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以動態車輛路線最佳化模型決定高速公路事件應變車隊任務

Using Dynamic Vehicle Routing Model to Dispatch Emergency Response Teams on Freeways

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本論文係戴至佑君（R05521506）在國立臺灣大學土木工程學系完成之碩士學位論文，於民國 107 年 7 月 17 日承下列考試委員審查通過及口試及格，特此證明

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誌謝

研究生的生涯很短暫，在結束碩論的撰寫後也跟著告一段落，但回想從碩零到即將畢業這段時間，發現生活過得非常充實又有趣，一方面在自己喜歡的領域鑽研學習，另一方面也認識許多志同道合的朋友，互相砥礪切磋分享見解。當然研究的過程並不輕鬆，需要修習許多專業課程與閱讀文獻，打好研究基礎，還要學習新的工具來幫助我們進行實驗或分析等等工作，這些佔據了研究生大多數的時間，剩下的時間則將研究進度向前推進。有時研究也會遇到瓶頸，此時老師和同學們的幫助尤其重要，透過一次次的討論與修改，方能克服研究中遇到的困難。

能完成這篇論文，首先要感謝的人是我的指導教授 許聿廷老師，老師總是耐心的聆聽我的問題，並幫助我釐清思緒，讓我可以不斷向前邁進。也要感謝柏傑家維，能跟你們一起吃飯運動，讓我的生活豐富了不少，你們也時常關心我的論文，給予我許多協助。乃慈學姊雖然認識不久但感覺已經是老朋友了，謝謝妳帶我去吃很多好吃的東西，關心我生活的大小事。薇□ 一起做計畫的好學妹，相信細心的你能繼續做好計畫順利畢業。另外也很感謝研究室的學弟妹們在報團咪時給我的許多建議，很高興能跟你們在同一家。

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最後，感謝我的父母支持我唸到碩士，平常的關心照顧我的你們是我堅強的後盾，讓我可以專心投入在研究中，完成我的學業。完成碩論讓我有許多的收穫，未來仍要繼續學習努力不懈，不枉費這兩年辛苦打下的基礎。

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中文摘要

高速公路的壅塞超過半數是由事件所造成，提升事件處裡的效率能夠降低壅塞所帶來的延滯時間。目前國道的管理係依賴事件應變車隊進行事件的清理與排除，最佳化事件應變車隊的調度為一種有效提升應變效率的方法。本研究的目標為應用最佳化方法提升事件應變作業指派的品質，以縮短應變車隊抵達各事件的應變時間。本研究提出動態調度系統的架構，釐清與分類系統所需輸入或取得的參數，並針對高速公路系統建立應變車隊路徑規劃問題的模型。模型除了最小化總體事件應變時間,也納入動態調度中重新指派車隊與事件類型優先順序的考量，以使調度模型能夠有更多彈性、符合實際的需求。本研究以臺灣北區高速公路路網為研究案例，比較分析動態調度模式與現行調度模式間應變時間的差異。從案例分析中可發現動態調度模式不但能在新事件發生後提供即時總應變時間最小化的指派策略，使尖峰時段的總應變時間下降，也能透過改變相關參數的權重來適度調整重新指派車隊的頻率或事件類別優先處理的順序。本研究可以作為高速公路管理單位建構動態調度系統的參考，特別對於多事件密集發生的狀況下，可幫助調度人員做出更有效率的派遣決策。

關鍵字：高速公路管理、決策支援系統、動態派遣、事件應變、車輛路徑規劃。

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ABSTRACT

According to historic data, more than half of freeway congestion is caused by incidents, and enhancing efficiency of incident response can reduce the delay caused by congestion. For most of freeway management systems, they depend on incident response teams to clean up and remove incidents, and optimizing decision of response team dispatch is an effective way to improve the efficiency of incident response. The goal of this study is to apply an optimization method to enhance the quality of the incident assignment strategy to reduce the response time for the response teams to arrive at each incident. We propose the framework of a dynamic dispatch system, clarify the parameters that need to be input or obtained, and develop a model based on the vehicle routing problem for incident response on the freeways. In addition to minimizing the total incident response time, the model also incorporates the considerations of reassignment and prioritizing incidents in dynamic dispatch, making the dispatch model more flexible and consistent with realism of operational needs. In this study, the roadway network of the Northern District of Taiwan Area Freeway is used for the case study to compare the dynamic dispatch model with the current dispatch approach. It is found that the dynamic dispatch model can provide an incident assignment strategy that minimizes the total response time after a new incident occurs so as to enhance the efficiency of freeway incident response, particularly for the peak period where multiple incidents are likely to occur concurrently. Additionally, it also allows the flexible adjustment of the reassignment frequency or incident priority by changing the weight of the related parameters. Our research can provide the insights agency for the construction of a dynamic dispatch system for freeway management units and help dispatchers make more efficient dispatch decisions.

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Key words: *freeway management, decision making system, dynamic dispatch, incident response, vehicle routing problem.*

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Chapter 1 Introduction

1.1 Research Background

The development of a freeway system, a national level transportation, shortens the travel time and accelerates intercity transportation, and it also promotes the growth of economy. The government has to maintain and manage freeways, and it induces a great amount of manpower, equipment, monetary and time costs. Emergency incident response is one of the works, which is a mechanism to contain the impact on traffic flows when incidents occur. To be specific, if an incident such as accident, scattered items or animal intrusion occurs, it may block lanes and cause severe congestion over the freeway system. There is the need of a freeway traffic control center to dispatch response teams to clear the incident and restore traffic. The duration from incident occurrence to clearance determines the delays caused to the upstream traffic volume. As a result, how to decrease incident-processing time is one of critical issues in the field of freeway maintenance and management.

1.2 Research Objective

In most of the current practice, the freeway management agencies may divide the freeway network into several districts, and each district has its own incident response team. When an incident occurs, the local control unit in the district will notify the freeway management agency and send a response team to clear the incident. In recent years, due to the development of Intelligent Transportation System (ITS), advance information, communication and computer technologies are applied to field of

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transportation management. The freeway management agency establishes traffic control centers to monitor real-time traffic on freeways and also manage response teams through real-time traffic censors, closed-circuit television cameras (CCTV) and GPS units. Incident information is reported to the traffic control center, and the traffic control center can directly assign appropriate response teams to process incidents. This new dispatch system for incident response increases the flexibility and efficiency of coordinating response teams and decrease the waste of resources. However, the current dispatch mode is relatively static and considerably based on dispatcher's personal judgement; it may not work smoothly when multiple incidents occurs in the same area, and the dispatcher has to rely on experience to assign response teams. As a result, this research seeks to develop a dynamic model using real-time traffic data on freeway to assign response teams. The model result will be compared with the currently-used static mode and analyzed with respect to relevant parameter will be discussed.

1.3 Thesis Organization

This study is composed of five chapters. The overall flowchart of its organization is shown in Fig. 1.1. Chapter 1 introduces the research background and current practice of freeway incident response, and thereby the motivation and objective of this research are proposed. Chapter 2 reviews important previous studies in the related areas and discusses the difference between static and dynamic dispatch model. Chapter 3 proposes the concept of the real-time dispatch decision-making system and develops a dynamic dispatch model for response team. In Chapter 4, this research uses Northern Taiwan Freeway Network for the case study, and the result are discussed with different scenarios and sensitivity analysis. Chapter 5 concludes the contribution of this research and suggests potential directions for future work.

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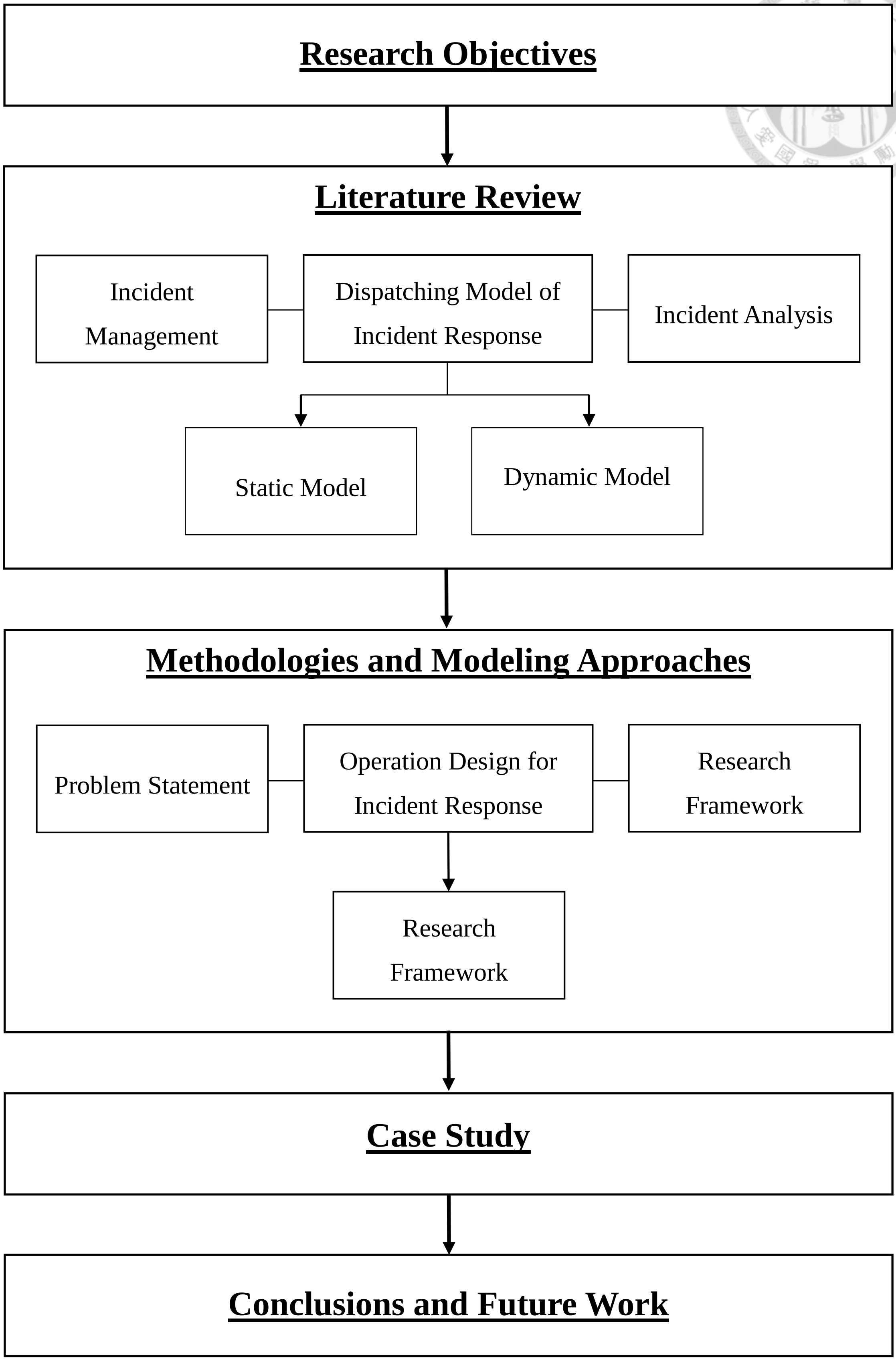

Fig. 1.1 Study Framework

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Chapter 2 Literature Review

Incidents may influence traffic and safety on freeways and cause loss of time, money and even lives. If an incident block some lanes, it will cause congestion on the upper freeway segment. Once vehicles queue to the near ramp, the response team may spend more time to arrive at scene and the delay of vehicles increases. In addition, some kinds of incident, such as animal intrusion, accident or scattered items, which are not processed right away, can derive more serious incident and make people get injury or property lose. As a result, we should do more research to improve management strategies and knowledge of incidents. To design and make progress of incident processing system or to provide strategies to alleviate the impact of incidents on freeway, many scholars studied freeway incidents from different aspects.

In this chapter, this research divides previous research into three categories. The first category is freeway incident management, the second is incident data analysis and the third is vehicle dispatch model.

2.1 Freeway Incident Management

In this category, some studies showed us the background of incident management. A study (Zografos et al., 1993) first introduced "traffic flow restoration unit (TFRU), which is dispatched to restore the traffic flow when an incident is detected. A traffic flow restoration unit may consist of a single vehicle, i.e. tow-truck, or it may be a multivehicle unit including tow-trucks, ambulances, and so forth." The emergency vehicle teams in our study were dispatched not only to restore traffic flow but also deal with other kinds of incident, so we called it "response team" in this study. The study

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then explained the relationship between cumulative traffic volume and time by quoting "the urban" (1989), see Fig. 2.1. They explained "the horizontal axis represents time, and the vertical, cumulative traffic volume. The initial traffic-flow rate is represented by the slope of the line AC. When an incident occurs, the actual traffic flow past the incident slows down due to the reduction of the capacity of the freeway. The slope of the line AB represents the flow rate past the incident site. At the time that the incident is remedied the traffic-flow rate increases (slope of line BC) until the delayed traffic passes the incident location and the traffic flow resumes its normal rate." Fig. 2.1 shows that the total incident-remedy time is a major determinant of incident delay.

