windows are listed in the tables of Appendix C.

6.6 Evaluation Experiment Result Analysis

The driving time for each experiment scenario and its corresponding ground-truth response time are displayed in Figure 28 from (a) to (e). The experiment result shows that the driving durations generated by the evaluation experiment model are shorter than the ground-truth response time recorded in the historical dataset for most of the collisions on this road network. There are only a few collisions waiting longer for the service vehicle to arrive in each scenario. The proposed vehicle assignment method can reduce the waiting time efficiently.

Table 24 Evaluation experiment processes

I. Create empty lists for recording the experiment outputs:

1) *Collision_ID:*

    The ID of the collision

2) *Event_Assist_Status:*

    The records indicating if the collision is assisted or missed. Three statuses are used: [*Collision_Assisted, Collision_Missed, Collision _Finished*].

3) *Demand_Segment_ID*:

    The ID of the demand segment that generated the collision.

4) *StationID_offer_assist*:

    The ID of the standby station that assigned the vehicle to the collision.

5) *Response_Time:*

    The time length (in minutes) that the service vehicle drives from the standby station to the collision's location.

6) *Timestamp*:

    The timestamps recording when each collision status happened.

II. Inputs:

1) Pairs between *StationID* and *Demand_Segment_ID*
2) The numbers of vehicles in each standby station based on the solution of the optimization model
3) Distances between each pair of standby stations and demand segments $\{\boldsymbol{d_{ij}}\}$
4) Collision data:

    Collision_ID, Collision location,
    Timestamp of collision occurred, Time of collision cleared

5) Collision status:

    Two statuses are included: [*Collision_Occured, Collision_Cleared*]

6) Time range:

    A list of time points within the range of the experiment time window.

III. Reshape the collision data:

1) Split the original Collision data into two subsets:

    Subset A:

        Collision_ID, *Collision location*, *Timestamp of collision occurrence*

    Subset B:

        Collision_ID, *Collision location*, *Timestamp of collision cleared*

2) Concat Subset A and Subset B vertically as a full incident set *Collision Set*.
3) Sort the *Collision Set* based on the timestamps of collisions ascendingly.

IV. Run the experiment:

For each timestamp having a collision record:

If the record shows a collision having the status "*Collision_Occured*":

1) Get the demand segment ID where the collision happens.
2) Get the IDs of the standby stations that provide coverages for this demand segment. Record their corresponding driving time to the demand segment.
3) Sort the standby stations based on their driving durations ascendingly.
4) For the standby station with the shortest driving duration, check its number of available vehicles based on the solution of the optimization model.

    If the number of available vehicles is equal to or larger than one:

    a) Assign the vehicle to assist the collision.
    b) Update the pre-defined empty list of *StationID_offer_assist* with the standby station ID
    c) Update the pre-defined list of *Collision_status* as *Collision_Assisted*
    d) Subtract one from the number of vehicles in the standby station that offered assistance.

    If the number of available vehicles is zero:

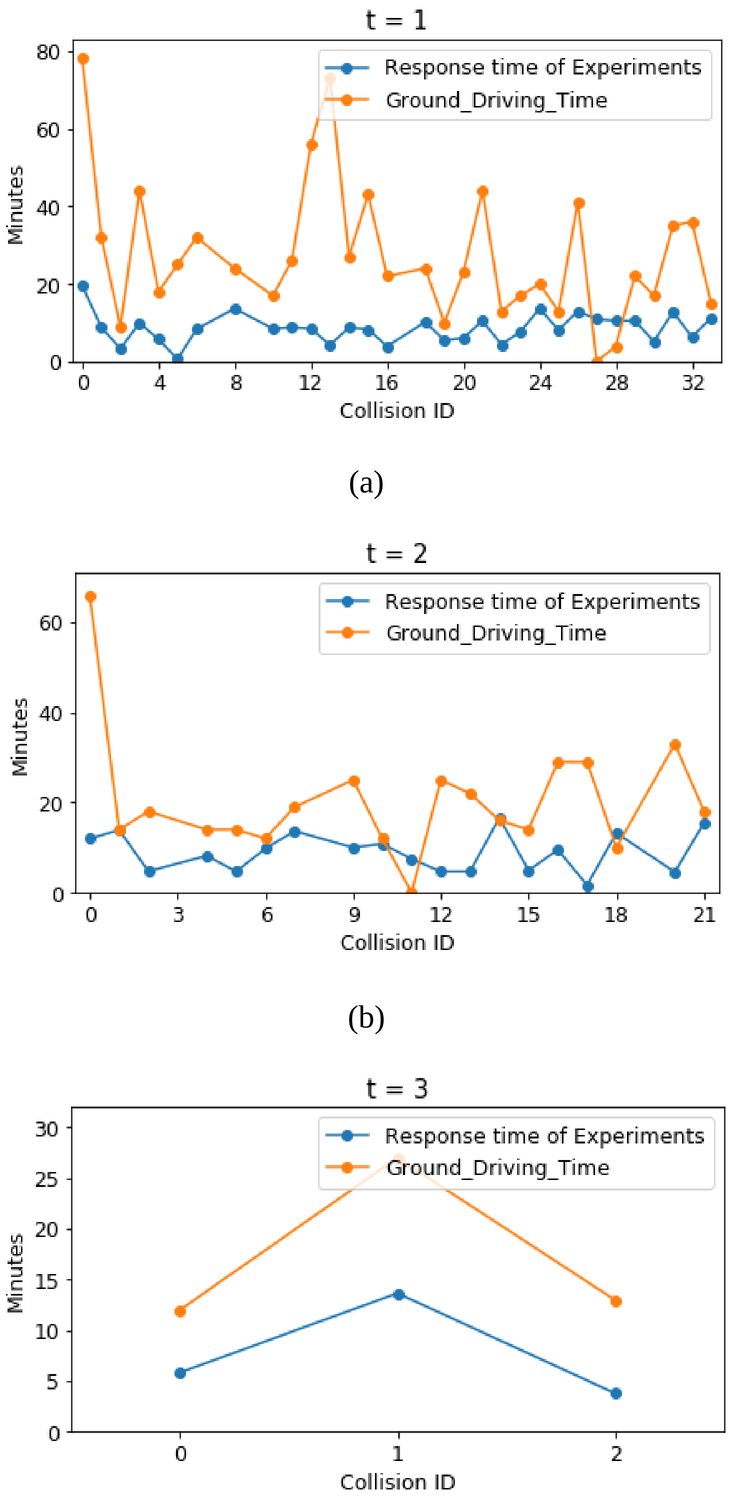
    a) Move on to the next closest standby station and check the vehicle number of this station.

    b) Repeat the steps listed in the above Part 4) until all the related standby stations are checked.
    c) If all the standby stations covering this collision have zero vehicles, update the *Event_Assist_Status* list as *Collision_Missed*.
5) Move to the next timestamp that has a collision record.

If the record shows a collision having the status “*Collision_ Cleared*”:

1) Mark the collision’s ID
2) Check the collision’s status in the *Collision_status* list in previous timestamps.
    a) If its status has been marked as “*Collision_Assisted*”:
        i. Update the *Event_Assist_Status* list as “*Assisted_Finished.”*
        ii. Add one to the number of vehicles on the standby station that offered assistance if not reaching its maximum capacity.
        iii. Add one to the number of vehicles on the next closest standby station that has not reached its maximum capacity if the vehicle’s original station has reached the full capacity.
    b) Otherwise, update the *Event_Assist_Status* list as “*Collision_Missed*

End the experiment when all the timestamps are searched.

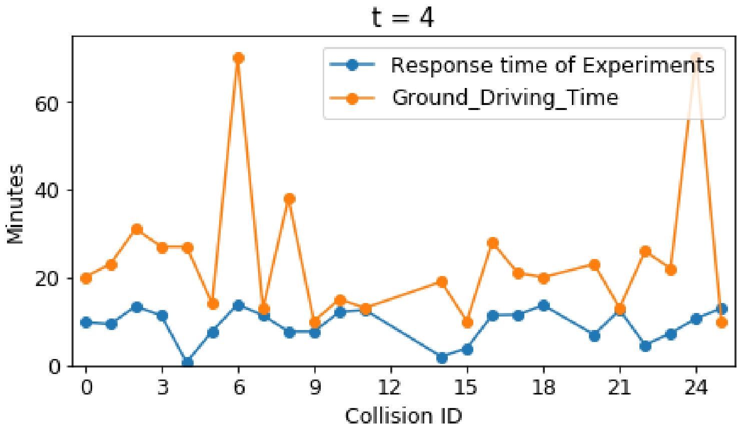


(a)

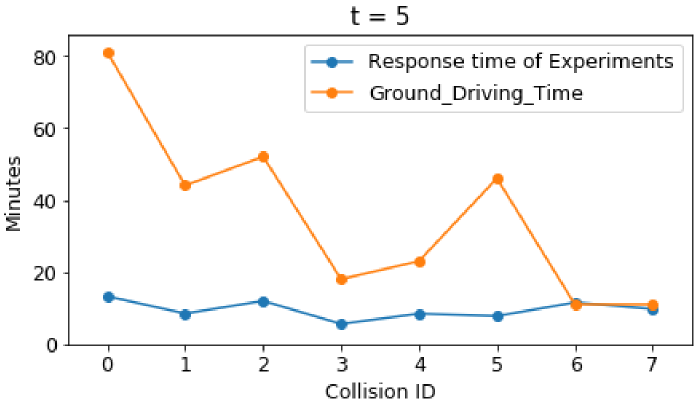
(b)

(c)

Figure 28 The response time in the evaluation experiments and the ground-truth response data of each scenario (minutes)



(d)



(e)

Figure 28 (Cont'd) The response time in the evaluation experiments and the ground-truth response data of each scenario (minutes)

Chapter 7 Sensitivity Analysis

7.1 Numbers of available vehicles and limits of the numbers of vehicles in each station

7.1.1 Comparison of the results between the model outputs and the ground-truth data

The evaluation experiment results show that there were missed incidents by the service vehicles, and they were not served during the experiment process based on the base condition, which limits at most two vehicles in one station and a total of 30 vehicles available. Therefore, scenarios with different settings of preliminary conditions were also analyzed to see the influences of different parameters. First, a larger number of available vehicles Q in the service system was tested. Q was set as 60 instead of 30 as the base scenario. The vehicle assignments with $Q = 60$ under different time windows are shown in Table 25.

The response time of evaluation experiments for each scenario and its corresponding ground-truth response time is displayed in Figure 29. The experiment result shows that the driving durations generated by the evaluation experiment model are shorter than the ground-truth response time recorded in the historical dataset for most of the collisions on this road network. There are only a few collisions waiting longer for the service vehicles to arrive in each scenario. The proposed vehicle assignment method can reduce the waiting time efficiently.

Table 25 Vehicle assignments under different experiment settings in the five time windows, $Q = 60$

q_j	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
0	1	1	1	1	1
1	1	1	1	1	1
2	1	1	1	1	1
3	0	0	0	0	0
4	1	1	1	1	1
5	1	1	1	1	1
6	1	1	1	1	1
7	1	0	1	1	1
8	1	1	1	1	1
9	0	1	0	0	0
10	0	1	1	1	0
11	1	1	1	0	0
12	1	0	0	0	1
13	0	0	0	1	1
14	1	1	0	1	1
15	1	1	1	1	1
16	3	1	0	0	0
17	3	0	0	0	0
18	0	0	1	1	1
19	0	3	3	0	0
20	0	0	0	0	0
21	3	1	3	1	1
22	1	1	3	1	3
23	3	1	1	1	1
24	1	1	1	1	1
25	0	0	0	0	0

26	2	0	3	0	0
27	3	1	1	1	1

Comparing these results to the performance of solutions under the setting of $Q = 30$, the mean values of the saved response time for each collision between the experiments and ground-truth data are listed in Table 26. The number of vehicles in use and the number of missed incidents under different numbers of all the available vehicles are also listed in Table 27.

It can be concluded that by increasing the number of total available vehicles in the service system, the response time that can be saved stays at a similar level for different scenarios, and the number of vehicles that are actually used does not increase significantly except for time window 1. At the same time, the number of missed incidents in the evaluation experiment scenarios decreased by increasing the value of total available vehicles Q.

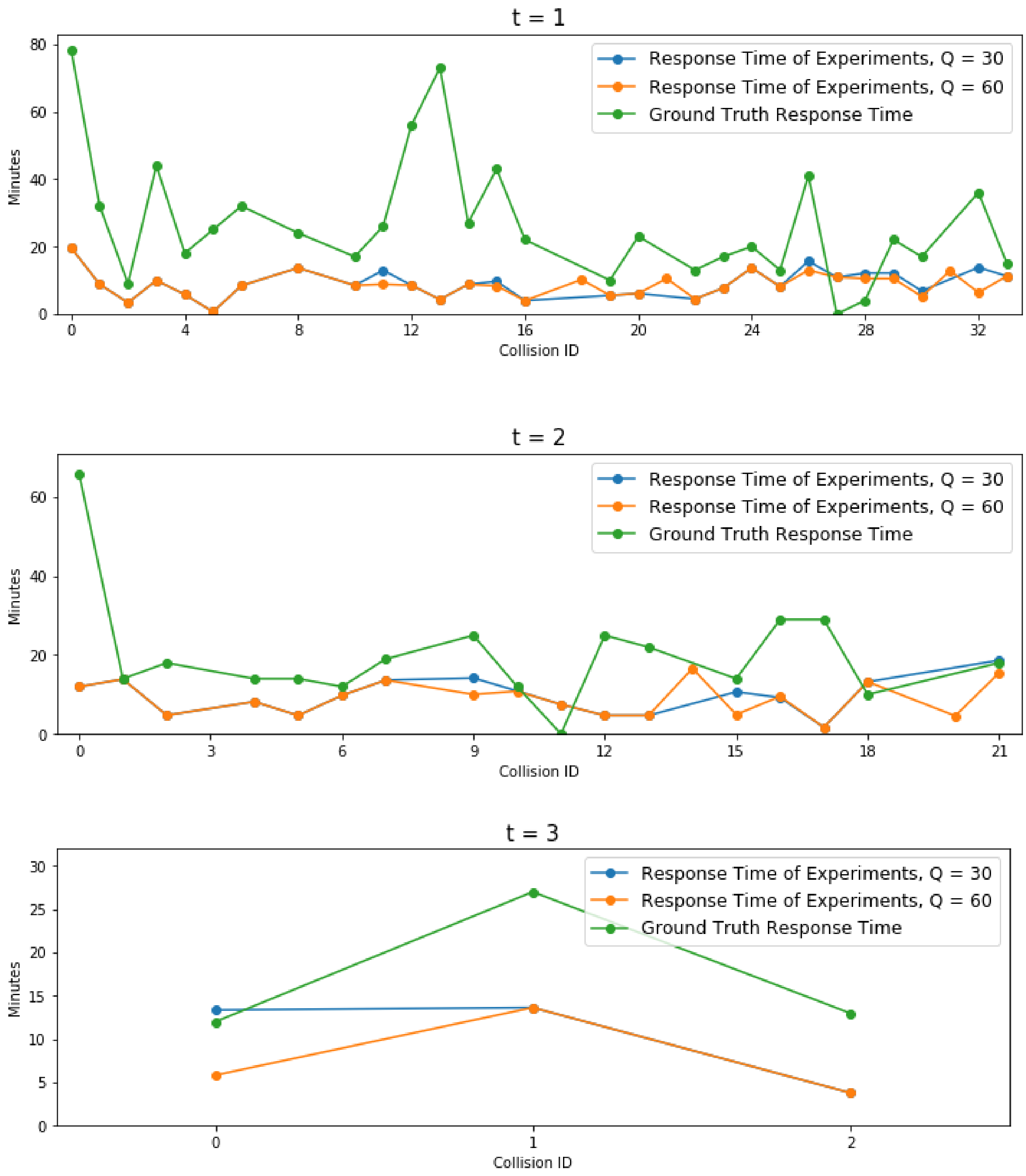


Figure 29 The response time of the evaluation experiments and the ground-truth data of each scenario (minutes)