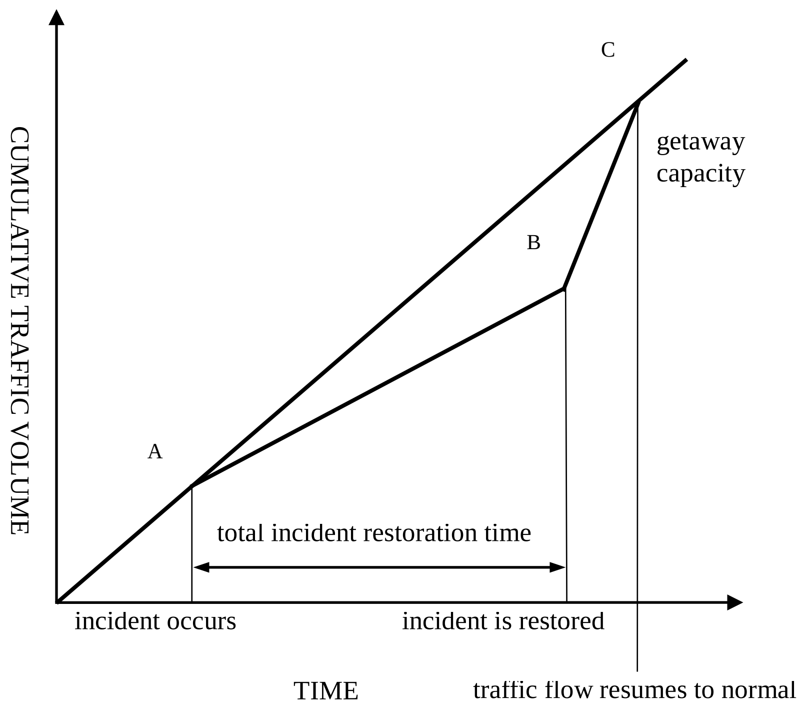

Fig. 2.1 Input-Output Estimation of Freeway-Incident Delay

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On the other hand, due to the development of Intelligent Transportation System Technology (ITS), incident information can be delivered to traffic control center as the crucial data of planning and management. Stephen G. et al. (1992) and Zografos et al. (2002) used ITS technology to create real-time decision making support system providing functions like districting, assigning response teams, routing and visualizing data to help the managers make proper decisions, and they believed this strategy enhancing the efficiency of incidents response.

These studies provide management logic of incident response through establishing systematic frames. The government can follow the studies to build decision support systems to help freeway managers make decisions and decrease incident response time. However, authors of these theses did not explain the methods to dispatch response teams, so it is hard to assess the performance of their models.

Some researchers analyzed data or built model with considering the characteristic of freeway system, which is different from other road systems. For example, RH Hall (2002) considered the interval of interchange and the additional time that response teams spend to change direction on freeway to derive model of response time and delay. They also indicated there are two dispatch strategies if a new incident occurs when the nearest response team is clearing another incident. The first one is to wait response team finishing previous incident and assign it to clear the new one, and the second one is to assign a farther response team to process the new incident. They believed future studies should discuss how to blend these two dispatch strategies to ensure utilization and stability of incident response time on peak hours. According to the study, this research will explore the characteristics of freeway system and these two strategies.

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2.2 Freeway Incident Analysis

Incident occurred on the freeway frequently and left a lot of data which can be analyzed to find the occurrence tendency, and managers could adopt prevention strategies to enhance the quality of freeway management. JA Lindley. (1987) quantified the degree and cost of congestion on urban freeway in the future. They discovered emergency incident causing over half of the congestion delay so that their study made people understand the importance of preventing incidents and increasing the efficiency of incident response. They also emphasized that managers need to adopt high cost-benefit strategies to solve incident deriving problem.

Based on previous research, reducing duration of incidents can relieve the congestion effectively. Giuliano, G. (1989) collected freeway incident data to analyze the key factors related to incident processing time. They set incident processing time as the dependent variable and find out that the main factors are category, time of a day, volume ratio of large vehicles and road conditions. According to the result, they proposed some strategies to facilitate the congestion caused by incidents. Because Giuliano, G's study deduced that different incident categories have different processing time, and the accident type incident caused the longest time to clear, Yang et al. (2012) used regression analysis with freeway accident data to find factors of the time from accident occurring to accident cleared and discuss ways to reduce accident processing time.

Different improvement strategies also need to do cost-benefit analysis to know the effectiveness. A study used big data of incidents and traffic volume collected from probe vehicles to analyze the difference between before and after implementing the vehicle patrol strategy and the factors of frequency of incident occurrence and duration.

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Skabardonis et al. (1996) found that the strategy reduced the incident response time, but not significant enough to affect the duration. We should also evaluate the effectiveness to prove it a beneficial strategy after building the model.

2.3 Dispatching Model of Incident Response

This research wants to propose a method to assign response teams, so we review some theses related to vehicle dispatch model. In the process of incident response, the dispatch strategy of response teams affects the travel time and clearance order of incidents. Many previous studies proposed different models or strategies to enhance the efficiency of vehicle assignment. The dispatch model can be divided into static model and dynamic model by observing whether its parameters chang with time. The introduction of static and dynamic model is in the following:

2.3.1 Static Model

The static dispatch model decides each response team is responsible for fixed area before incident occurs. It would not change the dispatch method when some new incidents happen, so it is inflexible and simple than dynamic model.

Zografos et al. (1993) introduced the operation procedure of a static model in their study, see Fig. 2.2. The number of response team started from one, and they used districting model to divide the area to the response team according to parameters such as the travel time from the response team stationary location to each road segment, the incident occurrence of each road segment and work load, and then estimating total delay. Next, they increased the number of response teams and repeat the procedure above until the new stage delay was more than last stage delay, and the number of response team which caused least delay and its solution of districting problem were the best result. The

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response team will be assigned to process incidents on the basis of the districting area.

However, deciding number of response team and districting area to them is not enough because it is possible that several incidents happen in the same area in a short time. Therefore, dispatchers follow strategies, such as First Called, First Served (FCFS) and Nearest Origin Assignment (NO) to assign response teams when they face this condition. A. Haghani et al. (2004) defined “The FCFS strategy assumes the service calls are assigned to available vehicles in the order in which requests are received. Service requests are added to a queue of requests on arrival; when a vehicle becomes available, it is assigned the first request in the queue. If one (or more) vehicles is (are) idle when the request arrives. The request is assigned to the vehicle that has been idle longest. A driver must contact the dispatch center upon completion of service” and “In nearest origin assignment, service requests enter the pool of unassigned requests. Upon assignment completion, the driver contacts the dispatch center for a new assignment, at which time an assignment is made to the nearest unassigned request. Service calls arriving when one or more vehicles are idle are assigned to the nearest idle vehicle. A driver must contact the dispatch center upon completion of service.” Although these strategies can help making decision in real time, they are heuristic methods and still have large development space.

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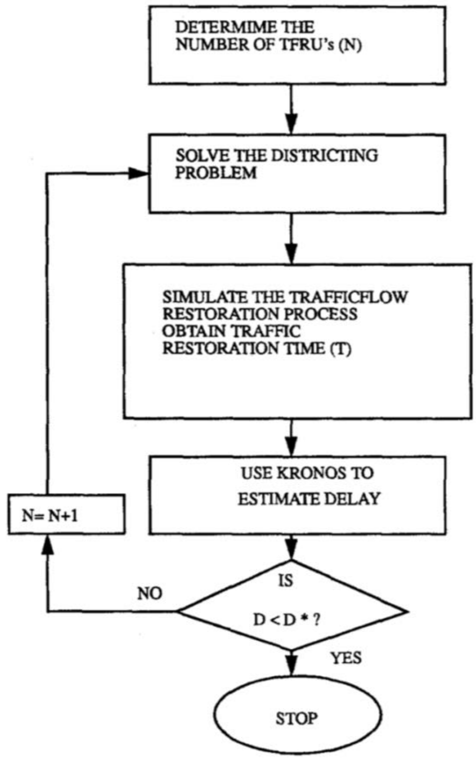

Fig. 2.2 Logic of Proposed Approach

G. Ghiani et al. (2003) defined that Vehicle Routing Problem which usually used to dispatch vehicles can also divide into static and dynamic model, and the way to distinguish them is if their parameters depend on time. In addition, the model can be divided into two groups depending on the uncertainty. The following Table 2.1 is made according to G. Ghiani et al.'s study. In real-time condition, the traffic volume and the positions of response team depend on time and all data are known in advance, so this study attempted to build a model belonging to deterministic and dynamic model. The next segment of this chapter will introduce dynamic model and related theses.

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Table 2.1 Type of vehicle routing problem model

	Static	Dynamic
Deterministic	•All data are known in advance. •Time is not taken into account.	•All data are known in advance. •Some elements of information depend on time.
Stochastic	•Vehicle routes are designed at the beginning of the planning horizon. • Uncertainty may affect which service requests are present, user demands, user service times or travel times.	•Uncertain data are gradually revealed during the operational interval. •Routes are not constructed beforehand. •User requests are dispatched to vehicles in an on-going fashion as new data arrive.

2.3.2 Dynamic Model

Real-time demands or incidents should be input into dynamic models, and the travel time affected by traffic conditions should be considered. Moreover, the dynamic model should be solved as fast as possible to avoid increasing incident response time. Recently the development and application of mathematical programming and algorithm utilizes solutions and fastens the solving speed. We began to review studies related to dispatch problem on freeway network and found a study used First Called, First Served to get the initial solution of vehicle routing problem and then used Tabu search algorithm at regular intervals to improve the solution. The simulation result confirmed the model shorten the total travel time of vehicles. (S Ichoua et al., 2003) Some studies attempted to propose their own model to dispatch response teams, H Zhao et al. (2009) developed dynamic dispatch model in which they considered priority of incidents, reassignment of vehicle teams and processing time constraint. However, the flexible model cannot schedule the dispatch order of incidents for each team, so they assumed that each response team should return to the stationary point before processing the next

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incident. H Deqi et al. (2012) also provided the framework of freeway incident response and used dynamic shortest path algorithm to calculate travel time and plan vehicle routes in real time, but they did not focus on the dynamic dispatch model. Therefore, we turned to other area like logistics, transfer transportation, emergency medical service and emergency supply transportation to learn how they designed dynamic vehicle dispatch models in different assumption and conditions.

Logistics is one of the issues in vehicle routing problem. In order to satisfy customers' need, some goods have to be delivered to customers in limited time. Therefore, MS Daskin et al. (1992) put time as a parameter into the real-time vehicle routing problem model and added some time window constraints, and he also developed heuristic algorithm to increase solving speed.

Warren B. Powell (2000) studied driver characteristics and operation rule of vehicle team and developed a mathematical model, which he proposed two adaptive labeling algorithms to solve, and he used a rail transfer case to compare the quality and speed of the algorithms.

A Haghani et al. (2004) made use of real-time traffic data and travel time data and connected with dynamic shortest path algorithm to propose a flexible dispatch model of emergency medical vehicles. They distinguished ambulances and incidents by giving different weights and constraints in the model, and they also classified and assigned numbers to conditions of vehicle teams. The flexible model can reassign vehicles teams or change routes to avoid congestion road and decrease the travel time of the medical vehicle teams because it keeps tracking the conditions and positions of response teams. Their research used simulation to confirm the effectiveness of the model and used sensitivity analysis to observe the influence of parameters.

Another research discussing the emergency supply transportation problem under

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large disasters, they developed a multi-period dynamic model to solve multi-OD pairs and network uncertainty problem, and used hybrid genetic algorithm to fasten the solving time. (X Ren et al., 2012)

We made Table 2.2 to arrange previous studies and divided them with dynamic or static and using algorithms, see Table.

To be more realistic and after reviewing former studies, this study chose to develop a dynamic vehicle routing problem model because it is flexible and can do vehicle scheduling, and we will also consider parameters and methods such as the priority of incident types, conditions of response teams, shortest path algorithm and response team reassignment constraints according to previous studies to design our model. The full model would be introduced in CHAPTER 3.

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Table 2.2 Comparison of studies on vehicle dispatch model

Author/Year	**Dispatch Method**					**Algorithm**				
	Static			Dynamic		Parallel Computing	Tabu Search	Hybrid Genetic	Dynamic Shortest Path	Cutting Planes
	District	FCFS	NO	Flexible	VRP					
Zografos et al. (1993)	V	V	V							
M. Daskin (1992)			V		V					V
Ichoua et al. (2001)		V								
Ghiani et al. (2002)					V	V	V			
Haghani et al. (2003)		V	V	V					V	
Iannoni et al. (2006)				V						
Zhao et al. (2009)		V	V	V					V	
Ren et al. (2011)				V				V		
Deqi et al. (2012)		V	V	V						

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2.4 Summary of Literature Review

In this study, we reviewed literatures which focused on how to enhance the efficiency of freeway incident response and reduced the vehicle delay on freeways. Incident management studies introduced the system framework of incident response and the operation procedures of response team that helped this study build the model more practical. The contribution of incident analysis studies finding key factors of incident processing time and analysis of response strategies, which can suggest this study for setting parameters. In order to build a model which can plan routes and schedule the order of incidents for response teams, we not only consulted flexible dispatch models for freeway network but also took models about logistics, medical vehicle and transferring vehicle as reference, and choosing to develop vehicle routing problem model to be our basic dispatch model for freeway network. The expectation contributions of this study are listed below:

(1) Proposing a dynamic model and its operation framework:

The time-dependent traffic volume should be considered in the dispatch model because it affects the travel time of response teams. As a result, this study provides a procedure to renew the vehicle speed of each freeway segment and the positions of response teams when solving the model. To insure the model is flexible but not over-altered, this study adds some constraints in the model to avoid reassign response teams frequently. The freeway managers can use the concept of this study to build a real-time decision support system to help dispatcher dispatching response teams in the future.

(2) Decreasing total response time for response teams:

According to previous studies, the duration of incident decides the delay of freeway

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traffic volume. This study focuses on shortening the total response time of incidents, so the main objective of the model is to minimize the total response time. By considering travel time of response teams and the priority of incident, the solution of the model provides dispatch suggestions that making response teams arrive at all the locations of incidents as fast as possible and reduce the delay on freeways.

Our study will use the history dispatch data and traffic volume data on Northern Taiwan Freeway Network as a case study, which inputs incident positions, occurrence time and real-time traffic volume into the model to get the solution, and comparing with static dispatch model using recently. In addition, we also observe the influence of changing priority and reassignment parameters by doing sensitivity analysis.

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Chapter 3 Methodologies and Modeling Approaches

This chapter goes deeper into details of this study with four sections. Section 3.1 states the problem that researchers face in this area recently and proposes the method used to overcome the challenge. Section 3.2 introduces the response procedure from incident occurrence to incident clearance and illustrates a scenario of the incident response. Then it presents the framework of operation design for the incident response system. The last section elaborates the proposed VRP model; the first part includes all assumptions, the second part introduces the variables and parameters, and the final part explains the objective function, constraints and the concept of the proposed model.

3.1 Problem Statement

It is complicated to dispatch response teams, as the dispatchers on the dispatch platform should consider various factors when to decide which team should be assigned to deal with the incident and which route the team should follow, such as positions and types of incidents, the associated direction and traffic condition on the freeway. These factors would affect the travel time of response teams. If several incidents occur within a short period in nearby areas, the dispatchers would have difficulty to make decisions, and such a condition usually happens in the peak hours and holidays according to the historical dispatch data. If there is a supporting dispatch system, which can gather real-time traffic data and process the information of incidents and response teams to quickly provide high-quality suggestions, the dispatchers only have to input relevant parameters through the user interface. Then, the system will feedback the dispatchers suggested teams and routes, which can enable them to make rational and more efficient

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assignment decisions.

To establish the decision supporting system, the crucial work is to form a model that provides necessary functions. Although some previous studies have investigated the concept of incident response system and dispatch strategies for freeways, however, they may not adquately consider parameters in environments changing over time. In addition, the strategies they suggested are heuristic solutions and still have much room to improve solution quality. On the other hand, some studies in other application areas such as logistics and medical service that have already developed dynamic dispatch models, but for freeway incident response dynamic dispatch is still rarely studied or implemented in practice. Some models are too complicated so that it may take much time to solve the problem, and some do not include considerations related to reassignment limits, scheduling, preparation time based on conditions of response teams, which are needed in reality. These defects may influence the efficiency of incident response, especially when there are several incidents on freeways simultaneously.

As a result, there is the need to develop a dynamic incident dispatch model for freeway management so that it can help the dispatcher assign response teams in real time and enhance the efficiency of incident response. According to previous studies, we propose the dynamic incident dispatch model for freeways as a multi-depot vehicle routing problem (MDVRP), which can meet operational needs and is flexible for adding model constraints corresponding to practical concerns. Thereby, this study proposes an operational framework for incident response and a dynamic multi-depot vehicle routing problem , where realistic considerations are reflected in the mathematical formulation.

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3.2 Operation Design for Incident Response

In order to design an incident response system and the associated dispatch model, we need to understand the role of incident dispatch and the timing to use the decision support system for incident response first. Dispatching a response team is one of the components in freeway-incident duration time. Zografos et al. (1993) shows the total remedy time by Fig. 3.1. The total remedy time is divided into four intervals in this figure. The first interval is T1 “Detection and Identification time”; it is the time interval from the time of incident occurrence to the time that the incident-management center is notified the incident type, position and severity. The sources of notification can be the freeway police, drivers, victims, monitors or even managers of the incident-management center. The second interval is T2 “Dispatch time”; it is the time between incident detection and the time that the incident is assigned to a response team. The dispatcher in the freeway-management center will firstly use CCTV (a camera on freeway) near the position of the incident to confirm the information from the source after receiving a notification, and then the dispatcher will input the parameters into the dispatch model through a user interface. The model solution will return suggestions regarding response team and route assignment to the dispatcher, and the dispatcher will make a final decision and contact the response team chosen. The third interval is T3 “Preparation and Travel time”; this is the time that the response team needs to arrive at the location of the incident from its previous position. This time is composed of preparation time and travel time. Before the response team departs to the location of the incident, the team should check workers and equipment or complete the duty of the current incident restoration; this period is named preparation time. The last interval is T4 “Clearance time”; this is the time that the response team spends on clearing the

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incident at scene. The worker must record the time and the condition at scene and send it back to freeway-management center as the dispatch data via an on-board unit of the incident response system.

Zografos et al. (1993) mentioned that reducing of any component of remedy time can decrease the incident delay on freeways. In this study, the main objective is to minimize the incident response time, which includes T1, T2 and T3, and we focused on how to support the dispatcher to make decisions faster and provide better suggestions that can enable response teams to arrive at the locations of incidents as quick as possible.

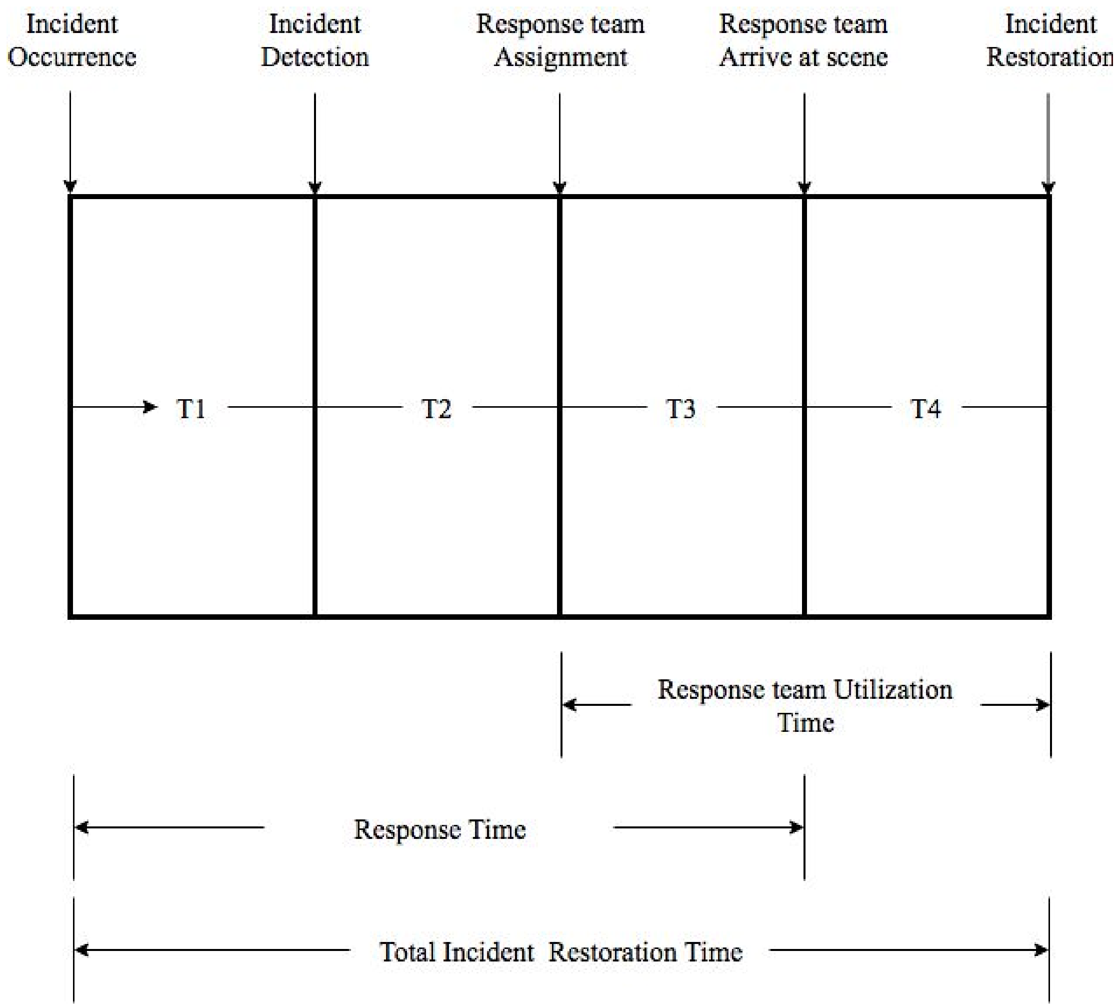

Fig. 3.1 Components of Freeway-Incident Duration Time

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Based on the background knowledge of freeway-incident duration time, this study designs the operation procedure of the incident dispatch system and shows it in

Fig. 3.2. A scenario that triggers the procedure starts from one or some incident notifications received by the dispatch platform. After the dispatchers check the incident and obtain enough information, they need to input required parameters into the dynamic dispatch model. The source data of the parameters can be divided into three groups, **Vehicle Information**, **Incident Occurrence** and **Real-time Freeway Network Traffic**. The introduction of these groups of data is in the following:

(1) Vehicle Information

The data of vehicle information contains the status and the position information. The vehicle position information can be collected by GPS devices. The vehicle status information, which indicates if the team is currently on duty, can be acquired through communicating with the response team. In practice, response teams need preparation time to check workers and equipment before they leave their stationary points. On the other hand, if a response team currently processing an incident is assigned another incident, the team needs time to clear the current one. In the model, these two statuses (at the stationary point or processing an incident) of response teams are calculated as waiting time, which means the interval between the time that a response team is assigned an incident and the time that this response team actually departs to the location of incident. The dynamic dispatch model has to calculate the total response time based on the status and position information of response teams upon the moment that the

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notification of an incident is received.

(2) Incident Occurrence

Incident information contains severity, positions and estimated processing time of an incident. The severity of incident may be of high, medium and low levels according to the incident type and the conditions at the scene, and the dispatcher will judge the severity level after integrating the information they receive. The position of the incident is related to the travel time in the model, and it is taken as the node in the virtual network used for formulating the problem. This study uses average processing time of each incident type as the estimated processing time in the proposed.

(3) Freeway Network Traffic

The freeway network including interchanges and stationary points of response teams should be constructed first. Traffic data every hour on the freeway are collected and a travel time matrix over the network made by using the shortest path algorithm and traffic data of the network to calculate the travel time between every node pair. The model can retrieve travel times of links through an inquiry function from the matrix when it is building the virtual network of response teams and incidents.

After the dispatcher inputs the value of the parameters, the dynamic dispatch model starts a solution process to determine the optimal assignment. This model seeks to handle all incidents in the freeway network with the minimum response time and must not violate the constraints. This model considers the incident priority order, reassignment and presents them in a minimax problem. The details of notation, formulation and the concept used in the model are explained and discussed in next section.

The output of the model is the dispatch strategy, including the assignment of each incident assigned to an appropriate response team and the associated route. The incident

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dispatch result upon the notification of a new incident will be stored and used as the parameters for the problem of the later incident.

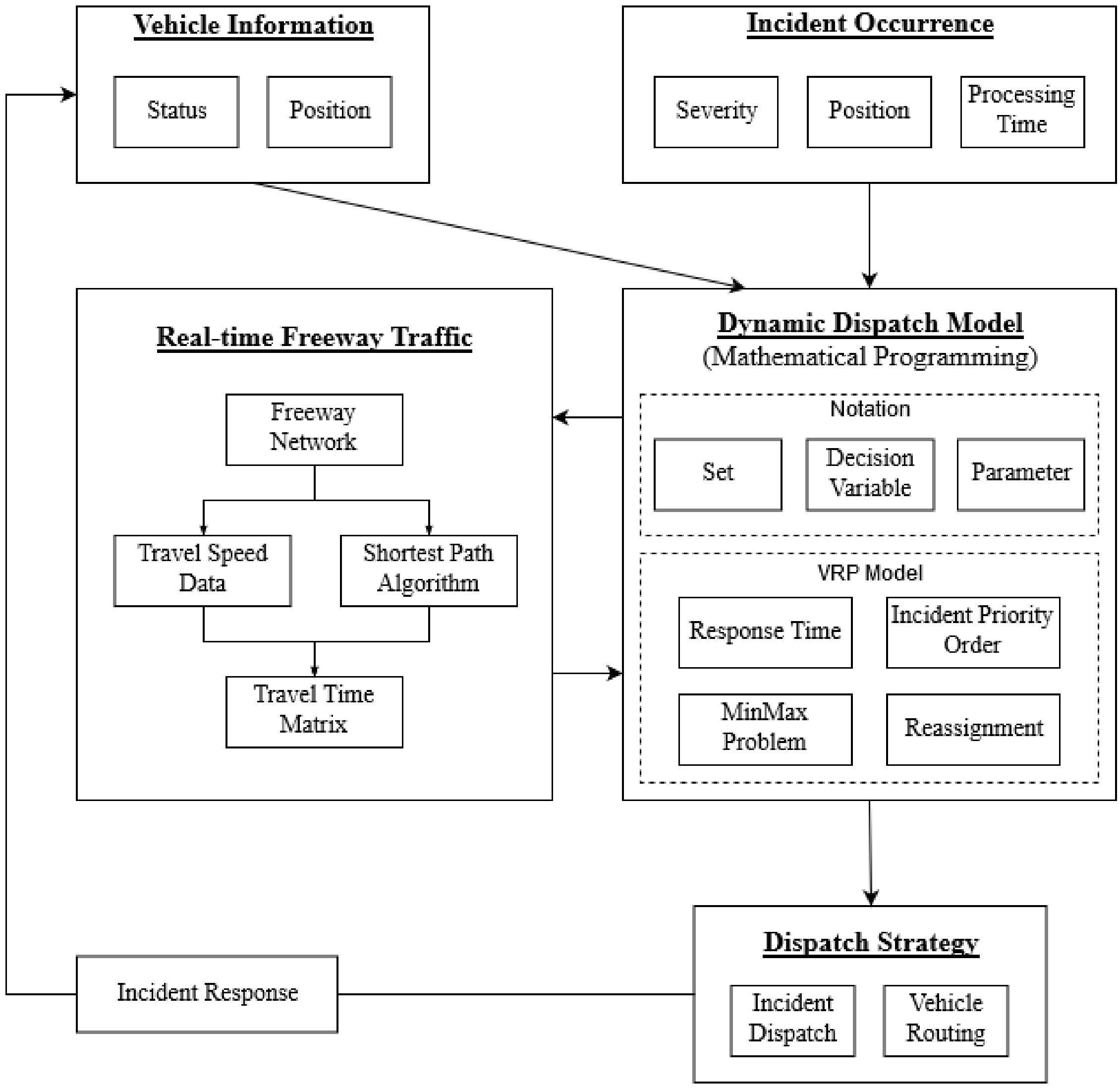

Fig. 3.2 Operation Design for Incident Response

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3.3 Model Development

This study develops the dynamic dispatch model based on the multi-depot vehicle routing problem, which is able to route response teams at different locations to handle all the incidents in the freeway network in a round-trip for each team and minimize the cost of the total response time. Each response team processes incidents assigned to it according to the schedule determined by the dispatch platform so that response teams can still work efficiently even though there are many incidents waiting to be processed.