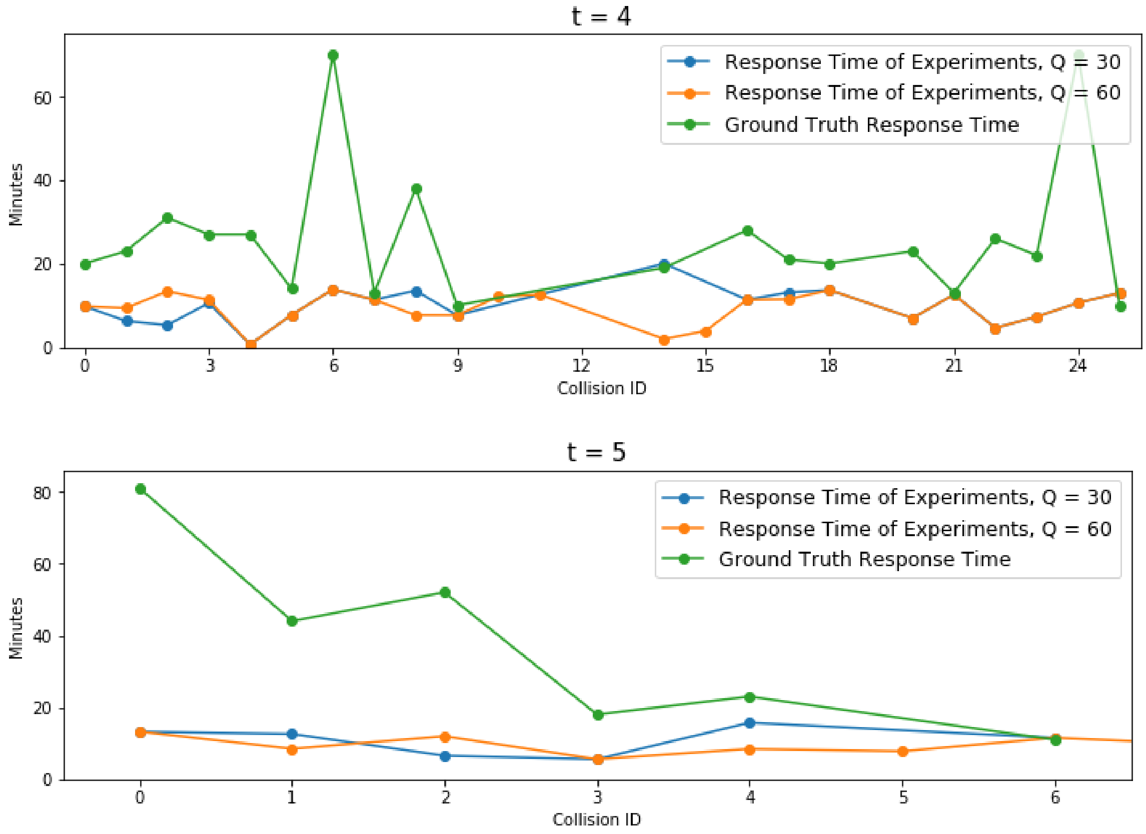


Figure 29 (Cont’d) The response time of the evaluation experiments and the ground-truth data of each scenario (minutes)

Table 26 Mean values of the saved response time for each collision between the experiment data and the ground-truth data (minutes)

$Q = 30$		$Q = 60$	
t	Saved response time	t	Saved response time
1	19.1029	1	17.9939
2	11.5532	2	10.5176
3	9.5733	3	7.06
4	15.1652	4	16.285
5	26.1663	5	27.3067

Table 27 The number of vehicles in use and the number of missed incidents under different values of Q

t	Number of vehicles in use		Number of missed incidents	
	$Q = 30$	$Q = 60$	$Q = 30$	$Q = 60$
1	22	31	5	2
2	20	21	5	3
3	23	27	0	0
4	18	18	6	3
5	19	20	2	0

7.1.2 Comparison of the results for different parameter settings

The impact of the total number of vehicles Q in use on the model is also checked together with the limits on the maximum number V that each station can have. The vehicle assignment in the scenario is listed in Table 28.

The impacts of the two parameters on the response time are shown in Figure 30. It can be found that the response time of evaluation experiments is not influenced by the values of Q. Increasing the total number of available vehicles may not reduce the total response time to the incidents. For the second time window, which stands for the weekday afternoon, the response time is reduced by increasing the maximum number of vehicles each station can have. However, this characteristic is not evident in other time windows.

The numbers of vehicles that are actually in use under different values of V and Q were also checked, and the results are shown in Figure 31. It can be found that the total number of available vehicles in the system Q does not have a strong impact on the numbers of vehicles that are actually in use. The total number of used vehicles remains at a level that is lower than 30 even the number of Q has been more than that. However, it shows that the numbers of vehicles actually in use have a positive relationship with V. Given the same number of total vehicles in the system, the higher the value of V is, the larger the number of vehicles that actually in use is. It may be inferred that a higher limitation of the number of a station can increase the utilization of available vehicles.

7.3 Hourly fixed cost c_f

The influence of the hourly fixed cost parameter is also checked. In the base scenario, the hourly fixed cost was set as \$20. A scenario with an hourly fixed cost of \$40 was built to check the model's performance. The vehicle assignment in the scenario is listed in Table 29.

Table 28 Vehicle assignments under different experiment settings on V and Q in the five time windows

t	***V***	***Q***	Numbers of vehicles on each station
1	1	20	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1]
	2	20	[1, 1, 1, 1, 1, 1, 0, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 2, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 2, 0, 0, 0, 2, 1, 2, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 2, 0, 0, 0, 2, 1, 2, 1, 0, 0, 1]
		30	[1, 1, 1, 1, 2, 2, 2, 2, 1, 0, 1, 2, 0, 0, 1, 1, 2, 2, 0, 2, 0, 1, 1, 2, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 2, 0, 0, 0, 2, 1, 2, 1, 0, 0, 1]
	3	20	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 0, 0, 0, 0, 1, 1, 3, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 3, 0, 0, 0, 3, 1, 3, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 3, 0, 0, 0, 3, 1, 3, 1, 0, 0, 1]
		30	[1, 1, 1, 1, 1, 1, 3, 1, 1, 0, 1, 1, 0, 0, 1, 1, 3, 3, 0, 2, 0, 1, 1, 3, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 3, 0, 0, 0, 3, 1, 3, 1, 0, 2, 3]
2	1	20	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 1, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 1, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 1, 1, 0, 0, 1]
	2	20	[1, 1, 1, 1, 1, 2, 0, 1, 1, 0, 1, 2, 0, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 0, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 2, 0, 1, 1, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 2, 0, 1, 1, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 2, 2, 2, 2, 2, 2, 0, 1, 2, 0, 0, 2, 2, 1, 1, 0, 2, 0, 1, 1, 0, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 2, 0, 1, 1, 1, 1, 0, 0, 1]
	3	20	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 2, 0, 1, 1, 1, 1, 0, 0, 1]

		40	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 3, 0, 1, 1, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 3, 0, 1, 1, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 3, 1, 3, 3, 1, 1, 0, 1, 3, 0, 0, 1, 1, 1, 1, 0, 3, 0, 1, 1, 0, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 3, 0, 1, 1, 1, 1, 0, 0, 1]
3	1	20	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 1, 1]
		30	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 1, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 1, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 1, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 1, 1]
	2	20	[1, 1, 1, 1, 1, 1, 2, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 0, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 2, 0, 2, 2, 1, 1, 0, 2, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 2, 0, 2, 2, 1, 1, 0, 2, 1]
		30	[1, 1, 1, 2, 1, 1, 2, 2, 1, 0, 2, 2, 0, 0, 2, 1, 2, 1, 2, 0, 0, 1, 1, 0, 1, 0, 2, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 2, 0, 2, 2, 1, 1, 0, 2, 1]
	3	20	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 3, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 3, 0, 3, 3, 1, 1, 0, 3, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 3, 0, 3, 3, 1, 1, 0, 3, 1]
		30	[1, 1, 1, 3, 1, 1, 3, 1, 1, 0, 1, 3, 0, 0, 1, 1, 3, 1, 0, 0, 0, 1, 1, 0, 1, 0, 3, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 3, 0, 3, 3, 1, 1, 0, 3, 1]
4	1	20	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
	2	20	[1, 1, 1, 1, 2, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 0, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 1, 2, 1, 2, 2, 1, 0, 1, 2, 0, 2, 2, 1, 2, 2, 0, 0, 0, 1, 1, 2, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]

	3	20	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 1, 3, 1, 3, 3, 1, 0, 1, 3, 0, 0, 3, 1, 2, 1, 0, 0, 0, 1, 1, 0, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
5	1	20	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
	2	20	[1, 1, 1, 1, 1, 1, 2, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 0, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 2, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 2, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 2, 1, 1, 2, 2, 1, 0, 1, 2, 2, 2, 1, 1, 1, 1, 0, 0, 0, 1, 1, 0, 2, 0, 2, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 2, 1, 1, 0, 0, 1]
	3	20	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 3, 1, 1, 0, 0, 1]
		40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 3, 1, 1, 0, 0, 1]
		50	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 3, 1, 1, 0, 0, 1]
		30	[1, 1, 1, 3, 1, 1, 3, 1, 1, 0, 1, 3, 0, 3, 1, 1, 1, 1, 0, 0, 0, 1, 1, 0, 1, 0, 2, 1]
		60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 3, 1, 1, 0, 0, 1]

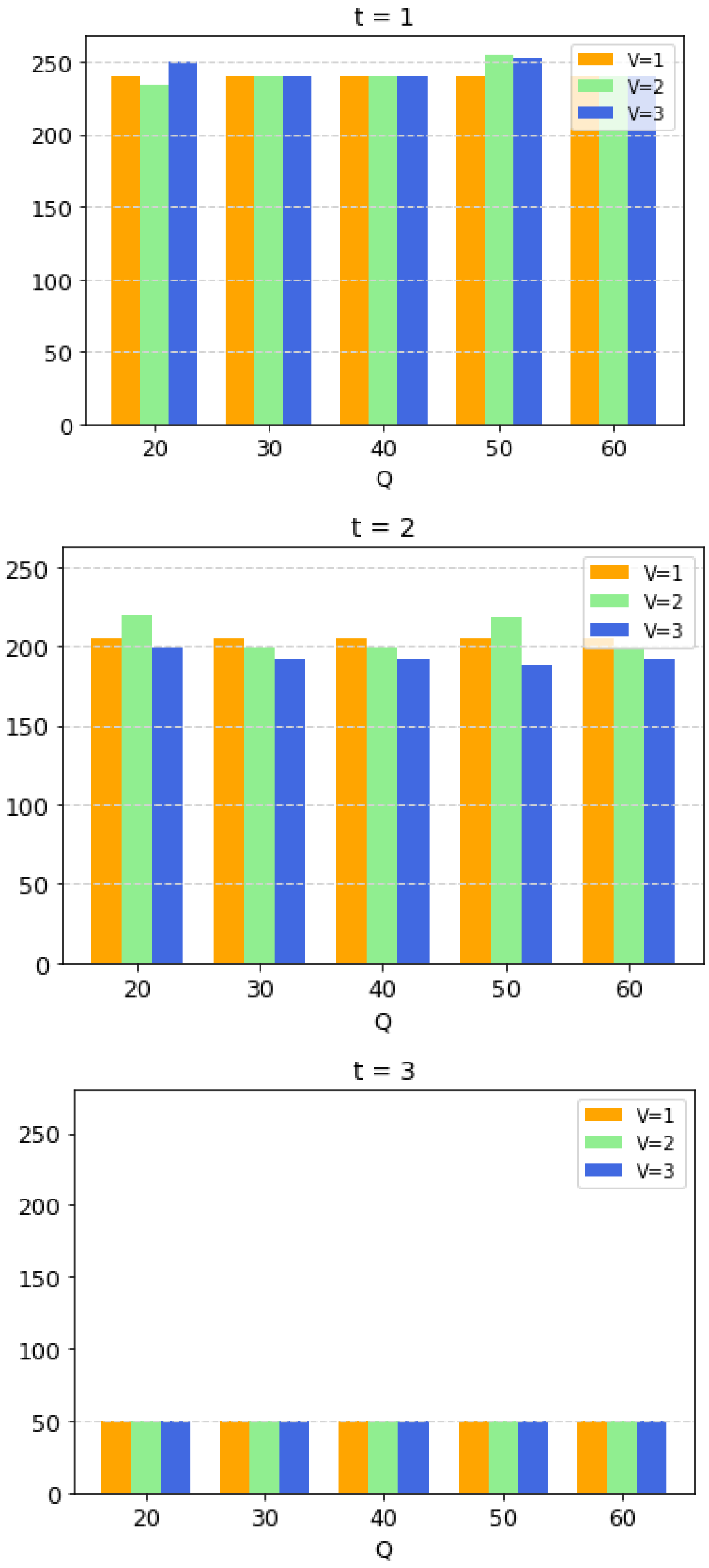


Figure 30 The response time (minutes) in evaluation experiments under different values of V and Q

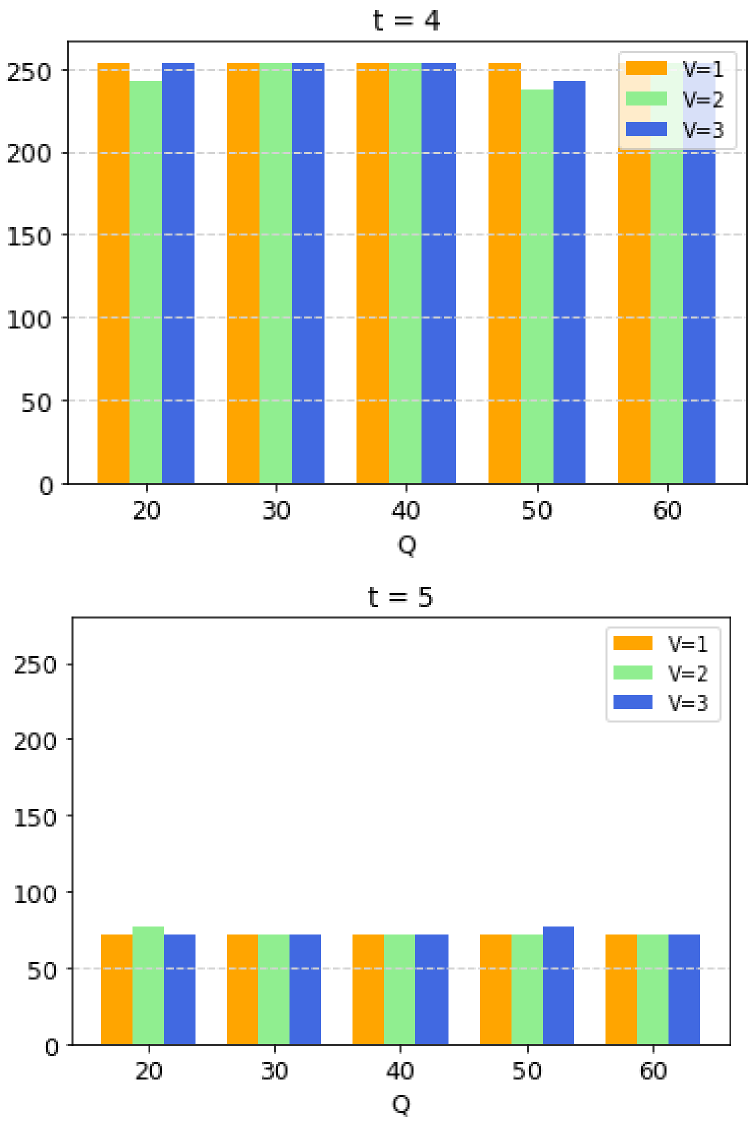


Figure 30 (Cont'd) The response time (minutes) in evaluation experiments under different values of V and Q

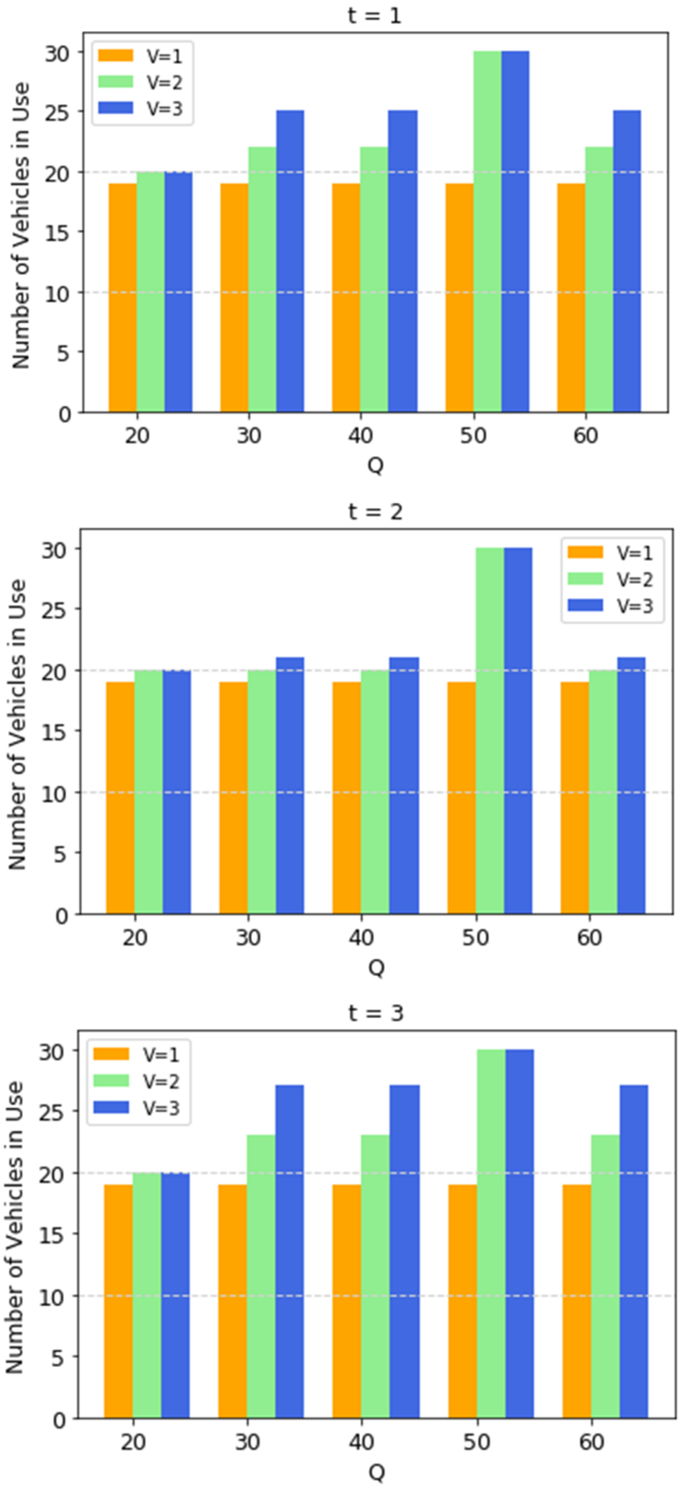


Figure 31 The numbers of vehicles actually in use under different values of V and Q

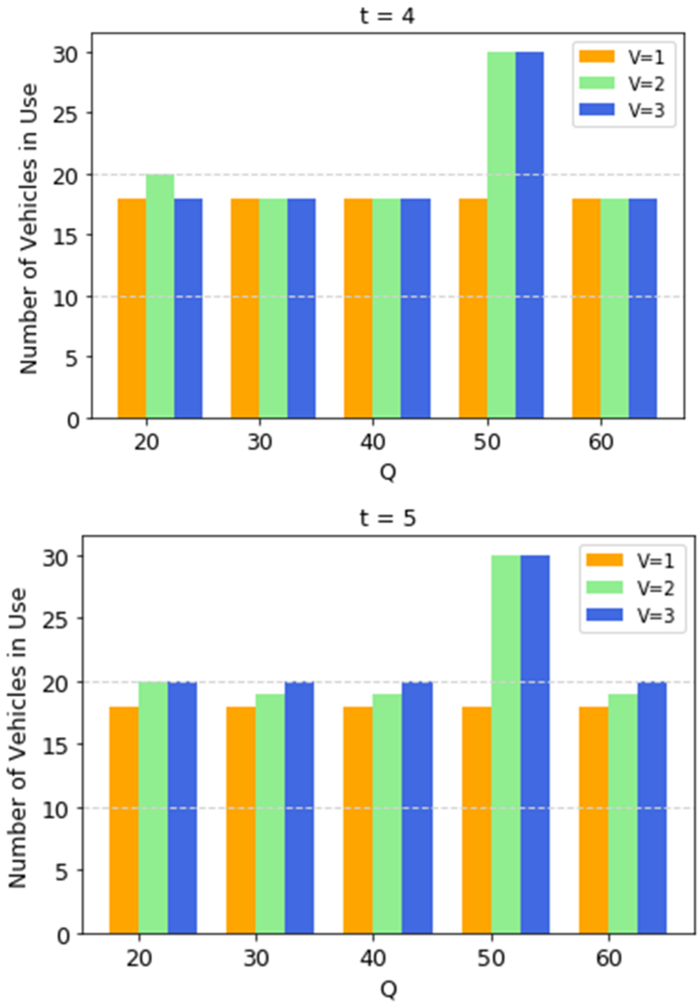


Figure 31 (Cont'd) The numbers of vehicles actually in use under different values of V and Q

Table 29 Vehicle assignments under different experiment settings in the five time windows, $c_f = \$40$, $Q = 30$

q_j	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
0	1	1	1	1	1
1	1	1	1	1	1
2	1	0	1	1	1
3	1	1	1	1	1
4	0	1	0	0	0
5	0	1	1	1	0
6	1	1	1	0	0
7	1	0	0	0	1
8	0	0	0	1	1
9	1	1	0	1	1
10	1	1	1	1	1
11	1	1	0	0	0
12	0	0	0	0	0
13	0	0	1	1	1
14	0	0	0	0	0
15	0	0	0	0	0
16	1	1	1	1	1
17	1	1	1	1	1
18	1	1	1	1	1
19	1	1	1	1	1
20	0	0	0	0	0
21	0	0	1	0	0
22	1	1	1	1	1
23	1	1	1	1	1
24	1	1	1	1	1
25	1	0	1	1	1

26	1	1	1	1	1
27	0	1	0	0	0

The response time of evaluation experiments for each scenario and its corresponding ground-truth response time is displayed in Figure 32. The evaluation experiment results show that the response time generated by the evaluation model is shorter than the ground-truth response time recorded in the historical dataset for most of the collisions on this road network. There are only a few collisions waiting longer for the service vehicle to arrive in each scenario. The proposed vehicle assignment method can reduce the waiting time efficiently.

Comparing these results to the performance of solutions under the setting of $c_l = 20$, the mean values of the saved response time for each collision between the experiments and ground-truth data are listed in Table 30. The number of vehicles in use and the number of missed incidents under different hourly fixed costs are also listed in Table 31.

It can be concluded that by increasing the hourly fixed cost per vehicle from $20 to $40, the saved response time is reduced, and the number of vehicles used for all five time windows decreased to the minimum number required to meet all model's constraints. At the same time, the number of missed incidents in the evaluation experiment scenarios also increased by increasing the hourly fixed cost per vehicle.

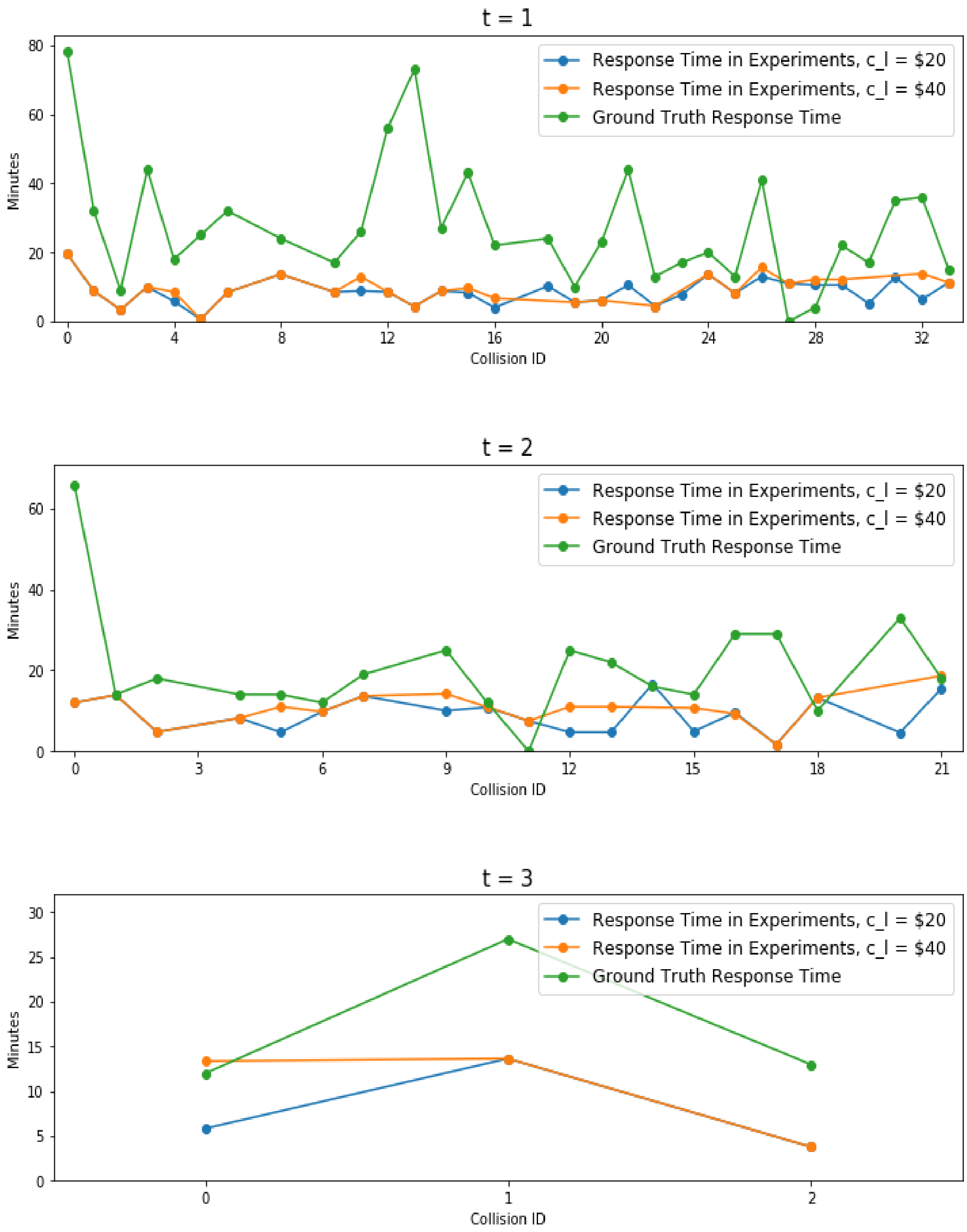


Figure 32 The response time of the evaluation experiments and the ground-truth response data of different first hour costs (minutes)

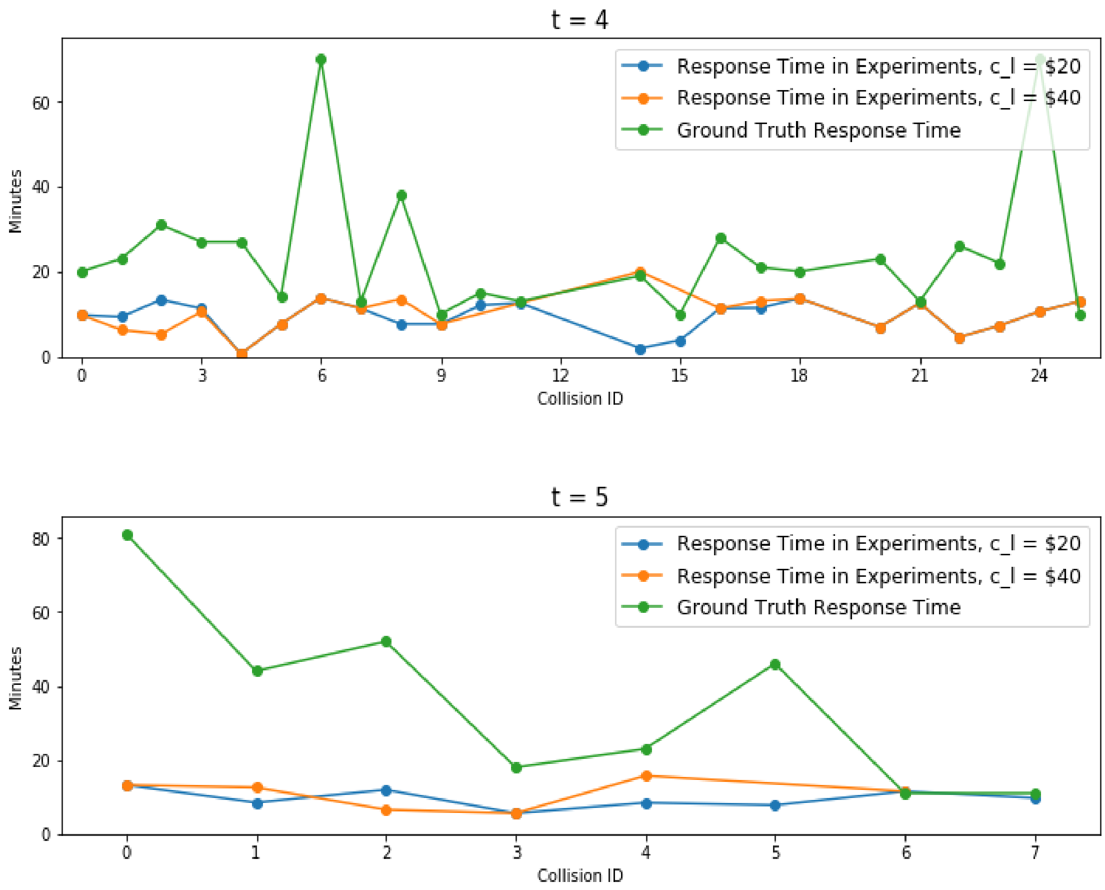


Figure 32 (Cont'd) The response time of the evaluation experiments and the ground-truth response data of different first hour costs (minutes)

Table 30 Mean values of the saved response time for each collision between the experiment data and the ground-truth data (minutes)

$c_l = 20$		$c_l = 40$	
t	Saved response time	t	Saved response time
1	19.1029	1	18.355
2	11.5532	2	9.4076
3	9.5733	3	7.06
4	15.1652	4	16.285
5	26.1663	5	27.3067

Table 31 The number of vehicles in use and the number of missed incidents under different values of c_l

t	Number of vehicles in use		Number of missed incidents	
	$c_l = 20$	$c_l = 40$	$c_l = 20$	$c_l = 40$
1	22	18	5	7
2	20	18	5	5
3	23	18	0	0
4	18	18	6	6
5	19	18	2	2

7.3 Financial loss c_l

The influence of the parameter c_l (financial loss for an incident not being served) is also checked. In the base scenario, the cost of financial loss was set as \$20. Other scenarios with the values of financial loss as \$40, \$60, \$100 were also built to check the model's performance. The vehicle assignments in these scenarios are listed in Table 32.