Other than the incidents under or waiting for processing, new incidents may appear anytime and anywhere in the freeway network and response teams may have to depart from their current locations to process the newly reported incidents. If the nodes of the model, which are composed by the positions of response teams and incidents, change with time, the routes of response teams may also change to satisfy new incident response demand. Therefore, the model must be designed in a dynamic context to adapt changes in reality. This study divides the time horizon into small intervals, and a new stage will be established if one or many incidents occur in an interval.

In a new stage, the travel time for a response team to arrive at an incident is different from the former stage, so the dispatch decision may also change. If an incident assigned to a response team in the former stage is assigned to other response team in a

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later stage, the workers may become confused due to such a reassignment. As a result, we need to formulate constraints to contain this situation in dispatch model. To develop the model, some assumptions are first introduced to construct freeway network and to meet the requirement of vehicle routing problem before we proceed the mathematic formulation of the model.

3.3.1 Assumptions

There are six assumptions made for model development:

i. Response teams only use the freeway network to travel to the locations of incidents;
ii. The travel speed of response team is limited to the speed of large-sized vehicles and the travel speed of shoulders on freeways;
iii. The time required for a response team to change direction by using any interchange is set equal;
iv. The preparation time of each response team at the stationary point is equal;
v. An incident must be processed by one response team;
vi. A response team can serve another incident without going back to its stationary point.

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3.3.2 Notation

The network of vehicle routing problem is represented with a graph *G (N, A)* with node set *N* and link set *A*. The node set consists of three types of subsets: the subset of response team nodes V, the subset of incident nodes I and a virtual end node F, which is a dummy node connected to all nodes with links of zero travel time. Response teams have their corresponding stationary points which are represented as a set *S*. Each link $(i, j) \in A$ is characterized by its link travel time. The network notation, sets, parameters and variables used in the model are summarized in the Table 3.1 Notation

Table 3.1 Notation

Notation	Description
Sets	
N	Set of node in the Network, $N = (V \cup S \cup I \cup F)$
V	Set of response team nodes
S	Set of response team stationary points
I	Set of incident nodes
F	Set of a virtual end node
A	Set of links in the network
C	Set of response team statues
P	The link set of all routes in the former stage
Parameters	
t	Time stage, it will add one when a new incident notified

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P_i	The weight of priority order of incident *i*
$TT_{ij}(t)$	The travel time cost from node *i* to node *j* at time stage *t*
$w_k(t)$	The waiting time interval between current time and depart time of response team *k* at time stage *t*.
PT_{ij}	The processing time cost from node *i* to node *j*
PT_k^0	The remaining processing time cost of the last incident processed by response team *k*
PR	The average preparation time for response teams
V_{kc}	The initial status of response team *k*, if *c* = 0, the response team *k* is waiting at its stationary point *c* = 1, the response team *k* is moving to an incident location *c* = 2, the response team *k* is processing an incident *c* = 3, the response team *k* is going back to its stationary point
τ	The weight of response team reassignment
R_k^0	The number of reassigning response team *k*; it would be zeroed after response team *k* goes back to stationary point.
B_1	A large value
B_2	A large value
Variable	
$Y_{ijk}(t)$	Binary variable, if response team *k* is not assigned to pass through link (*i*, *j*) both on current time stage *t* and its former stage, Y_{ijk} equals to 1; otherwise, it equals to 0.
$R_k\ (t)$	Binary variable, if any Y_{ijk} in the route equals to 1 for response team *k* at time stage *t*, $R_k(t)$ equals to 1 ; otherwise, it equals to 0.
z	Continuous variable, this variable is equal to the largest total operation time of a response team.

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X_{ijk} (t)	Binary variable, if response team *k* is assigned to pass through link (i, *j*) at time stage t, X_{ijk} equals to 1; otherwise, it is 0.

Fig 3.3 shows the virtual network composing of nodes *V*, *I* and *F*, and the green line and red line are the possible routes the response teams may go along. The locations of the response team nodes may change in different time stage, as response teams move to other places. The number of incident node may change in different time stage, as new incident occurs and previous incident cleared. That all routes have to go to the end node and return to its origin means response teams will go back to the stationary points after they clear all incidents in their routes. Fig. 3.4 Time cost on nodes and links illustrates that we put waiting time $w_k(t)$ on the response team nodes and travel time and incident-processing time on the links connecting to incident nodes, and the links from incident nodes to the virtual end node have no time cost. We will discuss more details and concepts of formulations in the next section.

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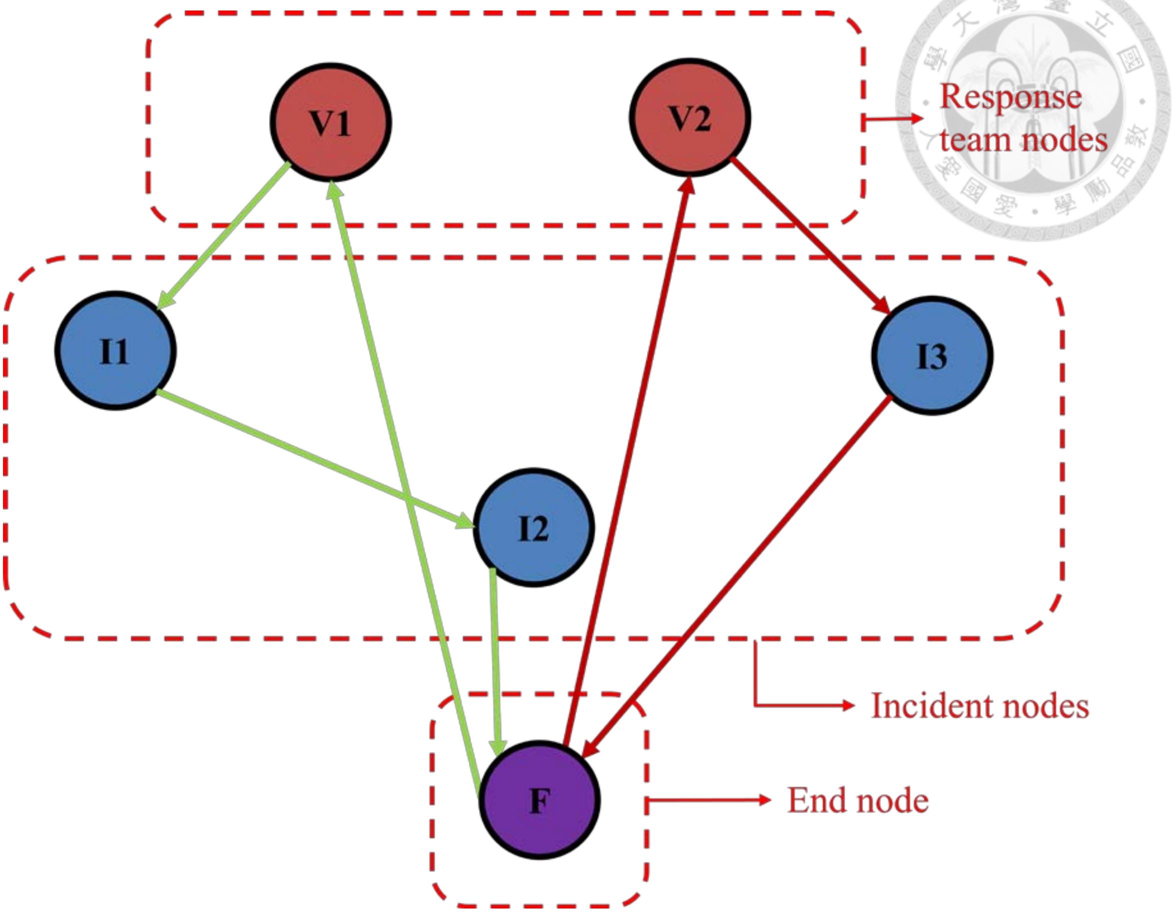

Fig. 3.3 Virtual network Diagram

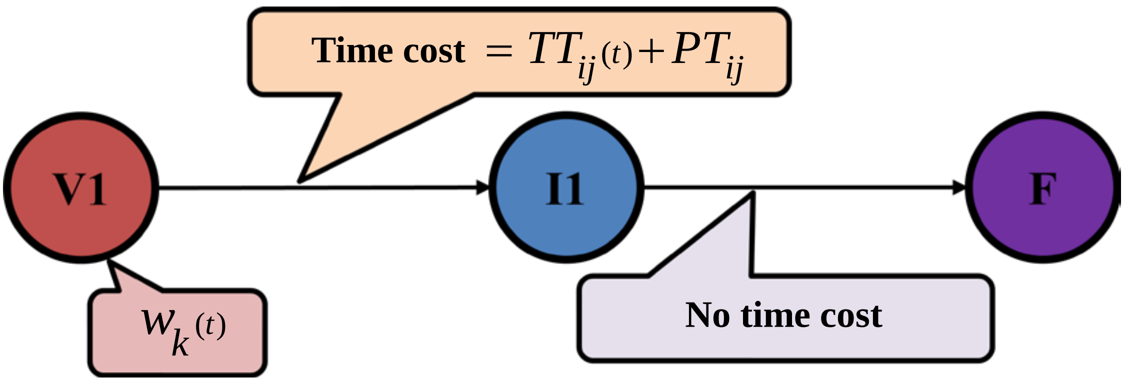

Fig. 3.4 Time cost on nodes and links

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3.3.3 Problem Formulation

The aim of vehicle routing problem is to assign vehicles to meet all demand in the minimum time or cost. However, the major objective is to minimize the total response time of incidents in this study. The response time introduced in previous chapter consists of preparation time and travel time, but we should also consider the processing time as response teams may process more than one incident in a round-trip. Therefore, the objective function for each time stage is written as:

$$Min\ Z = \alpha \times z + \beta \times \left(\begin{array}{l} \sum_{k \in N_V} \sum_{i \in N} \sum_{j \in N} X_{ijk}(t) \times P_i \times \left(TT_{ij}(t) + PT_{ij} \right) \\ + \sum_{i \in S} \sum_{j \in N_I} \sum_{k \in N_V} w_k(t) \times X_{ijk}(t) + \tau \times \sum_{k \in N_V} \left(R_k^0 + R_k(t) \right) \end{array} \right) \quad (2.1)$$

The objective function (2.1) can be defined as the summation of two parts: (i) the longest total operation time of a response team: the longest time of a response team to finish processing the latest incident, and (ii) the total operation time of all response teams: the total operation time of a response team which include preparation time, travel time, processing time and reassignment punishment. These two parts have different weights α and β, and $\alpha \gg \beta$. Both the first part first and the second part would be satisfied simultaneously.

If several incidents are closer to a response team, the dispatcher may assign all these incidents to this team. Nevertheless, even though it is reasonable, incidents that

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sorted later are processed by response teams after incidents sorted former are cleared, so the response time of incidents sorted later may be comparatively long. Hence, we design a minimax method by including the first part of objective function and combining it with Constraint (2.2) to minimize the upper limit of the total operation time of each response team.

$$\sum_{i\in N}\sum_{j\in N} X_{ijk}(t)\times P_i\times\left(TT_{ij}(t)+PT_{ij}\right)+\sum_{i\in N_S}\sum_{j\in N} w_k(t)\times X_{ijk}(t)+\tau\times\left(R_k^0+R_k(t)\right)\leq z,$$
$$\forall k\in V \tag{2.2}$$

The value of variable z must be larger or equal to the total operation time of each team. By adding this part in the objective function and including Constraint (2.2), the model may dispatch other response teams to support the response team which is close to several incidents to decrease the total response time. In addition, the work loading can be more balanced over each response team as the incidents will not be assigned to few response teams only based on distance.

To calculate the total operation time of each response team, we divided it into three parts: (i) travel and processing time: the travel time between nodes and the duration of processing incidents, (ii) waiting time: each response team has a waiting time before it can depart from its original location to the assigned incident, and (iii) reassignment punishment: the punishment time if the incident is assigned to a response team which is

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not the same as the one in the former stage. The first part calculates the time cost over the used links, and we weight incidents with a priority order according to their types. Based on the experience of the dispatchers, and the priority order is divided into three levels: high, median and low, and each level has its corresponding value. The high level means that the incident may cause serious congestion and longer delay. The median level incidents may influence the traffic and further cause an accident. The low level incidents may not affect traffic, but it still involves safety risk. If the incident has higher priority order, it should be processed as quickly as possible. This priority order can help the dispatcher assign response teams to process incidents with higher influence to traffic first and decrease overall delay on the freeway.

The second part sums the waiting time of all response teams. Each response team will be of a status(V_{kc})when a new stage is established. There are four statuses that a response team can be, and a response team will have waiting time only when it is waiting at its stationary point or it is processing an incident. The leader of response team should check workers and equipment before leaving its stationary point for the assigned incident. Also a response team must finish clearing the incident it is currently processing before going to process another one. These two kinds of waiting time are calculated in Constraint (2.3).

$$w_k(t) = V_{k_0} \times PR + V_{k_2} \times PT_k^0, \forall k \in V \quad (2.3)$$

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The third part limits the number of assignment changes across stages. In Constraint (2.4), if a link is not chosen for response team *k* in the previous stage, $X_{ijk}(t-1)$ will be zero, and Y_{ijk} will be one. Then, Constraint (2.5) sums all Y_{ijk} to determine if any link in each response team's route is changed. If a link is changed, R_k will be one and multiplied with τ, which is the filter of reassignment. τ can be a constant or a flexibly be a value equal to the duration between last stage and next stage. Appropriately setting the value of τ can avoid the model changes route frequently across stages, which may cause confusion and negatively affects response teams.

$$1 - X_{ijk}(t) \times X_{ijk}(t-1) \le B_1 \times Y_{ijk}(t), \forall (i, j, k) \in P \tag{2.4}$$

$$\sum_{(i, j, k) \in P} Y_{ijk}(t) \le B_2 \times R_k, \forall k \in V \tag{2.5}$$

Other constraints in the model are the basic constraints in the vehicle routing problem. Constraint (2.6) limits that only one response team will be assigned to process incident *j* from the stationary point or from the location of another incident, and Constraint (2.7) limits that a response team can only go to another incident location or the virtual end node. Constraint (2.8) is the constraint for flow conservation, which means the in-flow number of response teams equals to the out-flow number of response teams, and the response team must be the same one. Constraint (2.9) indicates that each team is assigned to process one incident one time from the stationary point. Constraint (2.10) means that each team goes back to the end node not more than one time.