The response time in the evaluation experiments for each scenario and its corresponding ground-truth response time is displayed in Figure 33. The experiment results show that the response time generated by the evaluation experiment model is shorter than the ground-truth response time recorded in the historical dataset for most of the collisions on this road network. There are only a few collisions waiting longer for the service vehicle to arrive in each scenario. The proposed vehicle assignment method can reduce the waiting time efficiently.

Table 32 Vehicle assignments under different values of financial lost c_l n the five time windows

t	c_l	Numbers of vehicles on each station
1	20	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 3, 0, 0, 0, 3, 1, 3, 1, 0, 0, 1]
2		[1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 3, 0, 1, 1, 1, 1, 0, 0, 1]
3		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 0, 0, 1, 3, 0, 3, 3, 1, 1, 0, 3, 1]
4		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0, 1, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
5		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 3, 1, 1, 0, 0, 1]
1	40	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 3, 0, 0, 0, 3, 1, 3, 1, 0, 0, 1]
2		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 3, 0, 1, 1, 0, 1, 0, 0, 1]
3		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 0, 0, 1, 3, 0, 3, 3, 1, 1, 0, 3, 1]
4		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 0, 0, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1]
5		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 0, 1, 3, 1, 1, 0, 0, 1]
1	60	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 3, 0, 0, 0, 3, 1, 3, 1, 0, 0, 1]
2		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 3, 0, 1, 1, 0, 1, 0, 0, 1]
3		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 0, 0, 1, 3, 0, 3, 3, 1, 1, 0, 3, 1]
4		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 0, 1, 0, 0, 1]
5		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 1, 1, 1, 0, 0, 0, 1, 3, 0, 1, 0, 0, 1]
1	100	[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 3, 0, 0, 0, 3, 1, 3, 1, 0, 0, 1]
2		[1, 1, 1, 1, 1, 1, 0, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 3, 0, 1, 1, 0, 1, 0, 0, 1]
3		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 3, 0, 3, 3, 0, 1, 0, 3, 1]
4		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, 0, 1, 1, 0, 1, 0, 0, 1]
5		[1, 1, 1, 0, 1, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, 0, 1, 3, 0, 1, 0, 0, 1]

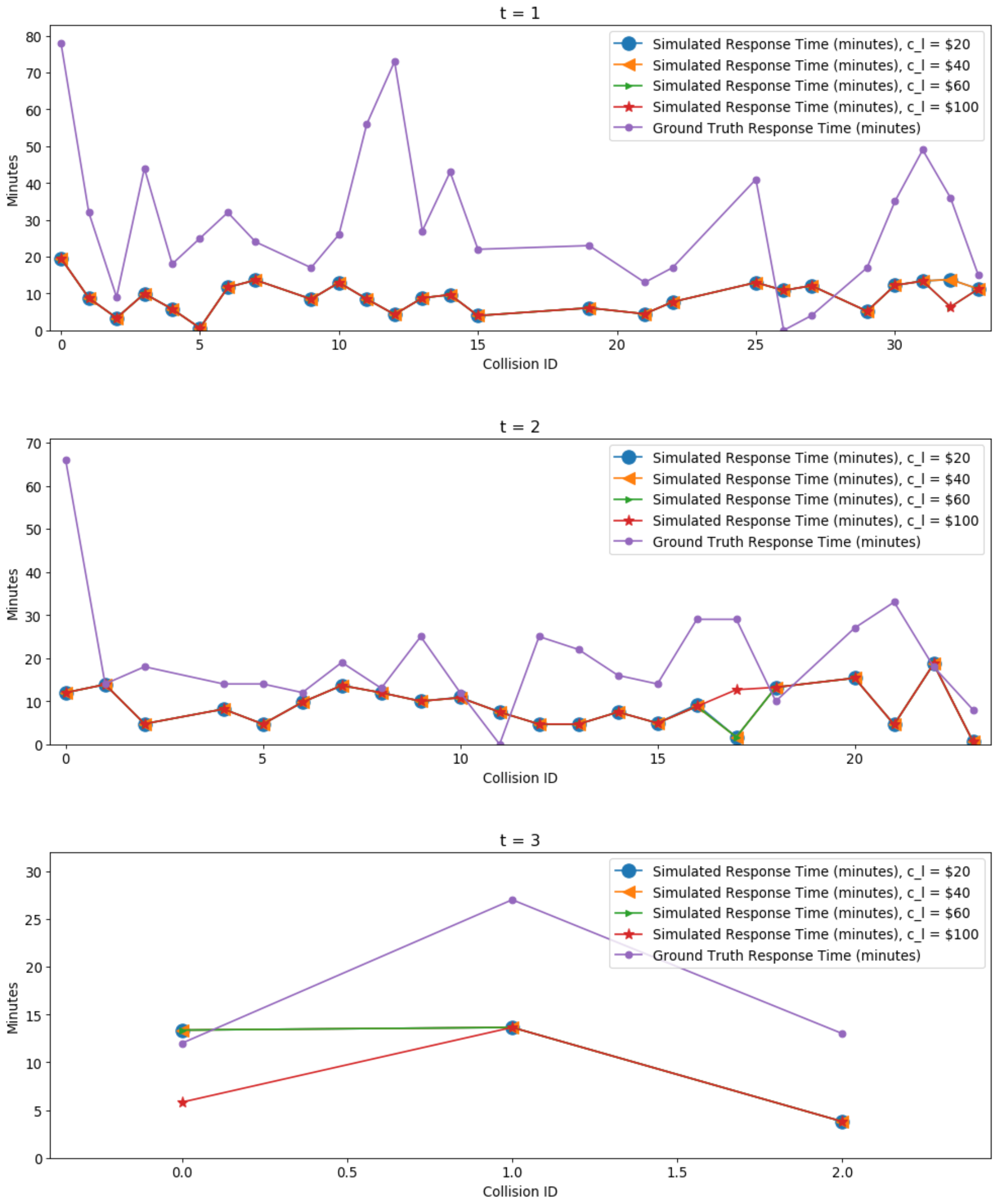


Figure 33 The response time in the evaluation experiments and the ground-truth response data for different values of financial loss c_l (minutes)

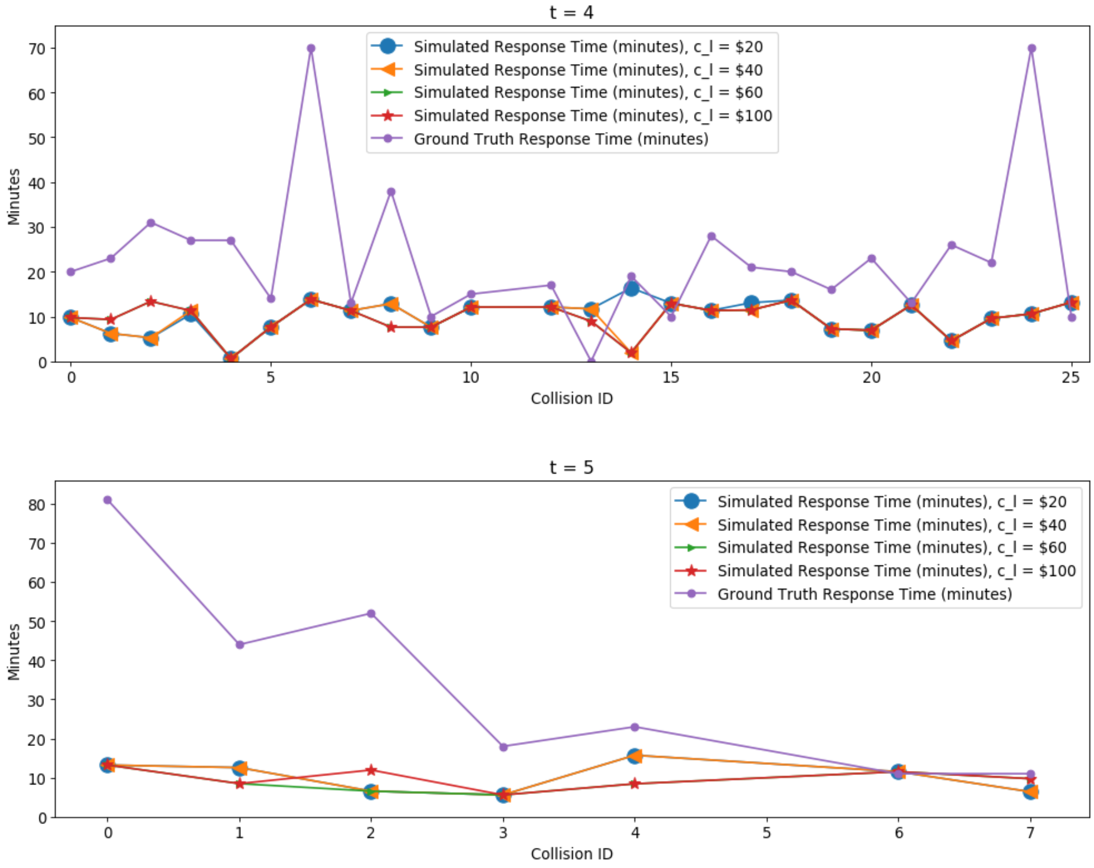


Figure 33 (Cont'd) The response time in the evaluation experiments and the ground-truth response data for different values of financial loss c_l (minutes)

The total response time in the evaluation experiments for each scenario under different values of financial loss c_l is displayed in Table 33. The results show that in the time windows with only a few incidents, such as time window 3, the c_l parameter does not show a significant influence on the total response time. The response time generated by the smaller values of financial loss is longer than the response time generated by higher values of financial loss values for the time windows with larger numbers of incidents.

Table 33 The total response time (minutes) of evaluation experiments under different values of financial loss c_l

t	$c_l = \$20$	$c_l = \$40$	$c_l = \$60$	$c_l = \$100$
1	239.9	239.9	232.45	232.45
2	192.3	191.78	191.78	202.78
3	49.5	49.5	49.5	49.5
4	253.73	238.41	241.65	241.65
5	71.56	71.56	63.5	68.9

Chapter 8 Conclusions and Future Works

8.1 Summary

Traffic incidents on freeways cause a considerable loss of life and property. Therefore, some organizations provide freeway safety services to improve the roadway's safety condition by assisting in detecting and clearing incidents. Incidents generally require timely assistance in removing debris and disabled cars from roads and transferring injured persons to medical care places. However, these fast reactions require more resources such as professional staff and service vehicles from the service providers. Limited funding sources constrain these operations. Thus, it is essential to design appropriate service plans for the service providers to offer in-time assistance to road users at reasonable costs.

This research aimed at developing a framework for providing appropriate freeway safety service plans based on historical traffic incident data and freeway road networks. First, clustering methods were applied to detect traffic incident hot spots. Second, with this hot spot knowledge integration, a standby service plan was formulated by configuring the whole freeway network and building an optimization model. A heuristic method was also developed to solve the optimization model. Experiments were conducted to assess the performances of the designed plan by several proposed metrics.

The proposed service plans were compared and evaluated by several metrics that were computed from evaluation experiments. Two resources provide the data used in the experiments. One is provided by the Coordinated Highways Action Response Team (CHART) in Maryland from the incidents they assisted in 2016. The second resource is from the PeMS platform operated by the California Department of Transportation, with the incidents assisted by the California Highway Patrol (CHP) in 2017. The evaluation experiment scenarios were built based on parts of road networks served by CHART and CHP.

The main work in this research includes the following parts.

1) Proposed a freeway service plan to solve the incident response problem.
2) Designed an HZ-DFS algorithm to configure the whole freeway network into several segments with reasonable length and risk levels.
3) Formulated an integer programming model with multiple optimization objectives. This model can select the best station locations and decide the number of vehicles in each station at the same time.
4) Designed a heuristic method to solve the above model.
5) Created multiple metrics to evaluate the model performance under different real-world preliminaries.
6) Evaluation experiment scenarios based on the real data to evaluate the service plan.
7) Analyzed the evaluation experiment results based on multiple metrics and compared the results to the ground-truth data.

8.2 Conclusions

In the study of incident hot spots detection, three types of KDE methods were applied. They are the single-KDE method with the distance kernel (*Single KDE - distance*), the single KDE method with the duration kernel (*Single KDE - duration*), and the multivariate-KDE method with both distance and duration kernels

(*Multivariate KDE*). The results of spatial autocorrelation analysis show that all three methods can detect the incident clustering patterns, but they have different characteristics in spatial distribution. The hot spots detected by the *Single KDE - distance* method have similarities with the distribution of incident counts. The difference is that the *Single KDE - distance* method can recognize those road segments with fewer incidents count but long driving distances to main roads as hot spots. The hot spots detected by the *Single KDE - duration* method differ from the *Single KDE - distance* method and the count distribution. The *Single KDE - duration* considered the duration of each incident on the road segments into account. Therefore, the road segments with incidents that need longer service time form up the clusters instead of road segments with higher incident counts. Both the *Single KDE - distance* method and the *Single KDE - duration* method have their limitations when detecting the incident clusters for the purpose of the freeway safety service. The results detected by the *Multivariate KDE* method show that this method can consider the impacts from the counts, distances, and durations of the incidents at the same time.

To design the standby service plan, four main questions need to be answered. 1) Where to set the standby stations for the service vehicles? 2) How many vehicles should be set to each station? 3) Under different budget limitations, will the decisions be different? 4) Under different budget limitations, will the decisions be different?

For the first two questions, the proposed model in this research determines where to set the standby stations for the service vehicles and how many vehicles should be set at each station in two steps. First, an HZ-DFS algorithm integrates the road network with multiple short segments into longer service zones based on the traditional

DFS algorithm. The service radius for each vehicle and the risk level of each short segment are all taken into account in this process. The experimental results in both the sample data of Section 4.2.3 and the large-scale freeway data in Section 6.2 show that this method can efficiently reduce the number of the pieces of road segments and therefore generate a network for the optimization model as the candidate stations for setting the service stations in the next step. Second, an optimization model determines the exact number of vehicles in each candidate station. Two numerical examples show that the solutions generated by this model can efficiently reduce the response time to the incidents compared to the ground-truth data.

A heuristic algorithm was proposed to solve the problem in a large-scale network by introducing another binary variable that indicates if a candidate station is selected or not and splitting the problem into three steps. The first step ensures the network's connectivity, the second step narrows the potential solution space and reduces the number of feasible solutions, and the third step determines the number of vehicles at each station. By splitting the problem into three steps, the original problem can be transformed into a problem that can be solved using the commercial solver Gurobi within an acceptable time.

To answer the third and fourth questions, this research applied the proposed method to a large-scale network in Southern California by conducting experiments using the proposed model and a few evaluation scenarios based on the real data. The different budget limitations are represented by different numbers of available vehicles of the agency.