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Constraints (2.11) and (2.12) are the sub-tour elimination constraints that are capable to remove all sub-tours in the solution space.

$$\sum_{i \in N_S, N_I} \sum_{k \in V} X_{ijk}(t) = 1, \forall j \in N_I, i \neq j \tag{2.6}$$

$$\sum_{j \in N_I, N_F} \sum_{k \in N_V} X_{ijk}(t) = 1, \forall i \in N_I, i \neq j \tag{2.7}$$

$$\sum_{i \in N} X_{ihk}(t) - \sum_{i \in N} X_{hjk}(t) = 0, \forall h \in N, k \in V \tag{2.8}$$

$$\sum_{i \in N_S} \sum_{j \in N_I} X_{ijk}(t) \leq 1, \forall k \in V \tag{2.9}$$

$$\sum_{i \in N_S} \sum_{j \in N_I} X_{ijk}(t) \leq 1, \forall k \in V \tag{2.10}$$

$$u_i - u_j + (|N_S| + |N_I|) \sum_{k \in N_V} X_{ijk}(t) \leq |N_S| + |N_I| - 1, \forall i \in N_S, N_I, j \in N_S, N_I, i \neq j \tag{2.11}$$

$$u_i \geq 0, \forall 1 \leq i \leq |N_S| + |N_I| - 1 \tag{2.12}$$

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Chapter 4 Case Study

To confirm that the model can help the dispatchers more efficiently assign response teams and reduce the total response time, this study uses the real dispatch data of Northern Taiwan Freeway Network for the case study to test the model, which is detailed in the four sections of this chapter. We use Python as our tool to build the network and model and use Gurobi Optimizer as the solver to solve the model. Section 4.1 introduces Northern Taiwan Freeway Network and the method to establish a simulation network for the case study based on the real dispatch data. In Section 4.2, we analyze test results and compare them with the original dispatch results to verify the effectiveness of the model. Section 4.3 reveals the influence of parameters to response time by changing values of parameters. Section 4.4 summarizes our findings from a series of tests.

4.1 Northern Taiwan Freeway System

Our case study focuses on the freeway system in Northern Taiwan, which is composed of four freeways (Freeway 1, Freeway 2, Freeway 3 and Freeway 5) and managed by North District Maintenance Engineering Sub-Bureau. The total length of this freeway system is about three hundred kilometers, and about fifty thousand vehicles

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travels in the system per hour. There are nearby twenty thousand incidents occurring in this freeway system every year, and the number is growing. The Engineering Sub-Bureau divides this system into five duty areas, and each duty area is managed by a branch and deployed with one or two response teams to handle the incidents on the freeways. Fig. 4.1 shows the duty area for each branch and the locations of two control centers and eight stationary points of incident response teams. Table 4.1 displays the mileage of stationary point of each response team along the freeways.

Due to the number of incidents that continuously grows up every year, the Engineering Sub-Bureau distributed the assistance work of incident response to the control centers. The control centers started to check equipment and support operation of incident processing to increase work efficiency. In 2016, the Engineering Sub-Bureau started a Central Dispatch System at the control centers where a dispatch platform is established, and the dispatchers communicate with response teams to obtain the situations at the scene and accelerate the speed of incident response. The response teams on Freeway 1, Freeway 2 and Freeway 3 is dispatched by the control center at Taishan, and the response teams on Freeway 5 are dispatched by the control center at Pinglin. According to the historic dispatch data, the incident response time decreases because Central Dispatch System can directly assign each response team to process incident or go to other duty areas to support other response teams.

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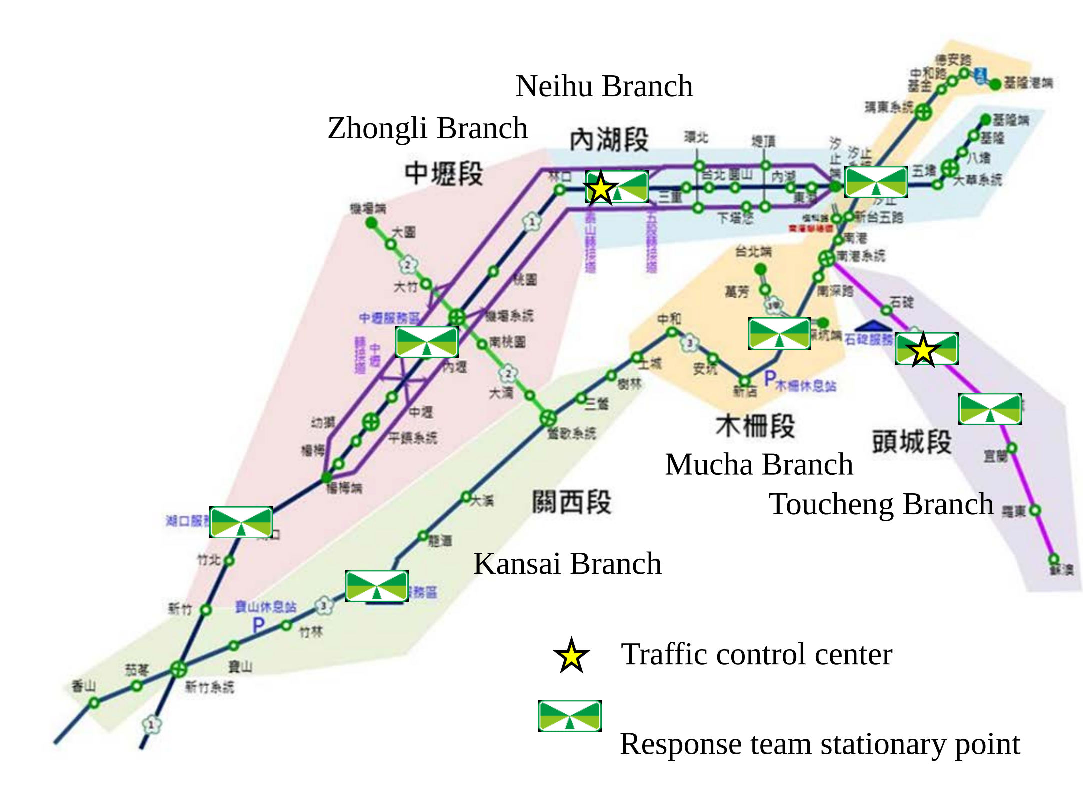

Fig. 4.1 The duty areas of branches and locations of traffic control centers and stationary points of response teams

Table 4.1 The mileage of stationary point of each response team

Response team	Freeway number	Mileage
Xizhi	Freeway 1	9
Wugu	Freeway 1	33
Zhongli	Freeway 1	55
Hukou	Freeway 1	86
Mucha	Freeway 3	21
Kansai	Freeway 3	79
Pinglin	Freeway 5	14
Touchen	Freeway 5	30

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When an incident occurs, the dispatchers assign it to a response team according to the duty ranges of incident response teams. Fig. 4.2 presents the duty range of each response team using the lines with different colors. Different freeway directions are also distinguished by two lines, and the elevated freeways are separated from the surface one. The boundaries of the duty ranges are located at interchanges for the consideration that the response teams can turn back faster by using these interchanges. Most of the incidents are assigned to response teams by this figure, but the dispatchers may assign a response team to support other response teams upon two conditions. The first condition is that a serious incident needing more than one response teams to handle occurs. The second condition is that the response team is too busy to handle all the incidents in its duty area. The dispatch for these conditions involves personal judgment and experience, and we cannot exactly understand all the dispatch rules. Each dispatcher may have different ways to assign response teams although there may be some common rules to follow. However, we still can compare the real dispatch results (in the historic data) with the dispatch strategies suggested by the proposed model. This study constructs a simulation freeway network and input the travel time according to the historic data. Based on this simulation freeway network, we can calculate point-to-point travel time over the network and create the travel time matrix for the model.

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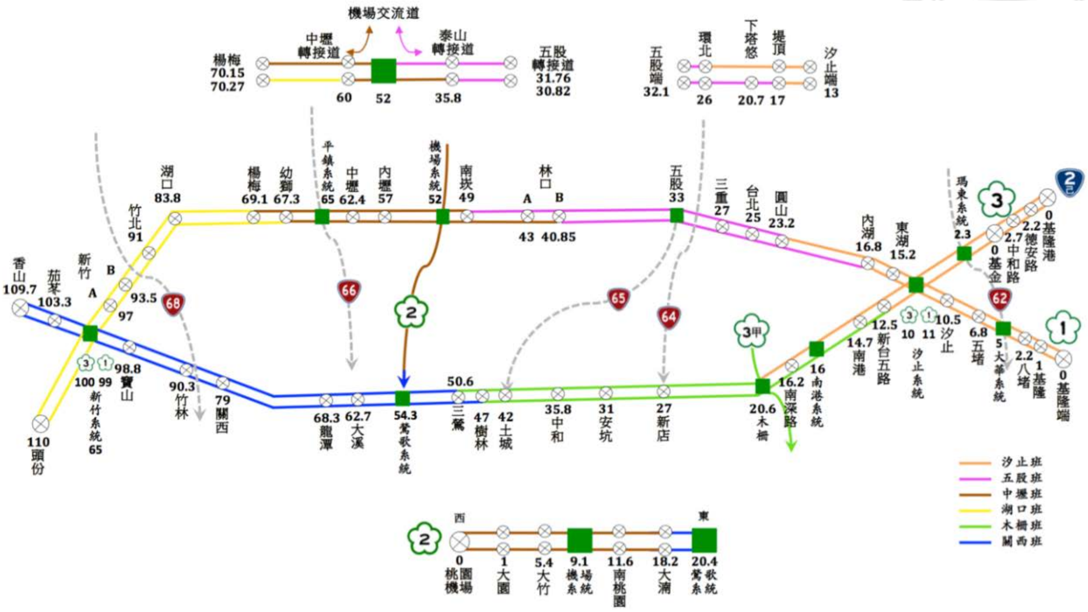

Fig. 4.2　Duty ranges of incident response teams

4.1.1　Network

The simulation network is built based on map of major highways in Northern Taiwan, (see Fig. 4.3). This map shows the locations and mileages of interchanges and system interchanges. An interchange is a group of ramps connecting a freeway and a general road. A system interchange is a group of ramps connecting different freeways (either surface or elevated ones). The simulation network does not include Freeway 5 because the two response teams on Freeway 5 are purely under controlled Pinglin control center; the dispatch of these two response teams is separated from the others and

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relatively straight forward. The freeways are divided into segments every two kilometers, and the middle points of segments and interchanges, frontage roads and the stationary points of response teams are regarded as nodes in the simulation network. The nodes are connected with directional links, and the travel time of links is obtained from freeway traffic data base. The data base has travel time data from an interchange to the next interchange. In Table 4.2, the vertical axis is the time of a day, and the horizon axis is the road segment from an interchange to the next one. The values are the travel time of road segments for the associated time of day. In addition to general links, some links such as the travel time of link from a stationary point to a freeway node is set three minutes because the response team needs average three minutes to check workers and equipment before departing from the stationary point. A link passing through an interchange takes five minutes, and the link passing through a system interchange takes three minutes. Based on these settings, we can form the simulation freeway networks in different time of day. After establishing the network, we apply Dijkstra's algorithm to find the shortest path from a node to any other node and calculate the travel time. Dijkstra's algorithm was proposed by Dijkstra, a Dutch computer scientist, in 1959. It solves the shortest path problem in directed graphs, finding the shortest path between two vertices. By employing Dijkstra algorithm over the simulation network, we can create the travel time matrix and enable the model to obtain the shortest travel time over

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any node pair by inquiring the travel time matrix.

Fig. 4.3　Map of major highways in Northern Taiwan

Table 4.2 The travel time between interchanges in a day time (sec)

Travel time (sec)	Keelung side to Keelung	Keelung to Badu	Badu to Dahua System	Dahua System to Wudu	Wudu to Xizhi System	Xizhi System to Donghu
00:00	44	45	112	69	142	174
01:00	43	45	107	66	142	178
02:00	46	46	112	69	143	177
03:00	46	48	119	74	153	181
04:00	46	48	117	73	156	192
05:00	45	48	122	75	158	196
06:00	45	48	116	72	154	189
07:00	46	47	115	72	154	182
08:00	43	46	114	71	149	189
09:00	44	46	115	70	147	187
10:00	44	46	113	71	151	186
11:00	44	46	114	71	152	188
12:00	45	47	115	71	151	187
13:00	45	47	116	72	152	188
14:00	47	50	123	80	175	208
15:00	48	51	129	94	230	257
16:00	46	49	128	104	277	268
17:00	49	52	132	98	245	274
18:00	48	51	131	101	254	234
19:00	48	50	125	80	172	197
20:00	47	49	122	76	160	193
21:00	46	48	118	73	156	189
22:00	44	46	116	72	154	187
23:00	43	45	111	69	145	179

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4.1.2 Incident data

Base on the built network and the relevant setting of travel time, now we can start to test the model with the history dispatch data. Four periods of peak hours and one period of non-peak hours (the last case) are selected for the case study because relatively more incidents occurred in these periods. We can use these cases to test whether the model can efficiently assign incidents to response teams and reduce the total response time.

Table 4.3 shows the information of these five cases. We know that the freeway may have different traffic pattern on weekdays and weekends so that incidents on different days of week are selected to help us analyze the influence of traffic patterns, and we also choose Case 5 to further compare the difference between peak period and non-peak period.

Table 4.3 The information of studied cases

Case number	Date	Day of week	Time of day	Incident number
1	2017/01/21	Monday	18:00~20:00	13
2	2016/10/29	Friday	18:00~20:00	14
3	2015/12/19	Saturday	12:00~14:00	17
4	2016/09/25	Sunday	12:00~14:00	15
5	2017/01/02	Monday	12:00~18:00	16

Table 4.4 represents an example of dispatch data of Case 1, which contains information about incident number, freeway number, direction, mileage (location of the

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incident), incident type, time of incident reported, assigned response team, response time and processing time. The freeway number is associated with N1, N2, N3 and N1V. N1 is Freeway 1 and so on. N1V is the elevated part of Freeway 1. There are two directions for each freeway segment in the study area, either south and north bound or west and east bound. Based on the information of freeway number, direction and mileage, we can first locate incidents. According to the time of incident reported, the incidents in the same minute are divided into the same time stage, and the position and status of response teams are deduced by the interval between two time stages and the former dispatch result. Moreover, there are five incident types considered: pavement, animal intrusion, accident, scattered object and traffic support. The processing time is unknown before the response team finishes clearing the incident in reality. Hence, we need to estimate the processing time for each incident type from the historic data. As a result, we use average processing time as the estimated processing time for each type of incident; the average processing time is listed in Table 4.5.

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Table 4.4 The history dispatch record data

2017/01/21 Monday 18:00~20:00								
Incident number	**Freeway number**	**Direction**	**Mileage**	**Incident Type**	**Receiving time**	**Response team**	**Response time (min)**	**Processing time (min)**
1	N1	N	49	Scattered Objective	06:11 PM	C	6	101
2	N1	S	55	Accident	06:11 PM	C	16	91
3	N3	S	81	Accident	06:13 PM	F	5	31
4	N1V	N	69	Scattered Objective	06:16 PM	D	20	6
5	N1	N	3	Traffic support	06:22 PM	A	46	0
6	N1	S	15	Accident	06:22PM	A	15	7
7	N3	N	3	Traffic support	06:39 PM	A	47	12
8	N1	S	77	Scattered Objective	06:46 PM	D	72	3
9	N1	S	81	Scattered Objective	06:46 PM	D	79	2
10	N1	N	63	Accident	06:51 PM	D	26	30
11	N1V	N	29	Accident	06:55 PM	B	30	19
12	N2	N	13	Accident	06:58 PM	C	16	44
13	N3	N	15	Scattered Objective	07:02 PM	E	6	18
Response team: A-Xizhi, B-Wugu, C-Zhongli, D-Hukou, E-Mucha, F-Kansai								

Table 4.5 Estimated incident processing time

Incident type	Average processing time
Pavement	4
Animal intrusion	3
Accident	11
Scattered objective	3
Traffic support	9

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4.2 Case Analysis and Comparison

The incidents are divided into different stages according to the time of incident reported, and one stage may have more than one incidents as several incidents may be reported in the same minute. Some parameters are set before testing each case. The value of priority order for each level equals one in five cases, and the value of reassignment filter is set to be ten. After setting constant parameters, we input the information of dispatch data as the case scenario into the model stage by stage, record the dispatch results and the response time of each incident, and finally calculate the total response time and make tables for these five cases. In the result of each case, for example Table 4.6, the column “time of incident reported” is marked by different colors for different stages. The column “dispatched response team” displays that which response team clears the incident. The column “actual response time” shows the response time of the incident calculated from historic dispatch data. We will compare “dispatched response team” and “actual response time” with the results of dynamic model. The column “dynamic model” presents the response teams dispatched by the model and the simulative response time, and it is marked by red, blue and green. Red means that the result of the proposed model is worse than actual response time of the incident, blue means even, and green means better.

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We can compare the test results with the response team and response time in reality to show the effectiveness of the proposed model. The results also reveal the capability that the model can dispatch multiple incidents at the same time and provide better suggestions. To test the computational efficiency of the model, we also test the cases with different numbers of incidents.

4.2.1 Monday peak period

Table 4.6 displays the result of the case study for Monday peak period. Incident 1 and 2 are located in Response team C's duty range, but the directions of the two incidents are opposite. We set the time to turn the direction by interchanges is five minutes, and the total response time is shorter if Response team B is dispatched to support Response team C in the model. It shows that the time to turn the direction can influence the decision of the model, and we need to set this time more precisely if we have the relevant data at each interchange.

Incidents 5, 6 and 7 are located in Response team A's duty range, and if all incidents are assigned to Response team A, Incidents 5 and 7 have to wait the process to clear Incident 6 for a relatively long time. Hence, the model assigns Response team E to support Response team A, which can reduce over half of the response time.

When Incidents 8 and 9 occur, Response team D may have cleared Incident 4 and

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is on the way back to its stationary point. Incidents 8 and 9 are located in the duty range of Response team D, but the position of Response team D is actually close to Response team C. Therefore, the model dispatches Response team D to Incident 8 and Response team C to Incident 9 to minimize the response time for the incidents in this stage.

Incident 10 is close to the edge between the duty ranges of Response team C and D in the next stage. The best way is to dispatch Response team C to clear Incident 10 directly and reassign Response team D to clear Incident 8 and 9, so the model reassign Response team C to Incident 10 and Response team D to Incident 9. This result proves that the model may reassign response teams if it can reduce response time significantly. Nevertheless, we can also find that Incident 12 has a longer response time dispatched in the result of the proposed model because Response team C is dispatched to handle Incident 10, which has a longer processing time. It shows the effect may be uncertain due to the randomness of incident occurrence, so we need to observe the effect over a certain operation horizon instead of comparing the effect in one stage (for one incident).

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Table 4.6 The result of Monday peak period

Incident number	Freeway number	Direction	Mileage	Incident Type	Time of incident reported	Dispatched response team	Actual response time (min)	Processing time (min)	Estimated processing time (min)	Dynamic Model			
										Original Assignment		Reassignment 1	
										Response team	Response time (min)	Response team	Response time (min)
1	N1	N	49	Scattered Object	6:11:33 PM	C	6.12	1.33	3.00	C	6.75	C	6.75
2	N1	S	55	Accident	6:11:36 PM	C	15.77	3.12	11.00	B	17.68	B	17.68
3	N3	S	81	Accident	6:13:00 PM	F	5.87	10.42	11.00	F	4.54	F	4.54
4	N1V	N	69	Scattered Object	6:16:02 PM	D	20.75	6.18	3.00	D	18.41	D	18.41
5	N1	N	3	Traffic support	6:22:01 PM	A	46.13	0.07	9.00	A	6.99	A	6.99
6	N1	S	15	Accident	6:22:27 PM	A	15.52	6.50	11.00	E	14.31	E	14.31
7	N3	N	3	Traffic support	6:38:58 PM	A	46.13	0.05	9.00	A	10.45	A	10.45
8	N1	S	77	Scattered Object	6:46:29 PM	D	73.48	2.1	3.00	D	19.17	D	19.17
9	N1	S	81	Scattered Object	6:46:29 PM	D	78.62	2.18	3.00	C	19.34	D	19.34
10	N1	N	63	Accident	6:51:12 PM	D	26.25	30.25	11.00			C	14.52
11	N1V	N	29	Accident	6:55:15 PM	B	30.32	0.37	11.00			B	7.69
12	N2	N	13	Accident	6:58:16 PM	C	15.88	7.77	11.00			F	28.44
13	N3	N	15	Scattered Object	7:02:31 PM	E	6.23	0.15	3.00			E	7.53
				Total response time			387.07			Total response time			177.68
Response team: A-Xizhi, B-,Wugu C-Zhongli, D-Hukou, E-Mucha, F-Kansai													

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4.2.2 Friday peak period

In this case study, Table 4.7 shows that Incident 1 and 2 are close to the stationary point of Response team B, but Response team B may be processing other incidents before six o'clock in the evening. Hence, the dispatcher assigns Response team A to support Response team B to clear Incident 2. This reveals that the dispatcher has the power to dispatch a response team to any other response team's duty range to process incidents, but the ways of judgment are different for different dispatchers.

That the response time of Incident 6 is longer than the estimated response time in the model is because the location of the incident is on a ramp of the interchange. The congestion may be serious if an incident happens on a ramp, and the response team may spend more time to arrive at scene, as there is no road shoulder to avoid the congestion.

Incidents from Incident 7 to Incident 12 are a series of traffic support incidents occurring simultaneously, and all incidents located in Response team D' duty range. The dispatcher may consider them as routing works and dispatch all incidents to Response team D, but the model results tend to dispatch Response teams from other places to support Response team D as it can reduce a lot of response time. The model can also schedule Response team D with minimum response time when several incidents dispatch to it. The dispatcher can take the schedule results as reference to speed up the

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decision time and increase the efficiency of incident response.

Yet, Incident 14 occurs in the duty range of Response team C when the team is dispatched to handle Incident 10 in the model. As a result, the model assigns Response team D to clear Incident 14 instead. It displays that the model not just dispatches a response team to support another on one-sided, it can also dispatch response teams to support each other in every stage to achieve the benefit of Central Dispatch. With this way, the decision supporting system keeps stable when facing complicated situations.

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Table 4.7 The result of Friday peak period

Incident number	Freeway number	Direction	Mileage	Incident Type	Time of incident reported	Dispatched response team	Actual response time (min)	Processing time (min)	Estimated processing time (min)	Dynamic Model	
										Response team	Response time (min)
1	N1	S	33	Accident	2017/10/29 18:03	B	42.63	8.07	11.00	B	3.00
2	N1	S	31	Accident	2017/10/29 18:22	A	18.13	0.05	11.00	B	15.65
3	N3	S	35	Accident	2017/10/29 18:24	E	12.22	12.55	11.00	E	15.00
4	N3	N	69	Traffic support	2017/10/29 18:41	F	6.70	1.52	9.00	F	13.29
5	N1	N	49	Accident	2017/10/29 18:43	C	9.02	21.35	11.00	C	8.00
6	N1	N	62	Accident	2017/10/29 18:54	C	47.18	0.42	11.00	C	15.05
7	N1	S	71	Traffic support	2017/10/29 19:03	D	70.13	12.85	9.00	F	42.08
8	N1	S	85	Traffic support	2017/10/29 19:03	D	84.83	3.55	9.00	B	41.02
9	N1	N	83	Traffic support	2017/10/29 19:03	D	40.38	14.88	9.00	D	24.93
10	N1	S	97	Traffic support	2017/10/29 19:03	D	101.10	3.98	9.00	C	32.10
11	N1	N	91	Traffic support	2017/10/29 19:03	D	17.70	1.20	9.00	D	11.07
12	N1	N	87	Traffic support	2017/10/29 19:04	D	26.28	6.38	9.00	D	15.50
13	N1	N	69	Animal intrusion	2017/10/29 19:38	D	28.73	0.10	3.00	D	12.00
14	N1	N	57	Accident	2017/10/29 19:43	C	13.97	32.02	11.00	D	22.66
					Total response time		519.02		Total response time		271.35
Response team: A-Xizhi, B-,Wugu C-Zhongli, D-Hukou, E-Mucha, F-Kansai											

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4.2.3 Saturday peak period

In Table 4.8, we find that both the dispatcher and the model dispatch the same response team to process Incident 1 to Incident 5, but the response time of Incident 4 and Incident 5 has gaps between dispatch record and the model results. The historic dispatch data does not provide the routes of response teams so that we do not know what causes response teams spend more time to the location of incidents. We check the travel time from the positions of the response teams to the locations of the incidents and find the estimated response time of the model is appropriate, so we do not have to validate our results.

Incident 6 is dispatched to Response team C in the model result because it has less response time on the network we built. The processing time of Incident 6 is almost one hour so if there are incidents happening in the duty range of Response team C, the model should dispatch other response teams to help Response team C.

Incident 7 and 8 locate in Response team B's duty range, but the model assigns Response team A to process Incident 7 in order to shortening the response time. In next stage, Incident 9 occurs at Response team C's duty range, but response team C is busy handling Incident 6 so that the model assigns Response team D to clear Incident 9 at first. However, there are some incidents happening in the duty range of Response team

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D in the next two stages, so the model reassigns Response team A to clear Incident 9. We also observe that if the Response team D is not dispatched to clear Incident 9 first, it can handle Incident 10 to 12 in a short routes without the support of response team B. That is why incident 9 to 12 takes more time in the model.

The response time of Incident 12 and 13 in the model is less than historic dispatch data because Response team F is available. The dispatcher assigns Response team F to process Incident 6 so that it needs more time to arrive at the location of Incident 12 and 13.

The model dispatches Response team E to handle Incident 15 and 17 as Response team A is supporting Response team C, and Response E can process Incident 17 on the way back to its stationary point so the response time is just zero. In addition, Response team C is assigned to support Response team E when Response team E was supporting Response team A.

The results in this case study shows that even though a response team is assigned to support another team when an incident occurs in its duty range, the model can decide to call it back or dispatch other response teams to support it.