The evaluation experiment results indicate that the driving durations generated by the model are shorter than the ground driving durations recorded in the historical dataset for most of the collisions on this road network. There are only a few collisions waiting longer for the service vehicle to arrive in each scenario. The proposed vehicle assignment method can reduce the waiting time efficiently. Comparing the performances of solutions between the setting of $Q = 30$ and the setting of $Q = 60$, it can be found that by increasing the number of total available vehicles in the service system, the saved response time stays at a similar level. However, the number of vehicles that are actually in use does not increase significantly. At the same time, the number of missed incidents in the evaluation experiment scenarios decreased by increasing the value of total available vehicles.

The results also indicate the differences in performances by comparing the performance of solutions under the setting of $c_l = 20$ to the setting of $c_l = 40$. It can be found that by increasing the hourly fixed cost per vehicle from \$20 to \$40, the saved driving time reduced, and the number of vehicles actually in use for all five time windows decreased to the minimum number required to meet all model's constraints. At the same time, the number of missed incidents in the evaluation experiment scenarios also increased by increasing the hourly fixed cost per vehicle.

Besides, the results also indicate the differences in performances by comparing the performance of solutions under the different settings of c_f. The values of $c_f = 20, 40, 60, 100$ were tested. It can be found that the different values of fixed hourly cost do not show an obvious impact on the response time. However, all values of c_f can reduce the response time compared to the ground-truth response time.

8.3 Future works

In this study, freeway segments with different levels of risk are detected by analyzing the traffic incidents and road network data. A standby service plan was proposed to provide freeway assistance services. However, the limitation of this plan is that it only considers assigning vehicles to standby on the networks. In the real-world application, more agencies conduct the freeway service by patrolling operations. One idea for further research is to develop a model that can mix patrol fleet services and the standby service that can also be based on the categorized risk levels.

This research also assumes no differences among all the service vehicles. Future research may develop a model considering different types of service vehicles together as a mixed fleet. Locations having a higher risk of having people injured may be assigned with more vehicles with medical service functions. Locations having a higher risk of having vehicle collisions may have more tow vehicles assigned. Having different types of vehicles for road networks with different features may increase the service efficiency to the road users and reduce the clearance time for the incidents.

An integrated model considering the mixed types of fleet and mixed service method of patrol and standby can also be developed in the next step. The integrated model can combine the advantages of different service methods and different fleet types to reduce the operation costs and the incident clearance time at the same time.

Besides, the problem can also be investigated by considering different types of incident information resources, such as incidents reported by police, or detected by cameras, or reported by other road users through calls. The whole service duration is also influenced by how the operation center receives the information resources. For example, an incident on a road network with lower traffic volume may take longer to report to the operation center by calls from other road users than by being detected directly by a patrolling vehicle.

Since some freeway safety service providers also assist incidents happening near the main freeway, the connected local roads and their incidents can also be integrated into the model in future research. The problem of building an abstract road network that can present different features of freeways and local roads with the integration of merging and exiting areas can also be a challenging avenue for research in the next step.

Appendix A: Driving Time (minutes) between Demand Segments to Standby Stations

Long Segment ID	Demand Segment ID	Driving Time (minutes)
1	33	3.77
1	34	10.42
1	35	8.43
1	160	9.73
1	161	6.37
1	162	7.62
1	163	8.13
1	164	3.7
1	165	2.77
1	166	4.2
1	167	5.08
1	249	7.52
1	250	8.42
1	251	9.35
1	252	6.8
1	253	6.1
1	254	2.77
1	255	1.75
1	256	11.27
1	257	12.12
1	258	12.95
1	259	13.8
1	260	14.67
1	261	15.52
1	262	5.15
1	294	1.9
1	295	2.82
2	33	7.25
2	35	10.45
2	156	16.12
2	157	16.95
2	158	5.17
2	159	8.72
2	160	5.95
2	161	2.58
2	162	3.83
2	163	4.33
2	164	1.55
2	165	3.82
2	166	1.92
2	167	2.82
2	249	9.52
2	250	10.43
2	251	11.37
2	252	8.8
2	253	8.12
2	254	4.78
2	255	3.75
2	258	14.33
2	259	15.18
2	260	16.03
2	261	16.9
2	262	6.53
2	294	5.38
2	295	6.3
3	30	10.05
3	42	7.25
3	142	9.97
3	143	10.82
3	144	4.7
3	145	6.95
3	146	2.97
3	147	2.03
3	148	1.2
3	149	10.67
3	150	14.97
3	151	12.47
3	152	13.33
3	153	14.22
3	154	15.2
3	155	18.5
3	156	17.13
3	157	17.95
3	216	11.63
3	217	11.93
3	218	13.4
3	219	14.95
3	220	15.02
3	221	15.77
3	222	14.4
3	223	15.67
3	224	17.2
3	225	17.33
3	284	9.13
3	285	8.23
3	286	7.32
4	27	6.05
4	30	8.67
4	37	5.97
4	42	7.78
4	43	6.88
4	44	7.82
4	45	8.7
4	46	9.58
4	47	10.52
4	48	11.38
4	49	12.25
4	75	7.3
4	76	8.25
4	77	9.2
4	78	10.15
4	79	11.07
4	142	6.47
4	143	7.3
4	144	9.87
4	145	10.92
4	146	20.68
4	147	19.75
4	148	18.92
4	149	12.87
4	150	17.17
4	216	4.87
4	217	3.6
4	218	2.62
4	219	4.17
4	220	4.23
4	221	4.98
4	222	3.62
4	223	4.88
4	224	6.42
4	225	6.55
4	284	7.77
4	285	6.85
4	286	5.95
5	27	16.88
5	37	18.53
5	42	18.73
5	43	16.02
5	44	16.95
5	45	0.83
5	46	1.72
5	47	2.65
5	48	3.52
5	49	4.38
5	50	5.27
5	51	6.15
5	52	7.02
5	53	7.92
5	75	18.13
5	76	19.08
5	77	20.03
5	78	20.97
5	79	21.88
5	80	20.47
5	81	21.38
5	82	22.32
5	142	16.63
5	143	17.48
5	144	20.03
5	145	22.47
5	216	18.77
5	217	19.28
5	218	20.77
5	219	22.32
5	220	22.38
5	221	23.13
5	222	21.75
5	223	23.03
5	224	24.57
5	284	18.73
5	285	17.82
5	286	16.92
6	48	12.68
6	49	13.57
6	50	14.43
6	51	8.9
6	52	9.77
6	53	10.67
6	54	11.55
6	55	12.47
6	56	0.93
6	57	1.77
6	58	2.67
6	59	3.53
6	60	4.38
6	61	5.23
6	62	6.08
7	58	17.97
7	59	18.82
7	60	19.68
7	61	20.52
7	62	11.85
7	63	12.7
7	64	13.55
7	65	10.07
7	66	0.83
7	67	1.7
7	68	2.55
7	69	3.42
7	70	4.28
7	71	5.15
7	72	6.03
8	27	15.17
8	37	13.72
8	42	17.02
8	43	14.65
8	44	15.57
8	45	16.47
8	46	17.35
8	47	18.27

Long Segment ID	Demand Segment ID	Driving Time (minutes)	Long Segment ID	Demand Segment ID	Driving Time (minutes)	Long Segment ID	Demand Segment ID	Driving Time (minutes)	Long Segment ID	Demand Segment ID	Driving Time (minutes)
8	48	19.15	10	100	1.17	11	288	8.52	14	38	6.07
8	49	20.02	10	101	2.17	11	289	9.42	14	39	9.75
8	50	20.88	10	102	3.38	11	296	10.98	14	40	8.55
8	51	19.43	10	229	11.18	11	310	8.45	14	103	9.42
8	52	20.3	10	230	10.17	11	311	9.55	14	104	8.45
8	75	16.42	10	231	9.1	11	316	14.85	14	105	10.12
8	76	17.37	10	232	8.12	11	317	13.57	14	106	11.88
8	77	18.32	10	233	7.05	11	318	14.12	14	107	11
8	78	19.27	10	297	10.3	11	319	10.33	14	108	16.8
8	79	20.18	10	298	5.88	11	320	6.93	14	109	15.93
8	80	9.15	10	301	13.5	11	322	2.88	14	168	0.38
8	81	0.47	10	303	7.08	12	171	14.85	14	169	1.35
8	82	1.4	10	321	10.02	12	172	15.85	14	170	2.28
8	83	2.32	11	11	15.85	12	173	13.68	14	171	3.28
8	84	3.22	11	15	6.77	12	174	12.52	14	172	4.3
8	85	4.2	11	17	11.7	12	175	10.35	14	173	5.23
8	86	5.18	11	19	10.37	12	176	11.28	14	174	6.12
8	87	6.08	11	20	10.42	12	177	10.37	14	175	7.07
8	88	6.98	11	21	9.98	12	178	7.45	14	176	8
8	216	16.95	11	23	11.33	12	179	8.2	14	188	9.58
8	285	16.12	11	24	0.07	12	180	9.18	14	242	18.98
8	286	15.2	11	25	1.43	12	181	1.02	14	243	17.97
9	83	17.03	11	28	8.38	12	182	2.02	14	272	12.37
9	84	10.78	11	29	3.95	12	183	2.93	14	273	9.63
9	85	11.77	11	36	9.65	12	184	3.87	14	274	10.6
9	86	12.75	11	68	18.53	12	185	4.83	14	292	6.98
9	87	13.65	11	69	13.1	12	186	5.85	14	293	7.92
9	88	7.83	11	70	13.97	12	187	13.23	14	312	18.05
9	89	8.73	11	71	9.27	13	105	7.15	14	313	14.43
9	90	4.82	11	72	10.15	13	106	6.23	14	323	9.37
9	91	0.4	11	73	11.05	13	107	5.35	15	28	6.53
9	92	1.33	11	74	11.92	13	108	4.45	15	29	12.53
9	93	2.23	11	201	12.85	13	109	3.58	15	31	1.98
9	94	3.22	11	202	11.28	13	110	2.67	15	32	0.87
9	95	4.22	11	203	14.95	13	111	1.78	15	38	6.78
9	96	5.13	11	204	15.98	13	112	0.92	15	39	12.45
9	97	6.15	11	205	15.05	13	113	0.07	15	40	7.1
9	98	6.98	11	206	14.1	13	114	7.05	15	74	17.52
10	4	13.47	11	263	18.58	13	115	11.92	15	103	13.65
10	5	12.13	11	264	13.75	13	116	10.95	15	104	12.7
10	7	8.88	11	265	14.97	13	117	10.07	15	105	14.35
10	8	11.63	11	266	12.23	13	118	13	15	106	16.12
10	12	4.75	11	267	12.07	13	119	12.07	15	168	9.08
10	93	12.47	11	268	11.37	13	120	17.92	15	188	8.13
10	94	10.92	11	270	10.95	13	121	17.05	15	242	14.3
10	95	9.72	11	271	11.15	13	122	16.17	15	243	13.28
10	96	10.63	11	278	5.05	13	123	23.67	15	244	15.2
10	97	9.7	11	279	6.08	13	124	22.8	15	245	14.22
10	98	7.77	11	280	7.13	14	31	15.5	15	246	13.25
10	99	0.08	11	287	7.65	14	32	19.97	15	247	16.88

Long Segment ID	Demand Segment ID	Driving Time (minutes)	Long Segment ID	Demand Segment ID	Driving Time (minutes)	Long Segment ID	Demand Segment ID	Driving Time (minutes)	Long Segment ID	Demand Segment ID	Driving Time (minutes)
15	248	15.88	16	292	15.33	17	310	6.7	18	315	6.53
15	270	9	16	293	16.25	17	311	7.78	18	316	7.65
15	271	9.18	16	296	21.12	17	312	8.87	18	317	8.83
15	272	3.02	16	299	15.87	17	313	9.95	18	318	12.08
15	273	3.98	16	300	15.08	17	314	5.02	18	319	12.5
15	274	4.95	16	302	13.52	17	315	8.27	18	320	9.08
15	278	13.63	16	310	5.28	17	316	6.1	19	11	17.17
15	279	14.68	16	311	6.37	17	317	1.2	19	14	5.28
15	280	15.72	16	312	7.45	17	318	6.22	19	15	10.32
15	292	7.7	16	313	8.53	17	319	14.27	19	16	5.7
15	293	8.63	16	314	11.22	17	320	10.85	19	17	3.67
15	310	10.2	16	315	14.47	17	322	13.63	19	19	2.33
15	311	7.83	16	316	12.28	18	11	15.3	19	20	2.38
15	312	8.92	16	317	11	18	14	3.42	19	21	17.72
15	313	5.3	16	318	11.55	18	15	8.45	19	22	6.97
15	322	12.73	16	319	20.47	18	16	3.83	19	23	3.3
15	323	5.93	16	322	12.13	18	17	1.8	19	24	17.33
16	15	17.43	16	323	13.55	18	19	0.47	19	25	14.85
16	16	16.5	17	11	20.13	18	20	4.32	19	26	4.08
16	17	14.47	17	14	10.53	18	21	16.95	19	28	10.18
16	19	13.13	17	15	11.25	18	22	6.02	19	29	16.83
16	20	15.43	17	16	10.93	18	23	5.23	19	36	8.97
16	21	15.9	17	17	8.9	18	24	16.67	19	41	7.4
16	22	13.95	17	19	7.57	18	25	14.18	19	74	21.82
16	23	16.35	17	20	8.12	18	26	6.02	19	197	15.7
16	24	15.02	17	21	17.38	18	36	7.12	19	198	12.82
16	25	16.38	17	22	7.77	18	41	6.93	19	199	10.47
16	26	11.45	17	23	9.03	18	196	19.62	19	200	10.65
16	28	1.13	17	24	16.52	18	197	13.85	19	201	11.62
16	29	11.95	17	25	15.85	18	198	10.97	19	202	10.03
16	31	9.6	17	26	5.27	18	199	8.6	19	203	16.27
16	32	19.08	17	28	6.78	18	200	8.8	19	204	18.9
16	71	14.27	17	29	13.43	18	201	9.77	19	205	17.97
16	72	15.15	17	36	13.6	18	202	8.18	19	266	15.88
16	73	16.03	17	41	8.2	18	203	14.42	19	267	16.95
16	74	16.92	17	74	18.42	18	204	18.13	19	268	17.98
16	242	18.12	17	201	16.25	18	205	17.2	19	270	8.9
16	243	17.08	17	202	14.67	18	206	16.27	19	271	7.75
16	244	19	17	270	5.5	18	267	16.18	19	278	17.93
16	270	8.38	17	271	4.35	18	268	17.22	19	279	18.97
16	271	8.58	17	278	14.53	18	270	10.7	19	280	20.02
16	272	10.63	17	279	15.57	18	271	9.55	19	287	11.2
16	273	11.6	17	280	16.62	18	287	9.33	19	288	0.48
16	274	12.57	17	287	12.12	18	288	10.2	19	289	1.37
16	278	13.05	17	288	12.98	18	289	11.1	19	296	10.3
16	279	14.08	17	289	13.88	18	296	8.45	19	299	6.8
16	280	15.12	17	296	14.92	18	299	4.95	19	300	8.1
16	287	18.32	17	299	9.67	18	300	7.15	19	302	6.53
16	288	19.18	17	300	8.88	18	302	6.05	19	310	10.08
16	289	20.08	17	302	7.32	18	314	6.62	19	314	4.22

Long Segment ID	Demand Segment ID	Driving Time (minutes)	Long Segment ID	Demand Segment ID	Driving Time (minutes)	Long Segment ID	Demand Segment ID	Driving Time (minutes)
19	315	7.48	21	191	16.58	22	212	13
19	316	9.52	21	192	10.25	22	213	12.1
19	317	7.03	21	193	11.22	22	214	11.17
19	318	10.28	21	194	9.73	22	215	13.17
19	319	13.25	21	195	10.72	22	226	15.95
19	320	9.83	21	196	11.73	22	227	14.97
19	322	16.32	21	197	0.02	22	235	8.5
20	11	4.43	21	198	0.98	22	236	7.62
20	15	7	21	199	1.98	22	237	6.75
20	18	9.23	21	200	2.98	22	238	5.88
20	21	10.18	21	201	3.95	22	239	4.98
20	190	17.03	21	202	4.85	22	240	4.1
20	191	17.98	21	203	6.05	22	241	3.17
20	192	15.02	21	204	12.02	22	269	10.08
20	193	15.98	21	205	11.08	22	275	7.8
20	194	14.5	21	206	10.15	22	276	6.8
20	195	15.48	21	207	14.05	22	277	9.5
20	196	16.5	21	208	13.13	22	281	11.95
20	197	10.73	21	209	19.3	22	282	10.9
20	198	7.33	21	210	18.37	22	283	12.07
20	199	8.32	21	211	17.47	22	290	0.65
20	200	9.32	21	212	16.57	22	291	7.45
20	201	10.28	21	263	16.92	22	304	8.43
20	202	11.18	21	264	12.07	22	305	9.07
20	203	3.53	21	265	13.3	22	306	9.62
20	204	2.63	21	266	8.92	22	307	8.58
20	205	1.7	21	267	9.98	22	308	9.95
20	206	0.75	21	287	9.83	22	309	11.05
20	207	7.65	21	296	7.3	23	2	5.83
20	208	6.73	21	319	8.68	23	125	4.87
20	209	12.88	21	320	10.25	23	126	3.95
20	210	11.97	22	1	5	23	127	3.05
20	211	11.07	22	6	1.85	23	128	2.08
20	212	10.15	22	9	13.43	23	129	1.1
20	213	14.38	22	10	8.68	23	130	0.15
20	214	13.45	22	13	6.38	23	131	12.1
20	263	10.07	22	136	7.72	23	132	13.12
20	264	5.55	22	137	6.73	23	133	12.13
20	265	6.62	22	138	5.72	23	134	11.07
20	266	6.97	22	139	4.75	23	135	15.13
20	267	8.03	22	140	3.9	23	136	17.72
20	268	9.07	22	141	2.88	23	137	16.72
20	282	11.27	22	189	7.32	23	138	16.78
20	319	6.17	22	190	8.33	23	139	17.55
20	320	11.02	22	191	9.3	23	276	19.8
21	11	6.95	22	192	10.3	23	277	18.73
21	15	8.95	22	193	11.27	23	304	19.6
21	18	15.82	22	194	12.25	23	308	18.72
21	36	5.97	22	210	14.8	23	309	22.23
21	190	15.63	22	211	13.92	24	1	13.4

Long Segment ID	Demand Segment ID	Driving Time (minutes)
24	3	5.2
24	6	13.45
24	10	16.8
24	13	14.48
24	134	18.57
24	135	17.48
24	136	16.48
24	137	15.5
24	138	14.47
24	139	13.52
24	140	12.67
24	141	14.48
24	189	15.43
24	190	16.45
24	191	17.42
24	192	18.4
24	193	19.38
24	234	4.33
24	235	3.47
24	236	2.57
24	237	1.7
24	238	0.83
24	239	13.6
24	240	12.72
24	241	14.4
24	269	18.47
24	275	15.85
24	276	14.85
24	277	17.57
24	281	20.07
24	282	19.02
24	290	16.67
24	291	15.57
24	304	16.48
24	305	17.43
24	306	17.67
24	307	16.63
24	308	18
24	309	19.12
25	1	7.18
25	6	4.03
25	9	9.4
25	10	4.67
25	13	1.8
25	137	8.92
25	138	7.9
25	139	6.93
25	140	6.08
25	141	5.07
25	189	2.73
25	190	3.75
25	191	4.72
25	192	5.72
25	193	6.68
25	194	7.67
25	210	10.77
25	211	9.88
25	212	8.97
25	213	8.07
25	214	7.13
25	215	9.13
25	226	11.92
25	227	10.93
25	228	14.22
25	229	13.22
25	236	9.8
25	237	8.93
25	238	8.07
25	239	7.17
25	240	6.28
25	241	5.37
25	269	0.68
25	275	9.98
25	276	8.98
25	277	10.13
25	281	7.92
25	282	6.88
25	283	8.03
25	290	2.83
25	291	1.73
25	304	9.07
25	305	6.93
25	306	9.45
25	307	8.4
25	308	10.58
25	309	11.92
26	8	20.32
26	9	1.92
26	10	6.03
26	12	19.17
26	13	7.7
26	189	8.65
26	190	9.67
26	191	10.63
26	210	7.85
26	211	6.95
26	212	6.03
26	213	5.13
26	214	4.2
26	215	3.28
26	226	0.93
26	227	7.38
26	228	10.68
26	229	9.67
26	230	13.35
26	231	12.27
26	232	14.6
26	233	15.42
26	269	12.23
26	276	14.42
26	281	4.93
26	282	3.9
26	283	2.87
26	290	8.27
26	291	7.17
26	297	18.97
26	298	15.87
26	303	17.23
26	304	13.33
26	305	11.2
26	306	13.7
26	307	12.67
26	308	14.85
26	309	16.17

Appendix B: Driving Time (minutes) and Distances between Demand Segments to Standby Stations in California

j	i	Driving Distance	Driving Duration	j	i	Driving Distance	Driving Duration	j	i	Driving Distance	Driving Duration
0	0	7.26	9.75	0	0	5	13.23	3	77	13.85	16.73
0	28	8.1	10.52	0	28	7.43	12.98	3	297	10.53	15.4
0	29	8.95	11.3	0	29	8.08	12.95	3	298	9.74	16.22
0	30	3.44	5.5	0	30	8.34	12.33	3	299	8.85	14.83
0	31	3.1	6.02	0	31	9.93	15.4	3	300	7.95	12.67
0	32	3.94	6.8	0	32	9.97	12.97	3	303	11.07	15.6
0	33	2.27	5.02	0	33	10.81	13.8	3	304	7.59	11.77
0	34	1.57	3.82	0	34	3.62	9.15	3	365	7.34	12.3
0	35	2.41	4.57	0	35	2.63	7.68	4	5	8.8	13.6
0	36	3.25	5.33	0	36	2.16	7.2	4	6	5.48	12.57
0	37	4.09	6.15	0	37	3.19	7.25	4	7	9.79	13.65
0	38	5.19	8.75	0	38	1.68	5.15	4	20	8.89	15.07
0	39	5.84	8.98	0	39	4.49	9.52	4	26	7.54	15.58
0	40	6.73	8.5	0	40	3.6	8.17	4	75	8.43	11.77
0	41	11.45	14.4	0	41	4.54	7.45	4	76	7.9	13.2
1	1	5.31	12.03	1	1	5.77	9	4	77	7.65	14.75
1	2	5.49	12.57	1	2	4.75	12.02	4	78	6.8	12.1
1	3	7.23	14.08	1	3	5.79	13.2	4	82	5.14	10.67
1	4	5.93	13.22	1	4	6.15	14.9	4	83	3.67	9.67
1	53	6.7	12.93	1	53	7.72	12.27	4	84	2.79	6.47
1	54	7.55	13.92	1	54	8.14	13.65	4	85	1.94	5.7
1	55	8.38	13.07	1	55	12.18	15.67	4	86	0.98	3.8
1	56	7.3	15.23	1	56	6.18	10.92	4	87	0.08	0.62
1	57	8.47	15.63	1	57	6.79	9.78	4	88	2.19	4.45
1	58	9.11	15.58	1	58	8.87	14.23	4	89	2.15	6.97
1	70	6.82	15.97	1	70	8.61	13.38	4	90	6.98	10.3
1	71	8.05	14	1	71	6.58	11.22	4	91	3.78	11.35
1	94	3.99	11.15	1	94	6.68	11.65	4	92	5.8	9.97
1	95	4.98	11.17	1	95	5.77	11.1	4	93	6.67	12.4
1	96	4.57	10.8	1	96	4.71	9.2	4	231	9.62	13.95
1	97	1.59	6.08	1	97	3.83	8.82	4	232	9.26	12.78
1	98	2.43	7.35	1	98	3.04	6.97	4	233	10.34	14.95
1	99	3.3	8.17	1	99	2.11	6.77	4	234	11.91	16.75
1	100	4.23	11.12	1	100	1.21	3.83	4	330	9.7	14.88
1	101	4.99	9.77	1	101	1.34	3.55	4	331	11.17	16.93
1	102	8.37	14.97	1	102	1.17	3.92	4	332	10.14	12.35
1	103	6.68	11.35	1	103	2.51	6.67	5	105	13.8	16.4
1	104	7.53	12.12	1	104	2.95	7.25	5	106	13.02	17.38
1	105	8.65	14.67	1	105	3.81	7.77	5	107	12.19	13.97
1	106	10.22	16.73	1	106	4.74	8.2	5	108	11.35	13.22
2	1	5.23	11.32	2	1	5.9	11.18	5	109	10.51	12.43
2	2	5.15	10.45	2	2	7.48	12.15	5	110	9.68	11.67
2	3	4.9	10.25	2	3	6.58	13.48	5	111	8.84	10.92
2	4	4.31	8.27	2	4	9.33	13.38	5	112	8	10.15
2	5	6.14	8.7	2	5	9.69	14.42	5	113	11.34	14.8
2	6	6.65	11.82	2	6	12.65	16.28	5	114	9.08	14.05
2	53	6.21	10.75	2	53	7.22	18.03	5	201	6.73	9.57
2	54	7.06	11.75	2	54	8.33	20.52	5	202	7.42	11.83
2	55	7.89	10.88	2	55	7.44	19.17	5	203	4.64	7.05

j	i	Driving Distance	Driving Duration
5	204	3.77	6.13
5	205	2.91	5.32
5	206	2.03	4.57
5	207	1.72	4.9
5	208	0.66	2.62
5	209	1.06	4.17
5	210	2.43	4.58
5	211	3.31	5.23
5	212	4.18	6.27
5	213	6.52	9.33
5	214	7.12	10.9
5	215	7.49	10.75
5	226	7.79	14.6
5	227	6.83	13.03
5	228	6.74	12.88
5	229	6.64	12.77
5	230	8.46	14.37
6	8	7.58	8.63
6	10	5.56	6.92
6	11	7.72	8.57
6	17	3.81	6.8
6	62	9.49	12.5
6	63	8.46	11.85
6	64	6.67	8.57
6	65	6.1	9.58
6	66	6.43	9.32
6	67	7.2	9.35
6	68	6.43	8.7
6	69	6.53	9.05
6	215	6.69	8.58
6	216	7.22	10.47
6	245	6.3	7.92
6	246	5.91	8.3
6	247	8.9	10.67
6	248	7.94	9.7
6	249	8.31	10.27
6	295	6.42	7.73
6	296	3.86	7.2
6	297	2.15	2.95
6	298	0.83	1.88
6	299	0.31	0.98
6	300	0.98	1.67
6	301	2.11	4.72
6	302	4	5.9
6	303	3.59	4.3
6	304	4.43	5.58
6	322	6.87	7.77
6	323	6.46	9.68
6	324	5.21	7.87
6	325	5.21	7.63
6	326	8.29	10.08
6	327	6.43	7.23
6	328	7.98	9.5
6	329	10.07	12.03
6	364	7.7	10.2
6	365	5.56	9.93
7	10	4.6	7.28
7	11	3.73	6.32
7	12	5.94	10.15
7	13	6.7	10.8
7	17	8.98	13.27
7	213	7.75	12.42
7	214	6.42	10.82
7	215	5.63	9.52
7	216	4.85	10.52
7	217	9.2	11.4
7	218	8.13	9.55
7	219	7.29	8.72
7	220	6.42	8.62
7	221	5.59	7.38
7	222	6.74	9.12
7	223	5.32	6.47
7	224	6.16	7.32
7	225	8.91	10.93
7	226	7.95	9.62
7	259	6.72	9.62
7	260	7.55	10.98
7	261	8.39	13.28
7	295	5.46	8.1
7	296	7.03	11.28
7	297	5.33	7.05
7	298	5.11	7.3
7	299	5.44	8.42
7	300	6.14	8.13
7	301	7.2	10.9
7	302	9.16	12.38
7	303	8.75	10.78
7	322	2.88	5.52
7	323	2	7.48
7	324	1.09	3.85
7	325	0.02	0.13
7	326	5.16	9.37
7	327	3.3	6.53
7	328	4.85	8.78
7	329	10.97	11.97
8	12	6.19	8.98
8	13	7.2	9.52
8	16	6.29	7.35
8	18	11.84	15.4
8	19	13.47	16.27
8	217	8.15	10.52
8	250	10.19	19.58
8	251	11.17	20.9
8	252	8.01	20
8	253	8.17	18.03
8	254	6.99	16.77
8	255	6.08	14.5
8	256	6.91	17.42
8	257	7.77	16.1
8	258	11.71	14.93
8	259	6.42	8.62
8	260	4.43	6.75
8	261	3.53	6.77
8	262	5.17	7.57
8	263	1.54	5.3
8	264	1.57	3.38
8	265	0.64	1.37
8	266	1.81	4.77
8	267	2.52	3.75
8	268	4.35	7.75
8	269	4.48	7.62
8	270	5.28	7.87
8	271	6.03	9.57
8	321	7.65	10.87
8	329	8.2	10.27
8	345	7.23	8.2
8	346	11.22	13.18
8	347	10.12	13.37
8	348	11.49	13.48
8	349	11.37	14.23
9	10	8.65	11.37
9	11	7.77	10.4
9	12	7.56	10.9
9	13	6.39	8.15
9	211	11.67	17.7
9	212	12.56	16.45
9	213	11.79	16.5
9	214	10.46	14.9
9	215	9.67	13.6
9	216	8.9	14.62
9	217	5.61	7.82
9	218	4.55	5.98
9	219	3.7	5.15
9	220	2.83	5.05
9	221	2.01	3.82
9	222	3.15	5.55
9	223	7.55	11.13