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Table 4.8 The result of Saturday peak period

Incident number	Freeway number	Direction	Mileage	Incident Type	Time of incident reported	Dispatched response team	Actual response time (min)	Processing time (min)	Estimated processing time (min)	Dynamic Model			
										Origin		Reassignment1	
										Response team	Response time (min)	Response team	Response time (min)
1	N1V	N	69	Scattered Object	12:06:52 PM	D	8.52	0.07	3.00	D	13.48	D	13.48
2	N3	N	0	Animal intrusion	12:15:31 PM	A	8.82	0.03	3.00	A	10.76	A	10.76
3	N3	N	15	Traffic support	12:21:56 PM	E	6.10	33.22	9.00	E	7.05	E	7.05
4	N1	N	15	Accident	12:28:19 PM	A	35.37	0.07	11.00	A	10.43	A	10.43
5	N1	N	67	Scattered Object	12:31:01 PM	D	36.15	1.93	3.00	D	11.14	D	11.14
6	N3	N	43	Scattered Object	12:34:44 PM	F	19.83	57.37	3.00	C	23.41	C	23.41
7	N1	N	25	Scattered Object	12:54:33 PM	B	42.83	3.78	3.00	A	19.29	A	19.29
8	N1V	N	31	Scattered Object	12:56:45 PM	B	12.35	5.08	3.00	B	6.61	B	6.61
9	N2	N	5	Accident	1:04:52 PM	C	15.62	0.18	11.00	D	9.29	A	46.57
10	N1	S	71	Traffic support	1:13:33 PM	D	3.30	0.98	9.00			B	30.45
11	N1	S	85	Traffic support	1:14:18 PM	D	14.73	0.03	9.00			D	23.43
12	N1	S	97	Traffic support	1:14:54 PM	D	28.17	0.05	9.00			D	31.57
13	N3	S	63	Traffic support	1:15:25 PM	F	50.70	4.53	9.00			F	22.19
14	N3	S	77	Traffic support	1:15:55 PM	F	61.92	0.03	9.00			F	37.97
15	N1	S	21	Accident	1:16:36 PM	A	16.20	0.02	11.00			E	19.41
16	N3	N	31	Scattered Object	1:28:38 PM	E	28.63	0.05	3.00			C	33.38
17	N1	N	19	Scattered Object	1:45:54 PM	A	11.25	0.03	3.00			E	0.00
					Total response time		400.48				Total response time		347.44
Response team: A-Xizhi, B-,Wugu C-Zhongli, D-Hukou, E-Mucha, F-Kansai													

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4.2.4 Sunday peak period

In Table 4.9, the model assigns Response team C to handle Incident 1 and 2 because even though Incident 2 has to wait until Incident 1 is cleared, the response time is less than dispatching Response team F to handle Incident 2. Then, the model assigns Response team B to support Response team C to process Incident 4 and 5. That reveals the model is flexible and effective to minimize the response time in each stage.

The model dispatches Incident 7 and 8 to Response team B because it is the closest response team just finishing its work. At the same time, Response team C is assigned to handle Incident 9 on the elevated road, which takes more travel time to reach. In the next stage, Incident 10 also occurs on the elevated road, but it takes much time to travel from Incident 9 to Incident 10 as the interval of interchanges is relatively longer on the elevated freeway. Therefore, the model dispatches Response team D to process Incident 10 to reduce response time, and we also discover the response time of Incident 12 is longer in the model result because of the dispatch result in the previous stage.

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Table 4.9 The result of Sunday peak period

Incident number	Freeway number	Direction	Mileage	Incident Type	Time of incident reported	Dispatched response team	Actual response time (min)	Processing time (min)	Estimated processing time (min)	Dynamic Model	
										Response team	Response time (min)
1	N3	S	56	Scattered Object	12:04:16 PM	F	28.10	2.03	3.00	C	16.90
2	N2	S	15	Scattered Object	12:05:37 PM	C	13.95	0.41	3.00	C	10.30
3	N1	S	21.7	Scattered Object	12:13:23 PM	A	13.05	0.30	3.00	A	11.46
4	N1	S	42	Scattered Object	12:21:28 PM	C	30.16	1.02	3.00	B	8.9
5	N1	S	49	Scattered Object	12:22:36 PM	C	36.87	2.18	3.00	B	14.02
6	N3	N	16.4	Scattered Object	12:28:20 PM	E	14.25	0.25	3.00	E	5.54
7	N1	S	51	Scattered Object	12:41:52 PM	C	24.02	1.96	3.00	B	15.03
8	N1	S	49.3	Scattered Object	12:42:50 PM	C	18.99	0.35	3.00	B	13.73
9	N1V	N	52.6	Scattered Object	12:43:42 PM	C	44.03	0.33	3.00	C	25.00
10	N1V	N	50	Scattered Object	12:44:29 PM	B	74.15	0.40	3.00	D	13.48
11	N3	N	89.2	Scattered Object	1:13:09 PM	F	10.25	1.20	3.00	F	14.72
12	N!	S	88.2	Scattered Object	1:23:48 PM	D	13.69	0.30	3.00	D	29.39
13	N1	N	87	Traffic support	1:48:22 PM	D	15.30	4.42	9.00	D	13.18
14	N1	N	83	Traffic support	1:49:00 PM	D	23.23	10.20	9.00	C	24.15
15	N3	N	68	Traffic support	1:49:43 PM	F	12.41	1.69	9.00	F	10.17
					Total response time		372.45		Total response time		225.97
Response team: A-Xizhi, B-,Wugu C-Zhongli, D-Hukou, E-Mucha, F-Kansai											

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4.2.5 Monday non-peak period

The period of this case study is longer than other case studies as the incidents in non-peak period are disperse. The average of the intervals between two incidents in this case is longer than previous cases so that each incident response team could handle incidents in their duty range and do not need other response team to support it. By comparing historic dispatch data and the result of the model, we found that only the dispatch team of Incident 5 is different. Incident 5 is on the border of Response team D and Response team F, and the model judged that dispatching team D is a little faster in the simulative freeway network. This case shows that the dispatch result of our model is close to the result assigned by dispatcher in non-peak period.

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Table 4.10 The result of Monday non-peak period

Incident number	Freeway number	Direction	Mileage	Incident Type	Time of incident reported	Dispatched response team	Actual response time (min)	Processing time (min)	Estimated processing time (min)	Dynamic Model	
										Response team	Response time (min)
1	N1	S	27.4	Scattered Object	2017/1/2 11:42	B	7.97	12.57	3.00	B	11.67
2	N1	S	28	Animal intrusion	2017/1/2 12:34	B	11.53	0.50	3.00	B	12.89
3	N1	S	35.7	Scattered Object	2017/1/2 12:36	B	16.60	0.05	3.00	B	14.18
4	N3	S	41.3	Accident	2017/1/2 12:53	E	25.08	37.35	11.00	E	16.62
5	N3	N	97.9	Traffic support	2017/1/2 13:49	F	15.17	0.05	9.00	D	14.36
6	N1	N	24.2	Scattered Object	2017/1/2 13:50	B	10.83	1.05	3.00	B	8.02
7	N1	S	17	Accident	2017/1/2 13:56	A	5.93	0.12	11.00	A	8.51
8	N3	N	0	Accident	2017/1/2 14:15	F	18.18	0.15	11.00	F	18.73
9	N1	S	99.6	Scattered Object	2017/1/2 14:47	D	22.87	0.87	3.00	D	11.00
10	N1	S	91	Animal intrusion	2017/1/2 15:06	D	10.82	0.67	3.00	D	22.60
11	N3	N	65.6	Accident	2017/1/2 16:00	F	16.93	7.02	11.00	F	13.59
12	N1	S	24.2	Accident	2017/1/2 16:10	B	15.17	0.00	11.00	B	13.03
13	N2	N	10	Accident	2017/1/2 16:49	C	3.32	0.02	11.00	C	15.00
14	N3	N	63.4	Accident	2017/1/2 17:00	F	22.48	0.03	11.00	F	16.71
15	N3	S	21.7	Scattered Object	2017/1/2 17:04	E	5.87	0.73	3.00	E	3.00
16	N1	N	25.1	Accident	2017/1/2 17:52	B	9.22	3.28	11.00	B	8.38
					Total response time		217.97		Total response time		208.29
Response team: A-Xizhi, B-,Wugu C-Zhongli, D-Hukou, E-Mucha, F-Kansai											

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4.3 Sensitivity Analysis

In the previous section, we have already tested the proposed model for the five cases. In this section, we further test the parameters including priority order and reassignment filter investigate their effects in the dynamic dispatch model. This study conducts sensitivity analysis on these parameters to compare the differences and to assure the parameters are functional as expected in the model.

4.3.1 Priority Order

Some incident types like vehicle overturning and crash have high priority to be cleared in real time because they may cause serious congestion on freeways. In this test, we take Case 3 “Saturday peak period” (see Table 4.8) as the control group where all incidents have same priority order, and we set the experimental group where the accident type has a high priority order, the pavement and scattered object types have a median priority order, and the animal and traffic support types have a low priority order. The value for the high priority order is ten, five for the median priority order and one for the low priority order. Table 4.12 demonstrates the total response time in both the control and experimental groups. The response time of high priority incidents reduces 28.95 percentages, but the response time of median and low-priority incidents increases

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3.51 and 22.44 percentages, respectively. The test result listed in Table 4.12 can be compared with the result of Case 3, and we find that the model does not reassign Incident 9 from Response team D to Response team A because Incident 9 has high priority and should be processed first. This decision influences Incidents 10, 11 and 12, which have a low priority order, because response team D is dispatched to handle incident 9. Hence, the model dispatches response team B to support Incidents 10, 11 and 12, and it increases the response time for these three incidents as the travel time is relatively longer than the case that response team D is assigned.

This result indicates that adjusting the value of priority order in the model can effectively reduce the response time and make response teams to arrive at a part of locations of high priority incidents faster. Conversely, some incidents with low priority are cleared slower, and their response time increases. The incidents with median priority are less influenced by the changed value of the priority order in this test.

Table 4.11 Response time of control group and experimental group

Priority Order	Control Group (Case 3)		Experimental Group		Change Rate (%)
	value	Response time	value	Response time	
high	1	76	10	54	-28.95
median	1	114	5	118	3.51
low	1	156	1	191	22.44

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Table 4.12 The result of priority order test

Incident number	Freeway number	Direction	Mileage	Incident Type	Time of incident reported	Dispatched response team	Actual response time (min)	Processing time (min)	Estimated processing time (min)	Priority order	Dynamic Model	
											Response team	Response time (min)
1	N1V	N	69	Scattered Object	12:06:52 PM	D	9	0	3	median	D	13
2	N3	N	0	Animal intrusion	12:15:31 PM	A	12	0	3	low	A	11
3	N3	N	15	Traffic support	12:21:56 PM	E	7	33	9	median	E	7
4	N1	N	15	Accident	12:28:19 PM	A	35	0	11	high	A	10
5	N1	N	67	Scattered Object	12:31:01 PM	D	36	2	3	median	D	11
6	N3	N	43	Scattered Object	12:34:44 PM	F	20	57	3	median	C	23
7	N1	N	25	Scattered Object	12:54:33 PM	B	43	4	3	median	A	19
8	N1V	N	31	Scattered Object	12:56:45 PM	B	13	5	3	median	B	7
9	N2	N	5	Accident	1:04:52 PM	C	16	0	11	high	D	30
10	N1	S	71	Traffic support	1:13:33 PM	D	3	1	9	low	B	30
11	N1	S	85	Traffic support	1:14:18 PM	D	15	0	9	low	B	43
12	N1	S	97	Traffic support	1:14:54 PM	D	29	0	9	low	B	52
13	N3	S	63	Traffic support	1:15:25 PM	F	51	5	9	low	F	22
14	N3	S	77	Traffic support	1:15:55 PM	F	62	0	9	low	F	33
15	N1	S	21	Accident	1:16:36 PM	A	18	0	11	high	A	14
16	N3	N	31	Scattered Object	1:28:38 PM	E	33	0	3	median	E	15
17	N1	N	19	Scattered Object	1:45:54 PM	A	12	0	3	median	A	23
					Total response time		414			total response time		365
Response team: A-Xizhi, B-,Wugu C-Zhongli, D-Hukou, E-Mucha, F-Kansai												

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4.3.2 Reassignment filter

Due to the uncertainty of incident occurrence, sometimes dynamic model will reassign response teams to handle incidents in order to minimize the total response time in that stage. However, changing incident assignment frequently may confuse workers of response teams and even take more time to change to other routes. Hence, this model adds a punishment time in objective function, and the punishment time can be increased by setting a higher value of reassignment filter parameter. In this test, we take Case 1 "Monday peak period" (see Table 4.6) as the control group where the value of reassignment filter is ten, and we set the experimental group whose the value of reassignment filter is one hundred.

Table 4.13 shows that the total response time increased with the higher value of the reassignment filter, and we find that Incident 9 is not reassigned by the model in

Table 4.14. Also, there are no incidents reassigned in stages before the stage of Incident 9, as the punishment time of changing routes is very high. Incident 10 is assigned to Response team B because Response team C is dispatched to support Response team D. Thereby, Response team B needs to spend more time to arrive at Incident 10. Moreover, Incident 11 is located in response team B's duty range, so the model has no choice but assigns Response team A to support Response team B. The

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change of this parameter causes chain reaction and increases the total response time significantly in the test.

	τ=10	τ=100
Reassignment times	1	0
The number of reassigning response team	1	0
Total response time	178 minutes	216 minutes

Table 4.13 The total response time of reassignment filter test

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Table 4.14　The result of reassignment filter test

Incident number	Freeway number	Direction	Mileage	Incident Type	Time of incident reported	Dispatched response team	Actual response time (min)	Processing time (min)	Estimated processing time (min)	Dynamic Model	
										Origin	
										Response team	Response time (min)
1	N1	N	49	Scattered Object	06:11:33 PM	C	6	1	3	C	7
2	N1	S	55	Accident	06:11:36 PM	C	16	3	11	B	18
3	N3	S	81	Accident	06:13:00 PM	F	5	10	11	F	5
4	N1V	N	69	Scattered Object	06:16:02 PM	D	20	6	3	D	18
5	N1	N	3	Traffic support	06:22:01 PM	A	46	0	9	A	7
6	N1	S	15	Accident	06:22:27 PM	A	15	6	11	E	14
7	N3	N	3	Traffic support	06:38:58 PM	A	47	0	9	A	10
8	N1	S	77	Scattered Object	06:46:29 PM	D	72	2	3	D	19
9	N1	S	81	Scattered Object	06:46:29 PM	D	79	2	3	C	19
10	N1	N	63	Accident	06:51:12 PM	D	26	30	11	B	34
11	N1V	N	29	Accident	06:55:15 PM	B	30	0	11	A	29
12	N2	N	13	Accident	06:58:16 PM	C	16	8	11	F	28
13	N3	N	15	Scattered Object	07:02:31 PM	E	6	0	3	E	8
					Total response time		384		Total response time		216
Response team: A-Xizhi, B-,Wugu C-Zhongli, D-Hukou, E-Mucha, F-Kansai											

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4.4 Summary of Findings

Table 4.15 displays that the results of the model are all better than the original results, and Fig. 4.4 shows the cumulative response time of each case. These tests verifies that the proposed model can dispatch response teams with shorter response time to handle incidents in the whole operation horizon compared with the results in the dispatch data. The model also effectively determines appropriately whether to assign a response team to support another response team when the response team is busy. Even though there are new incidents occurring in the duty range of the response team which is on the way to support another response team, the model may reassign the response team or dispatch other response team to process the new incidents in order to reduce the response time in the new stage. This model can enhances the functionality of Central Dispatch System as response teams can support each other without constraining response teams by their duty ranges and still maintain the stability of the incident response system.