j	i	Driving Distance	Driving Duration
9	224	1.28	3.32
9	225	4.03	6.95
9	226	3.08	5.63
9	227	5.11	7.88
9	228	4.67	6.52
9	229	9.87	12.18
9	230	6.39	7.98
9	295	9.5	12.18
9	296	11.16	16.32
9	322	6.93	9.62
9	323	4.51	12.27
9	324	5.29	9.83
9	325	5.51	10.28
9	326	9.95	10.83
9	327	7.21	9.82
9	328	8.24	9.22
9	329	7.38	8.4
10	14	7.64	10.45
10	16	5.54	10.53
10	18	7.2	13.45
10	19	10.48	15.43
10	21	8.27	14.28
10	22	9.63	14.13
10	137	9.18	15.57
10	257	12.24	16.35
10	258	8.72	14.08
10	266	7.86	12.13
10	267	8.47	12.68
10	268	6.09	11
10	269	5.08	9.27
10	270	4.37	8.98
10	271	3.87	10.65
10	272	6.41	13.82
10	273	4.62	13.27
10	274	4.27	11.97
10	275	3.74	11.95
10	276	4.11	10.6
10	277	4.69	13.33
10	278	6.27	15.23
10	279	6.97	15.23
10	280	7.82	15.25
10	281	8.83	15.98
10	284	9.85	12.52
10	314	7.34	12.47
10	315	6.35	11.85
10	316	4.26	11.98
10	317	4.66	9.03
10	318	2.54	8.1
10	319	2.35	7.33
10	320	1.6	6.35
10	321	2.86	8.12
10	345	4.24	7.35
10	346	6.14	12.95
10	347	4.07	9.52
10	348	8.5	12.63
10	349	8.1	14.03
11	8	11.28	12.67
11	12	8.04	22.2
11	15	7.9	11.45
11	17	6.68	9.43
11	18	7.52	9.13
11	19	8.36	11.3
11	245	5.72	6.48
11	246	5.33	9.67
11	247	4.02	4.92
11	248	3.65	6.37
11	249	2.62	4.75
11	250	1.72	3.2
11	251	1.98	4.55
11	252	1.12	1.92
11	253	1.95	2.7
11	254	2.78	3.5
11	255	3.67	6.68
11	256	4.62	6.83
11	257	5.31	5.87
11	258	8.07	10.6
11	259	9.92	20.68
11	260	6.86	20.78
11	261	6.44	18.82
11	262	8.09	20.32
11	263	8.15	19.13
11	264	8.46	18.08
11	284	7.73	8.38
11	285	7.75	11.4
11	286	11.01	13.47
11	287	12.19	15.37
11	288	11.53	13.62
11	289	12.7	14.62
11	290	13.41	15.48
11	291	13.99	14.47
11	301	9.3	11.73
11	302	7.73	8.58
11	303	7.87	11.42
11	304	8.13	9.62
11	328	9.95	21.5
11	329	9.09	20.68
11	335	9.89	12.97
11	336	9.31	12.18
11	337	7.83	11.8
11	338	8.72	10
11	339	9.97	13.08
11	340	10.92	13.83
11	341	11.63	16.17
11	349	7.41	8.33
11	364	9.09	12.85
12	14	7.9	15.43
12	16	10.13	18.87
12	18	5.64	8.53
12	19	8.05	13.03
12	21	10.39	14.28
12	22	10.51	14.53
12	23	7.73	11.38
12	24	6.69	10.5
12	137	6.56	15.45
12	138	6.91	14.08
12	139	6.96	9.65
12	140	6.5	11.18
12	141	8.52	11.98
12	142	7.25	10.42
12	143	8.93	12.87
12	144	9.32	13.6
12	145	6.85	13.57
12	146	10.63	12.83
12	147	8.92	19
12	258	7.09	11.03
12	270	8.95	17.33
12	271	12.72	17.37
12	272	4.85	8.9
12	273	4.01	7.95
12	274	3.59	8.43
12	275	2.47	7.95
12	276	2.61	6.52
12	277	0.8	2.43
12	278	1.4	5.33
12	279	2.07	6.55
12	280	3.08	6.67
12	281	4.09	7.4
12	282	4.88	9.32
12	283	6.92	11.65
12	284	7.42	10.13
12	305	7.18	11.12
12	314	6.99	18.03
12	315	6.43	16.37
12	316	5.68	14.43
12	317	4.91	12.52
12	318	4.64	11.88
12	319	5.42	14.85

j	i	Driving Distance	Driving Duration	j	i	Driving Distance	Driving Duration	j	i	Driving Distance	Driving Duration
12	320	6.21	13.8	14	25	4.94	14.23	15	24	4.61	12.42
12	321	12.71	17.05	14	26	4.44	11.58	15	137	7.12	12.85
12	345	8.82	15.7	14	27	9.28	17.98	15	138	5.95	12.53
12	346	9.38	11.77	14	88	8.57	13.25	15	139	4.59	8.4
12	347	9.05	13.67	14	89	7.87	14.47	15	140	5.81	10.28
12	348	7.5	9.98	14	90	6.86	11.55	15	141	2.89	6.6
12	349	6.54	9.12	14	91	4.74	14.27	15	142	2.26	6.68
13	18	7.57	10.47	14	92	4.31	12.47	15	143	2.59	7.52
13	19	6.72	10.53	14	93	3.74	11.02	15	144	4	9.53
13	25	6.66	10.97	14	160	4.55	15.63	15	145	5.83	10.07
13	27	9.87	14.23	14	161	4.78	15.32	15	146	5.56	8.35
13	160	7.51	13.43	14	162	5.7	16.6	15	147	5.86	13.88
13	181	9.02	13.47	14	163	6.78	17.6	15	148	7.52	11.73
13	182	8.45	12.98	14	164	10.33	20.42	15	149	8.15	10.85
13	249	15.32	18.28	14	181	8.43	17.2	15	150	9.02	11.65
13	250	14.42	16.72	14	182	7.86	16.72	15	279	7.51	11.95
13	251	15.4	18.02	14	183	9.53	18.7	15	280	6.77	12.02
13	252	13.48	16.38	14	231	5.41	12	15	281	6.64	13.25
13	253	12.39	15.15	14	232	6.06	11.75	15	282	6.44	12.02
13	254	7.33	14.45	14	233	7.6	13.87	15	283	6.24	10.75
13	255	11.2	14.6	14	234	8.72	15.72	15	305	3.51	9.82
13	256	5.61	14.47	14	290	10.01	18.65	15	306	4.22	11.05
13	257	6.01	15.23	14	291	11.14	20.05	15	307	2.14	6.75
13	258	8	11.53	14	292	8.38	17.08	15	308	2.16	6.6
13	272	8.76	12.7	14	293	6.68	18.2	15	309	2.65	5.72
13	284	6.78	10.08	14	294	6.49	14.17	15	310	4.17	10.53
13	285	4.62	6.37	14	330	2.26	5.95	15	311	4.61	10.12
13	286	2.84	6.27	14	331	1.45	4.57	15	312	5.79	12.08
13	287	2.15	5.53	14	332	1.54	5.52	15	313	7.08	11.97
13	288	1.81	4.85	14	333	2.45	8.77	15	350	5.03	8.68
13	289	1.09	3.05	14	334	3.94	11.28	15	351	6.69	11.17
13	290	1.75	5.42	14	335	6.2	12.75	15	352	8.03	12.93
13	291	3.05	5.17	14	336	5.61	11.52	15	353	8.41	14.97
13	292	4.19	8.28	14	337	6.84	13.67	15	354	8.78	12.33
13	293	4.81	7.07	14	338	6.2	14.17	15	355	8.96	13.65
13	294	7.66	12.6	14	339	6.65	14.77	15	356	10.1	16.38
13	338	13.58	17.68	14	340	4.26	14.42	15	357	10.53	15.75
13	339	10.91	14.52	14	341	4.51	13.22	15	358	11.76	16.68
13	340	9.9	13.7	14	342	3.96	12.22	15	359	9.45	18.28
13	341	6.88	14.62	14	343	4.24	11.42	16	7	10.13	15.18
13	342	8.38	12.65	14	344	5.12	12.35	16	20	7.89	15.23
13	343	7.36	10.23	14	360	3.12	8.78	16	25	5.02	9.6
13	344	8.63	12.67	14	361	4.19	10.87	16	26	8.44	15.15
13	348	8.29	9.85	14	362	5.95	15.62	16	27	7.81	13.38
13	349	7.33	8.98	14	363	4.49	14.72	16	93	9.17	16.45
14	7	3.57	8.62	14	364	7.76	12.47	16	160	5.69	10.9
14	8	7.65	14.68	14	365	9.11	15.5	16	161	3.63	8
14	15	6.88	13.08	15	21	8.02	13.03	16	162	2.37	7.48
14	20	3.57	10.58	15	23	5.3	10.37	16	163	1.56	5.3

j	i	Driving Distance	Driving Duration	j	i	Driving Distance	Driving Duration	j	i	Driving Distance	Driving Duration
16	164	3.22	7.63	17	172	7.16	9.73	18	291	9.66	11.97
16	165	0.9	3.25	17	173	6.3	7.85	18	292	6.9	8.98
16	166	1.94	5.83	17	174	6.12	9.33	18	293	8.75	11.3
16	167	3.22	9.83	17	175	4.7	8.32	18	294	5.01	6.08
16	168	3.46	6.87	17	176	4.68	9.15	18	342	7.01	9.4
16	169	6.67	14.78	17	177	5.76	9.08	18	343	5.99	7
16	170	5.14	8.47	17	178	2.07	4.22	18	344	7.27	9.42
16	171	10.13	14.92	17	179	1.32	5.18	18	360	9.83	11.87
16	172	7.55	13.63	17	180	0.2	1.17	18	361	10.87	13.92
16	173	7.66	10.78	17	231	7.16	12.27	18	362	7.95	9.57
16	174	7.8	14.85	17	232	6.8	11.1	18	363	6.96	11.1
16	175	7.25	16.63	17	233	5.58	9.37	19	9	7.85	10.28
16	176	7.32	16.72	17	234	2.83	8.43	19	46	9.77	11.78
16	177	11.09	14.35	17	235	2.39	8.18	19	47	8.13	9.38
16	178	11.89	16.77	17	236	4.13	11.1	19	48	7.28	8.72
16	179	12.81	16.72	17	237	1.64	3.97	19	49	8.71	11.38
16	181	6.96	12.62	17	238	2.92	5.77	19	50	5.59	7.07
16	182	7.22	12.3	17	239	2.76	7.7	19	51	6.36	8.97
16	183	5.01	10.88	17	240	4.83	8.95	19	52	3.95	8
16	184	5.12	10.45	17	241	6.05	10.17	19	101	11.7	14.35
16	185	5.32	11.42	17	242	6.96	11.55	19	102	6.55	8.42
16	186	5.34	10.22	17	243	7.95	15.23	19	103	10.08	13.17
16	187	6.18	11.48	17	244	8.76	16.05	19	104	6.43	10.5
16	188	7.44	11.87	17	360	9.07	13.2	19	105	4	6.85
16	189	7.09	10.98	18	25	4.46	7.37	19	106	3.22	7.82
16	190	7.61	10.95	18	27	4.24	5.25	19	107	2.39	4.42
16	231	7.23	14.18	18	160	5.31	9.83	19	108	1.55	3.65
16	232	6.03	10.95	18	161	7.03	10.78	19	109	0.71	2.88
16	233	6.9	12.7	18	162	3.82	11.52	19	110	1.84	4.68
16	234	8.06	14.78	18	163	3.98	12.12	19	111	4.23	6.77
16	235	8.26	15.67	18	164	8.22	13.52	19	112	3.39	6
16	293	9.5	14.5	18	165	5.68	11.77	19	113	3.38	4.98
16	294	5.76	9.27	18	166	5.75	13.93	19	114	4.2	5.77
16	330	8.48	15.67	18	167	6.26	15.67	19	115	7.55	9.98
16	331	11.51	18.47	18	168	8.42	12.15	19	116	5.87	7.25
16	342	7.8	12.78	18	169	8.33	20.37	19	117	8.02	13.67
16	343	6.78	10.38	18	170	10.09	13.73	19	201	5.71	9.87
16	344	8.05	12.8	18	181	3.39	4.47	19	202	7.12	10.72
16	360	6.41	10.13	18	182	2.6	5.35	19	203	8.2	10.7
16	361	7.45	12.18	18	183	1.84	5.48	19	204	7.33	9.77
16	362	4.53	7.82	18	184	0.87	3.13	19	205	9.85	12.32
16	363	4.07	10.78	18	185	0.42	1.82	19	206	8.98	11.47
17	7	10.66	14.65	18	186	1.49	4.85	19	207	9.43	11.92
17	20	9.52	15.67	18	187	2.33	6.12	19	208	10.06	11.18
17	26	8.16	13.33	18	188	3.21	8.35	19	209	11.02	13.83
17	93	8.9	14.65	18	189	4.11	7.7	20	9	4.99	11.47
17	165	13.64	17.42	18	190	4.92	9.95	20	43	11.17	20.87
17	166	12.71	15.7	18	191	5.91	10.52	20	44	12.22	22.78
17	167	12.46	15.32	18	192	6.93	10.23	20	45	10.85	19.45

j	i	Driving Distance	Driving Duration	j	i	Driving Distance	Driving Duration	j	i	Driving Distance	Driving Duration
20	46	9.28	17.97	22	155	2.22	6.82	24	196	1.19	5.48
20	47	7.65	15.57	22	156	2.97	7.62	24	197	2	7.45
20	48	6.8	14.9	22	157	4.61	9.18	24	198	3.41	8.12
20	49	7.93	18.02	22	158	4.84	9.72	24	199	3.98	9.67
20	50	8.43	14.55	22	159	6.08	11.22	24	200	6.18	13.65
20	51	5.85	14.12	23	163	9.62	14.45	25	14	7.37	12.5
20	52	6.79	15.63	23	164	8.89	12.87	25	21	4.11	9.93
20	112	7.21	13.28	23	165	6.34	15.53	25	22	4.2	10.73
20	113	10.55	17.93	23	166	5.84	13.37	25	23	3.25	6.9
20	114	8.21	16.65	23	167	7.09	12.83	25	24	4.4	10.02
20	115	4.69	11.18	23	168	6.42	13.35	25	137	3.2	8.37
20	116	7.02	14.55	23	169	4.83	12.33	25	138	5.51	12.13
20	117	3.28	11.12	23	170	5.74	12.57	25	139	4.54	7.2
20	118	8.54	15.68	23	171	4.31	6.3	25	140	5.1	9.25
20	119	2.82	9.03	23	172	3.29	6.4	25	141	6.58	9.95
20	120	7.01	14.42	23	173	2.44	4.5	25	142	5.3	8.38
20	121	3.5	9.85	23	174	2.01	6.23	25	143	6.98	10.83
20	122	7.45	13.9	23	175	0.41	1.48	25	144	7.37	11.57
20	123	5.19	11.4	23	176	1.35	4.48	25	145	8.96	12.52
20	124	8.56	16.83	23	177	2.24	4.43	25	278	8.96	13.05
20	125	6.87	13.18	23	178	3.81	7.27	25	279	7.69	10.55
20	126	7.7	13.75	23	179	3.95	6.82	25	280	6.95	10.62
20	127	8.54	14.52	23	180	4.95	10	25	281	5.74	11.3
20	128	9.65	16.42	23	232	10.33	13.82	25	282	5.77	11.27
20	201	5.86	11.98	23	233	9.11	12.07	25	283	5.53	9.7
20	202	8.99	17.17	23	234	8.72	12.67	25	305	3.9	9.13
21	123	13.16	15.77	23	235	7.39	11.28	25	306	5.27	13.37
21	124	6.47	8.27	23	236	7.75	13.67	25	307	7.71	14.38
21	125	7.62	10.07	23	237	5.16	6.7	25	308	6.8	12.87
21	126	6.01	10	23	238	6.44	8.52	25	309	10.57	14.2
21	127	4.73	8	23	239	7.31	10.35	25	310	8.13	15.17
21	128	3.45	8.53	23	240	8.35	11.7	25	314	6.93	13.78
21	129	2.29	4.37	23	241	9.56	12.92	25	315	8.43	14.8
21	130	1.46	3.52	23	242	10.47	14.3	25	316	8.47	15.6
21	131	1.72	3.8	23	243	11.47	17.97	25	350	2.99	5.98
21	132	1.12	2.13	23	244	12.27	18.8	25	351	3.02	6.38
21	133	2.03	3.35	24	155	10.08	21	25	352	3.5	7.78
21	134	2.85	4.12	24	156	9.36	18.95	25	353	3.96	10.32
21	135	3.85	6.42	24	157	8.08	17.98	25	354	6.74	9.63
21	136	4.54	5.68	24	158	7.58	16.17	25	355	3.3	7.93
22	146	8.91	11.92	24	159	4.71	16.5	25	356	3.35	8.83
22	147	8.89	14.2	24	188	6.95	10.45	25	357	2.38	6.58
22	148	5.83	8.72	24	189	6.97	11.1	25	358	2.83	7.97
22	149	6.72	9.95	24	190	6.61	11.5	25	359	3.42	9.7
22	150	5.15	8.4	24	191	4.77	8.43	26	7	8.51	16.35
22	151	3.26	6.58	24	192	3.78	8.23	26	8	4.14	13.55
22	152	1.85	4.22	24	193	4.06	8.97	26	15	2.29	10.25
22	153	0.99	3.37	24	194	1.38	4.17	26	17	8.54	17.53
22	154	1.65	5.82	24	195	0.27	1.43	26	20	10.51	21.17

j	i	Driving Distance	Driving Duration
26	25	5.9	11.95
26	26	9.38	19.32
26	27	9.11	15.08
26	67	8.15	16.58
26	68	7.38	15.93
26	69	6.77	15.37
26	90	11.81	19.28
26	91	11.32	22.07
26	92	10.08	20.8
26	93	9.22	18.3
26	160	6.75	14.42
26	161	7.64	14.5
26	181	8.26	14.3
26	245	7.58	14.57
26	246	6.89	17.03
26	247	5.82	12.67
26	248	6.79	15.35
26	249	7.53	15.73
26	250	9.11	17.32
26	251	9.2	16.12
26	252	10.03	16.83
26	288	11.96	17.72
26	289	11.31	18.02
26	290	9.84	15.75
26	291	10.97	17.15
26	292	8.21	14.17
26	293	5.64	15.67
26	294	6.32	11.27
26	302	8.55	16.47
26	303	8.79	18.43
26	304	7.1	15.22
26	330	9.09	19.23
26	331	7.54	18.45
26	332	6.64	14.8
26	333	3.74	15.8
26	334	3.15	12.82
26	335	2.69	10.12
26	336	2.41	8.73
26	337	3.65	11.78
26	338	1.67	7.38
26	339	1.02	6.4
26	340	1.6	8.08
26	341	2.69	10.23
26	342	3.86	10.05
26	343	4.07	8.52
26	344	4.95	9.45
26	360	10.44	15.58
26	361	10.91	18.22
26	362	8.57	13.27
26	363	7.57	14.8
26	364	4.84	11.48
26	365	6.19	14.52
27	9	10.64	14.55
27	38	8.26	12.6
27	39	6.89	10.63
27	40	7.76	10.72
27	41	4.63	7.23
27	42	5.78	8.73
27	43	3.03	7.97
27	44	3.5	9.73
27	45	2.57	7.08
27	46	1.13	4.3
27	47	2.3	5.62
27	48	5.96	10.35
27	49	2.94	6.02
27	50	6.74	10
27	51	4.65	7.5
27	52	5.73	10.32
27	109	9.24	11.73
27	110	8.41	10.97
27	111	7.57	10.22
27	112	6.73	9.45
27	113	10.07	14.1
27	114	7	10.02
27	115	10.35	14.25
27	116	8.67	11.52
27	117	8.1	18.27
27	118	18.05	20.82
27	119	7.37	15.45
27	120	16.53	19.55
27	121	12.81	15.28
27	122	16.9	19.6
27	123	14.5	16.85
27	124	18.21	21.92
27	201	9.04	14.57

Appendix C: Evaluation Experiment Outputs

C.1 Scenario I

Time	**Incident ID**	***i***	**Event Status**	**Event Assist Status**	**Assisted by the vehicle from *j***	**Response Time (minutes)**
5:05	0	120	Incident Open	Incident_Assisted	27	19.55
5:35	1	333	Incident Open	Incident_Assisted	14	8.77
5:50	2	133	Incident Open	Incident_Assisted	21	3.35
6:00	3	149	Incident Open	Incident_Assisted	22	9.95
6:03	2	133	Incident Closed	Assisted_Finished		
6:12	4	238	Incident Open	Incident_Assisted	17	5.77
6:23	0	120	Incident Closed	Assisted_Finished		
6:28	5	87	Incident Open	Incident_Assisted	4	0.62
6:39	4	238	Incident Closed	Assisted_Finished		
6:55	6	150	Incident Open	Incident_Assisted	22	8.4
7:08	5	87	Incident Closed	Assisted_Finished		
7:10	8	200	Incident Open	Incident_Assisted	24	13.65
7:23	9	191	Incident Open			
7:27	10	170	Incident Open	Incident_Assisted	16	8.47
7:28	11	58	Incident Open	Incident_Assisted	2	12.95
7:41	12	40	Incident Open	Incident_Assisted	0	8.5
7:46	6	150	Incident Closed	Assisted_Finished		
7:47	13	303	Incident Open	Incident_Assisted	6	4.3
7:54	14	328	Incident Open	Incident_Assisted	7	8.78
7:55	15	246	Incident Open	Incident_Assisted	11	9.67
7:56	16	237	Incident Open	Incident_Assisted	17	3.97
7:57	17	198	Incident Open			
8:02	3	149	Incident Closed	Assisted_Finished		
8:02	10	170	Incident Closed	Assisted_Finished		

8:02	11	58	Incident Closed	Assisted_Finished		
8:15	18	364	Incident Open			
8:22	19	30	Incident Open	Incident_Assisted	0	5.5
8:26	20	97	Incident Open	Incident_Assisted	1	6.08
8:30	21	104	Incident Open	Incident_Assisted	19	10.5
8:34	16	237	Incident Closed	Assisted_Finished		
8:39	12	40	Incident Closed	Assisted_Finished		
8:43	19	30	Incident Closed	Assisted_Finished		
8:44	1	333	Incident Closed	Assisted_Finished		
8:44	22	88	Incident Open	Incident_Assisted	4	4.45
8:57	23	239	Incident Open	Incident_Assisted	17	7.7
8:57	9	191	Incident Closed	Incident_Missed		
8:58	18	364	Incident Closed	Incident_Missed		
8:59	24	200	Incident Open	Incident_Assisted	24	13.65
9:01	25	198	Incident Open	Incident_Assisted	24	8.12
9:02	8	200	Incident Closed	Assisted_Finished		
9:03	20	97	Incident Closed	Assisted_Finished		
9:04	26	57	Incident Open			
9:08	22	88	Incident Closed	Assisted_Finished		
9:14	17	198	Incident Closed	Incident_Missed		
9:14	21	104	Incident Closed	Assisted_Finished		
9:20	14	328	Incident Closed	Assisted_Finished		
9:21	23	239	Incident Closed	Assisted_Finished		
9:22	25	198	Incident Closed	Assisted_Finished		
9:27	13	303	Incident Closed	Assisted_Finished		
9:31	27	214	Incident Open	Incident_Assisted	5	10.9
9:39	15	246	Incident Closed	Assisted_Finished		
9:44	24	200	Incident Closed	Assisted_Finished		
9:55	28	104	Incident Open	Incident_Assisted	19	10.5

9:57	29	104	Incident Open	Incident_Assisted	19	10.5
9:59	26	57	Incident Closed	Incident_Missed		
10:24	27	214	Incident Closed	Assisted_Finished		
10:24	28	104	Incident Closed	Assisted_Finished		
10:41	29	104	Incident Closed	Assisted_Finished		
10:49	30	179	Incident Open	Incident_Assisted	17	5.18
10:59	31	342	Incident Open	Incident_Assisted	16	12.78
11:38	30	179	Incident Closed	Assisted_Finished		
11:42	32	320	Incident Open	Incident_Assisted	12	13.8
12:10	31	342	Incident Closed	Assisted_Finished		
12:14	33	159	Incident Open	Incident_Assisted	22	11.22
12:19	32	320	Incident Closed	Assisted_Finished		
12:45	33	159	Incident Closed	Assisted_Finished		

C.2 Scenario II

Time	Incident ID	i	Event Status	Event Assist Status	Assisted by the vehicle from j	Response Time (minutes)
13:58	0	316	Incident Open	Incident_Assisted	10	11.98
14:10	1	147	Incident Open	Incident_Assisted	15	13.88
14:23	2	249	Incident Open	Incident_Assisted	11	4.75
14:45	3	283	Incident Open	Incident_Assisted	25	9.7
14:58	1	147	Incident Closed	Assisted_Finished		
15:08	4	76	Incident Open	Incident_Assisted	2	8.17
15:09	3	283	Incident Closed	Assisted_Finished		
15:22	4	76	Incident Closed	Assisted_Finished		
15:33	2	249	Incident Closed	Assisted_Finished		
15:34	5	110	Incident Open	Incident_Assisted	19	4.68
15:44	0	316	Incident Closed	Assisted_Finished		
15:49	6	0	Incident Open	Incident_Assisted	0	9.75
15:56	7	200	Incident Open	Incident_Assisted	24	13.65
16:05	6	0	Incident Closed	Assisted_Finished		
16:21	7	200	Incident Closed	Assisted_Finished		
16:26	8	313	Incident Open			
16:40	9	338	Incident Open	Incident_Assisted	26	7.38
16:43	10	214	Incident Open	Incident_Assisted	7	10.82
16:45	11	162	Incident Open	Incident_Assisted	16	7.48
17:00	12	110	Incident Open	Incident_Assisted	19	4.68
17:00	10	214	Incident Closed	Assisted_Finished		
17:01	11	162	Incident Closed	Assisted_Finished		
17:01	13	110	Incident Open	Incident_Assisted	19	4.68
17:04	14	162	Incident Open	Incident_Assisted	14	16.6

17:11	9	338	Incident Closed	Assisted_Finished		
17:17	15	247	Incident Open	Incident_Assisted	6	10.67
17:21	5	110	Incident Closed	Assisted_Finished		
17:31	15	247	Incident Closed	Assisted_Finished		
17:32	12	110	Incident Closed	Assisted_Finished		
17:37	14	162	Incident Closed	Assisted_Finished		
17:54	16	328	Incident Open	Incident_Assisted	6	9.5
18:22	17	300	Incident Open	Incident_Assisted	6	1.67
18:23	16	328	Incident Closed	Assisted_Finished		
18:31	18	341	Incident Open	Incident_Assisted	26	10.23
18:45	18	341	Incident Closed	Assisted_Finished		
18:45	19	354	Incident Open	Incident_Assisted	25	9.63
18:49	8	313	Incident Closed	Incident_Missed		
18:51	17	300	Incident Closed	Assisted_Finished		
19:06	13	110	Incident Closed	Assisted_Finished		
19:08	20	210	Incident Open	Incident_Assisted	5	4.58
19:09	19	354	Incident Closed	Assisted_Finished		
19:12	21	290	Incident Open	Incident_Assisted	26	15.75
19:32	21	290	Incident Closed	Assisted_Finished		
20:34	20	210	Incident Closed	Assisted_Finished		

C.3 Scenario III

Time	Incident ID	*i*	Event Status	Assistance Status	Assisted by the vehicle from *j*	Response Time (minutes)
21:14	0	166	Incident Open	Incident_Assisted	16	5.83
21:51	0	166	Incident Closed	Assisted_Finished		
23:38	1	200	Incident Open	Incident_Assisted	24	13.65
0:20	1	200	Incident Closed	Assisted_Finished		
3:29	2	86	Incident Open	Incident_Assisted	4	3.8
3:54	2	86	Incident Closed	Assisted_Finished		

C.4 Scenario IV

Time	Incident ID	i	Event Status	Event Assist Status	Assisted by the vehicle from j	Response Time (minutes)
9:26	0	101	Incident Open	Incident_Assisted	1	9.77
9:28	1	174	Incident Open	Incident_Assisted	23	6.23
9:40	2	27	Incident Open	Incident_Assisted	16	13.38
9:50	0	101	Incident Closed	Assisted_Finished		
10:02	1	174	Incident Closed	Assisted_Finished		
10:13	2	27	Incident Closed	Assisted_Finished		
10:25	3	19	Incident Open	Incident_Assisted	13	10.53
10:42	4	87	Incident Open	Incident_Assisted	4	0.62
11:23	5	71	Incident Open	Incident_Assisted	2	7.68
11:37	5	71	Incident Closed	Assisted_Finished		
11:49	6	272	Incident Open	Incident_Assisted	10	13.82
11:58	3	19	Incident Closed	Assisted_Finished		
12:01	4	87	Incident Closed	Assisted_Finished		
12:05	7	1	Incident Open	Incident_Assisted	2	11.32
12:15	8	164	Incident Open	Incident_Assisted	16	7.63
12:30	9	156	Incident Open	Incident_Assisted	22	7.62
12:32	10	78	Incident Open			
12:35	11	6	Incident Open			
12:38	7	1	Incident Closed	Assisted_Finished		
12:43	9	156	Incident Closed	Assisted_Finished		
12:55	12	104	Incident Open			
13:00	8	164	Incident Closed	Assisted_Finished		
13:03	10	78	Incident Closed	Incident_Missed		
13:04	11	6	Incident Closed	Incident_Missed		

13:10	6	272	Incident Closed	Assisted_Finished		
13:19	12	104	Incident Closed	Incident_Missed		
13:31	13	240	Incident Open	Incident_Assisted	17	8.95
13:43	13	240	Incident Closed	Assisted_Finished		
13:50	14	252	Incident Open	Incident_Assisted	8	20
14:00	15	61	Incident Open			
14:13	16	103	Incident Open	Incident_Assisted	1	11.35
14:22	15	61	Incident Closed	Incident_Missed		
14:29	14	252	Incident Closed	Assisted_Finished		
14:42	17	15	Incident Open	Incident_Assisted	14	13.08
14:57	16	103	Incident Closed	Assisted_Finished		
15:00	18	200	Incident Open	Incident_Assisted	24	13.65
15:04	19	73	Incident Open			
15:22	18	200	Incident Closed	Assisted_Finished		
15:30	20	10	Incident Open	Incident_Assisted	6	6.92
15:44	17	15	Incident Closed	Assisted_Finished		
15:51	21	2	Incident Open	Incident_Assisted	1	12.57
15:56	22	206	Incident Open	Incident_Assisted	5	4.57
16:24	20	10	Incident Closed	Assisted_Finished		
16:29	22	206	Incident Closed	Assisted_Finished		
16:38	23	65	Incident Open	Incident_Assisted	3	7.25
16:45	24	276	Incident Open	Incident_Assisted	10	10.6
16:57	25	346	Incident Open	Incident_Assisted	10	12.95
17:07	23	65	Incident Closed	Assisted_Finished		
17:12	25	346	Incident Closed	Assisted_Finished		
17:30	21	2	Incident Closed	Assisted_Finished		
18:23	24	276	Incident Closed	Assisted_Finished		
18:51	19	73	Incident Closed	Incident_Missed		

C.5 Scenario V

Time	**Incident ID**	***i***	**Event Status**	**Event Assist Status**	**Assisted by the vehicle from *j***	**Response Time (minutes)**
21:03	0	108	Incident Open	Incident_Assisted	5	13.22
21:03	1	170	Incident Open	Incident_Assisted	23	12.57
21:29	2	279	Incident Open	Incident_Assisted	12	6.55
21:39	3	304	Incident Open	Incident_Assisted	6	5.58
22:03	4	234	Incident Open	Incident_Assisted	14	15.72
22:05	1	170	Incident Closed	Assisted_Finished		
22:13	5	66	Incident Open			
22:33	3	304	Incident Closed	Assisted_Finished		
22:42	6	116	Incident Open	Incident_Assisted	27	11.52
22:54	4	234	Incident Closed	Assisted_Finished		
23:17	7	172	Incident Open			
23:37	2	279	Incident Closed	Assisted_Finished		
23:42	6	116	Incident Closed	Assisted_Finished		
23:50	5	66	Incident Closed	Incident_Missed		
1:05	7	172	Incident Closed	Incident_Missed		
4:34	0	108	Incident Closed	Assisted_Finished		

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