In Fig. 4.4, the blue line is the actual cumulative response time, the red line is the model cumulative response time. we find that the differences between actual and model cumulative response time have tendencies to grow bigger in Cases 1, 2 and 4, but the differences of cumulative response time is not significant in Cases 3 and 5. The reason

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for Case 3 is that some response teams are assigned to support other response teams, but new incidents occur in their duty ranges in the following stages. Hence, the response teams need to spend extra time to go back, and the model reassigned other response teams to handle the previously assigned incidents. In future work, we should consider the risk that response teams support others, as there is possibility that incidents may happen in their duty ranges before they come back. The reason for Case 5 is that the intervals between stages are long, so dispatched response teams have already cleared former incidents when a new incident occurs. There is less chance to improve the dispatch solution.

In addition, when there are multiple incidents, the model assigns and scheduled them to response teams in only a few seconds. We test the computational efficiency of the model by a series of numbers of incidents, as presented in Table 4.15 and Fig. 4.5. In Fig. 4.5, the growth rate of computation time becomes steeper when the number is more than sixteen. However, the largest number of incidents the model processes in this study is only seven; it takes about five seconds to solve the model. This test confirms that the model can provide high quality suggestion in each stage for the dispatchers in real-time operation.

Other than shortening the total response time, we discover that the model can support the consideration to adjust decisions in light of varying priority for different

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types of incidents and to limit the frequency of reassignment as shown in the sensitivity analysis. In the analysis, some incidents with high priority order are considered first, so the response time of these incidents declines. On the contrary, incidents with low priority order may be processed later. Additionally, increasing the reassignment filter will decrease the times of reassignment and may increase the total response time, but this way can stabilize the dispatch results and avoid response teams changing routes too frequently. These tests reveal that the dispatchers could input these parameters according to the condition at the scene or their own considerations to adjust the dispatch strategies.

Table 4.15 Total response time of study cases

Study Case	Real total response time (min)	Model total response time (min)	Reduce rate (%)
Monday peak period	387.07	177.68	54.10
Friday peak period	519.02	271.35	47.72
Saturday peak period	400.48	347.44	13.24
Sunday peak period	372.45	225.97	39.33
Monday off-peak period	217.97	208.29	4.44

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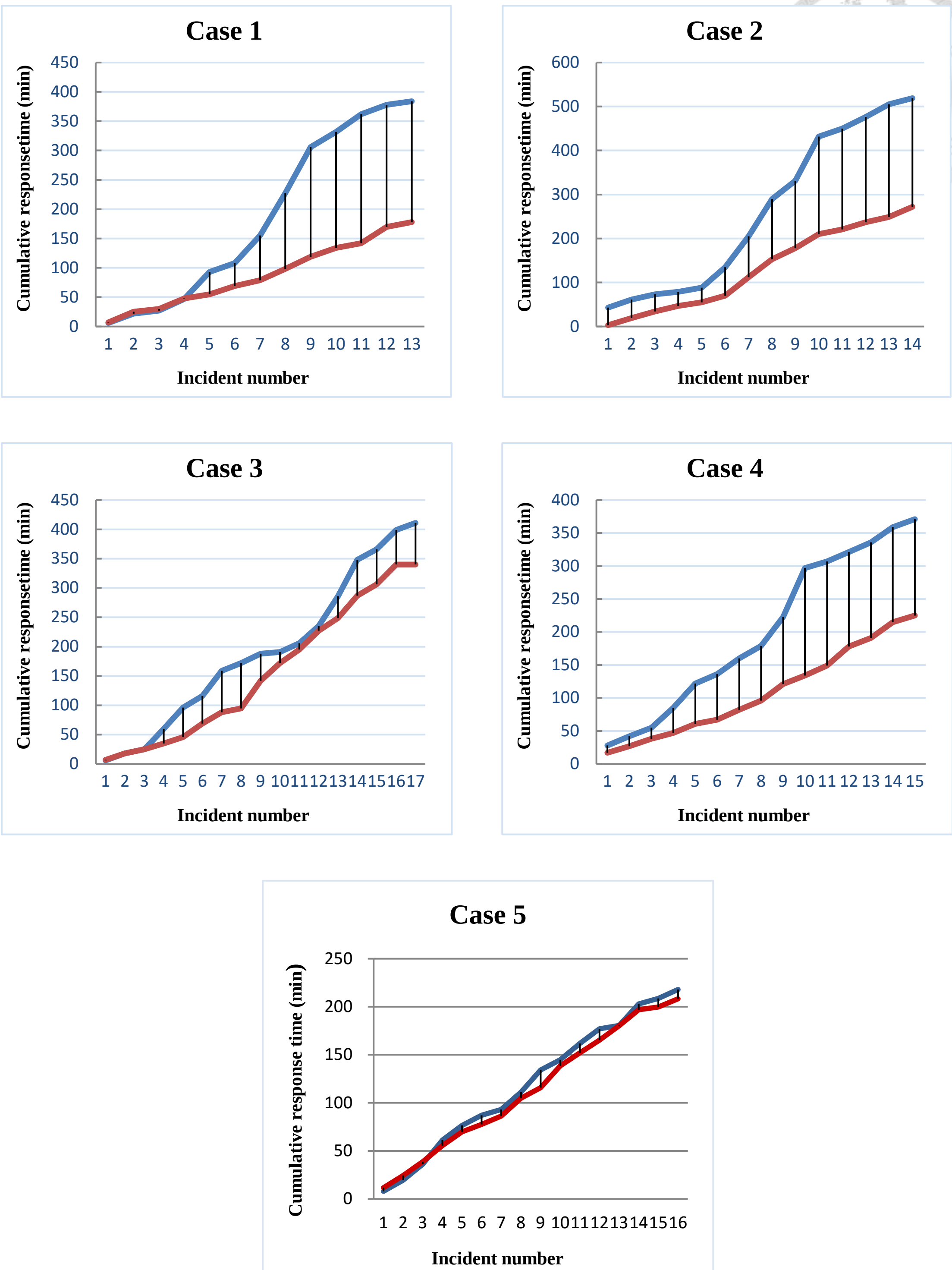

Fig. 4.4 The chart of cumulative response time of five cases (red-model cumulative response time/ blue-actual cumulative response time)

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Table 4.16 Computer processing time of the model

Incident number	Computer processing time (sec)
1	0.14
2	0.48
3	1.01
4	1.76
5	2.71
6	3.84
7	5.19
8	6.62
9	8.49
10	10.54
11	13.10
12	15.62
13	18.58
14	21.36
15	24.96
16	28.10
17	37.80

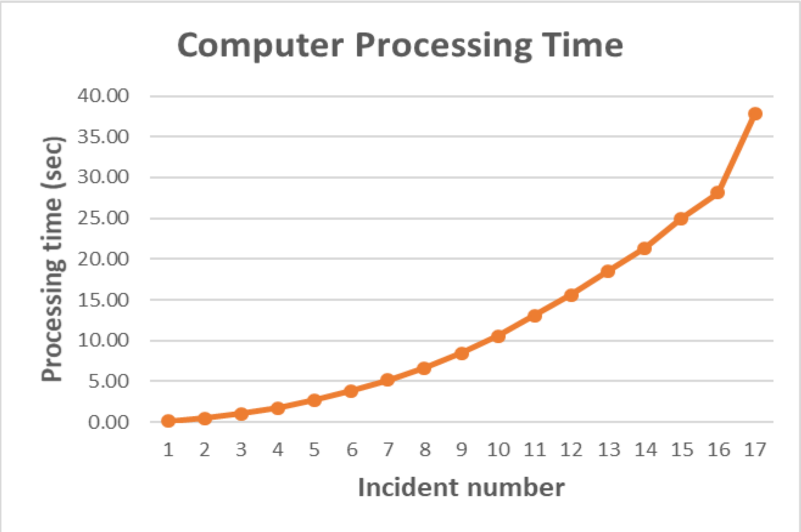

Fig. 4.5 Computer processing time of the model

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Chapter 5 Conclusions

This chapter concludes the research findings by summarizing what we have done in this study, proposing the contributions and limits of this research and indicating some potential directions for future work.

5.1 Research Summary

In this research, we overview the current literature of freeway incident response and identify that the most significant way to improve the efficiency of incident response on freeways can be the optimization of the dispatch decisions. Therefore, this study focuses on proposing the framework of a real-time decision-making support system, and the core of this system is the dynamic dispatch model that schedules the order of incident processing by response teams and the associated routes on each stage. We propose the mathematical model based on the formulation of the vehicle routing problem as its basic assumptions meet the characteristics of freeway incident assignment and it is flexible to add relevant constraints to reduce total response time and reflect the consideration of operational realism. After designing the system framework and forming the model, we use incident dispatch data of the freeway system in northern Taiwan for the case study to make a comparison with current approach of

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response team dispatch and validate the proposed model. In the case study, the simulation freeway network is built and the parameters are set according to the real data. Incidents are divided into stages, and we tested them stage by stage. The parameters of priority order and reassignment filter are also tested to illustrate their effects in the model. Finally, the research findings from the analysis of the test results are summarized in the next section.

5.2 Contributions

(1) This study developed a mathematical model based on the vehicle routing problem to assign incidents to response teams in the real-time operation context. Whereas the model needs to be reformed by updating parameters when a new stage begins, we propose the framework of a dispatch system for freeway incident response and procedure to implement the model. Following the proposed framework and the simulation network of the freeway system in northern Taiwan, we can test the model with the historic dispatch data and verify our model by the results.

(2) The aim of this study is to develop a dynamic dispatch model to minimize total response time for incident response in each stage. Minimizing total response time of incidents is different from minimizing total operation time of response teams. The response time starts at the occurrence of the incident and ends at the clearance of the

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incident. A response team handles incidents by order so that incidents cleared later have longer incident response time. Therefore, we use the minimax method which minimizes the cost of the response team which has the maximum operation time, to attain the defined objective. The case study proves that the minimax method provides enhanced efficiency of incident response compared with the strategy to send all incidents to the nearest response team. It is highlighted that the model can balance travel time and workload across response teams and provide better suggestions to the dispatcher.

(3) The positions of response teams and the traffic conditions of the freeway change with time, and new incidents may occur along the proceeding of the operation horizon. The dynamic dispatch model considers both new incidents and incidents in the previous stages to form a new network, and the model can reassign some incidents if it can significantly reduce response time. In the case study, a response team may be assigned to support another response team, while some incidents occurs in its duty range later. Hence, the model may reassign the response team to clear these new incidents and dispatch other response teams to support the originally assigned incidents. It presents that the proposed dynamic model can support decision making by accounting for the evolving situations in different time stage.

(4) The time cost of the links in the virtual network has to be precisely estimated so that the model can better address the needs to handle the cases with multiple incidents. This

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study divides the time cost into three parts and proposes the mathematic formulation to calculate the operation time of each response team. This approach clearly describes the procedure of incident response, and the benefit is that the proposed model can precisely estimate the response time of each incident and schedule incidents for response teams.

(5) We test the model with the sensitivity analysis on the priority order and reassignment filter parameters to illustrate different dispatch strategies for different types of incidents and situations. Based on sensitivity analysis, we assure that some of the dispatch results change when the parameters are adjusted. The response time of some incidents with high priority decreases while some incidents with low priority have to wait for a longer time to be processed if the difference of weights of priority order become larger. Besides, the number of reassignment decreases if a larger number for the reassignment filter is adopted. The results indicate that the dispatch strategy of the model is flexible as the parameters can be calibrated according to the practical needs.

(6) The formulation complexity of the model affects computational efficiency. The equations in the model are all formulated to be linear to reduce the time to solve the problem. According to the case study, solving the model with ten incidents in a stage takes only a few seconds. If the dispatch support system is established on the dispatch platform, the dispatchers can obtain dispatch suggestions in real time, which can be particularly helpful for the busy hours with multiple incidents to be assigned.

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5.3 Future Research

(1) To develop the model, we need to input the parameters of incident processing time. However, incident-processing time is unknown until an incident is cleared, so this parameter has to be estimated a priori. In this research, the estimated incident processing time is the average incident processing time according to the types of incidents, and the estimation precision can be improved by further investigating the distribution of incident-processing time. It is suggested that future research can explore models appropriate to predict incident-processing time and the factors which may influence it.

(2) Response teams will turn back to their stationary points after clearing incidents, but currently the time to return is not considered in the model. The time will be longer if the response team is assigned to support another response team (for the incidents occurring in other duty ranges), and it may take more response time to handle new incidents located in its original duty range in the next stage. In addition, the distance between two interchanges affects the time to return. Response team may have to spend extra time to return if the distance between two interchanges is relatively long, and it may increase the incident response time, as well. Such risk that may increase incident response time should be more explicitly factored in future work.

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(3) In future research, the prediction of travel time can be more accurate if real-time GPS data and Google Map API are better integrated. The positions of response teams and locations of incidents can be tracked by GPS devices and input to the model. On the other hand, the Google Map API provides real-time traffic on freeways, which may be further developed as the module to predict travel time between two points. Combining these technologies, the control center can better reflect real traffic conditions in the model and test to prove the effectiveness and real benefit of it.

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