Evaluation of Resource Allocation Strategies
in Incident Management Systems

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Abstract. Considering an incident management system (IMS), this paper focuses on how to use existed resources efficiently to reduce the average incident duration. Traffic Management Centers (TMC) have two ways to manage incidents, namely, waiting until an incident is detected and then dispatching a traffic flow restoration unit (TFRU) from the depot to clear them, or having TFRUs out running along specific routes and clear the incidents they run into. We examine the effects of these two options using computer simulation technology. Based on simulation results, response surfaces are constructed demonstrate the impacts of these two alternatives on the incident duration, and an equilibrium point between them is determined.

Keyword: Incident Management Systems, response surface methodology, simulation, FSP

1. Introduction

Traffic incidents cause bottlenecks on the roadway, slowing down or even stop the traffic. When an incident occurs, it blocks one or more lanes and a queue starts building up on the upstream of the incident due to the reduction of the capacity. It is now widely accepted that these congestion and congestion-related problems can be reduced by the proper use of efficient incident management systems. A traffic flow restoration unit (TFRU) is responsible for the restoration of traffic. In practice, a TFRU may be a single tow-truck or a fleet consisting of multiple vehicles including tow-trucks, ambulances and so forth. Here, we abstract TFRU as a single unit. Generally, Traffic Management Centers (TMC) have two ways to manage incidents, namely, waiting until an incident is detected and then dispatching a TFRU from the depot to the site of the incident, or having TFRUs out driving along specific routes and clear the incidents they run into. The second method is usually called Freeway Service Patrol (FSP) in practice. The expectation of FSP is that if the TFRUs are driving around on the freeway they are likely to detect and respond to an incident faster than any other means.

A mix of these two options coexists in a real incident management system. We make two assumptions about the regular operations of these two options. First, if the incident is not on the FSP route, then the incident have to be cleared by the TFRUs dispatched from the depot, i.e., FSP TFRU cannot leave the patrol route. Second, if the incident is on the patrol route, shortest path rule is applied to determine which party is

responsible for the incident. If the distance from the closest depot to the site of the incident is shorter than the distance from the current location of patrolling TFRU, then TFRUs in that depot is responsible for the incident; otherwise, patrolling TFRU is responsible for the incident. Pros and cons of these options are summarized in table 1.

Table 1. Depot vs FSP

	Pros	**Cons**
Depot	1. Cover all the incidents occurred over the network; 2. Less operational cost, i.e., less gas consumption, less maintenance cost, etc.	1. Slower response than FSP due to longer detection time and travel time.
FSP	1. Shorter incident detection time and travel time.	1. Benefit only the incidents occurred on the patrol route. 2. Higher operational cost.

If all TFRUs are busy, newly detected incidents would be put in the waiting list. This happens when either all the TFRUs are busy, or all depot TFRUs are busy and the new incident is not on a patrol route with FSP TFRUs. When a TFRU becomes available, it will be dispatched to the incident which ever occurs first.

Increasing attention in the literature has been drawn to the incident management systems. Zografos *et al.* (1993) proposed an analytical framework that can minimize the freeway incident delays through the optimum deployment of TFRU, which is shown to be an effective tool that can model and evaluate the effects of deployment of TFRU on overall freeway incident delays. Recognizing the highly stochastic nature of traffic and incident management operations, Pal and Sinha (2002), introduced a simulation model that can be used for designing a new freeway service patrol as well as improving the operations of existing programs. Petty (1997) examined the incident detection techniques and evaluates the Freeway Patrol Service in his thesis. Petty et al (1997) presented a methodology for determining where to place FSP tow trucks so as to maximize the expected reduction in congestion. Ozbay *et al.* (2004) proposed a mixed-integer programming model with probabilistic constraints to address the TFRU dispatching problem with consideration given to the stochastic resource requirements at the sites of the potential incidents. All these models failed to address the combined effects of two incident response strategies: depot and FSP.

With a limited number of available TFRUs, increasing the fleet size of FSP forces to downsize the TFRU assigned to the depots. It is important to determine the equilibrium point between "waiting" and "patrolling" to achieve the highest effectiveness of the IMS. In this study, we use a methodology combined with computer simulation and Response Surface Methodology (RSM) to study these two incident clearance options and the interactive effects between them. Perry and Gupta (2001) applied RSM to toll plaza design for the transition to electronic toll collection (ETC) at tool roads, bridges and tunnels, optimum tollbooth allocation between traditional tollbooth and ETC is obtained for a given mix of vehicles. Gartner (1976) and Montgomery et al (1972) used RSM to study the traffic signal settings. Fowkes et al (1998) proposed a methodology which

permits optimal strategic transportation models to be found by the use of a limited number of model runs together with regression modeling of the resulting response surface.

The remainder of this paper is organized as follows. First, we introduce the problem and the methodology. Then, simulation models used to collect data are briefly described. Based on the simulation results, we demonstrate the impact of adjustable factors under different traffic situations using response surfaces. This paper concludes with a brief summary of results.

2. Problem Definition

Consider the daily operations of the incident management system implemented for the South Jersey highway network depicted in Figure 1. There are seven major highways in this area. For analytical purposes, we divide these highways into short sections using hypothetical nodes. A patrolling route consists of connected sections. The patrolling TFRUs travel along the route repeatedly until they encounter an incident. After the incident is cleared, the TFRUs resume their patrolling duties along the route. In this study, we only consider single depot and single patrolling route case. Consider an existed IMS, where the location of the depot and the patrol route are both fixed. To improve the efficiency of such a system, we focus on the following factors that remain adjustable, namely, the number of TFRUs assigned to the depot, and the number of TFRUs assigned to FSP. Table 2 summarizes these factors as candidate independent variables for the response surface we are going to construct. The values in the parenthesis in the last column specify the range of these variables.
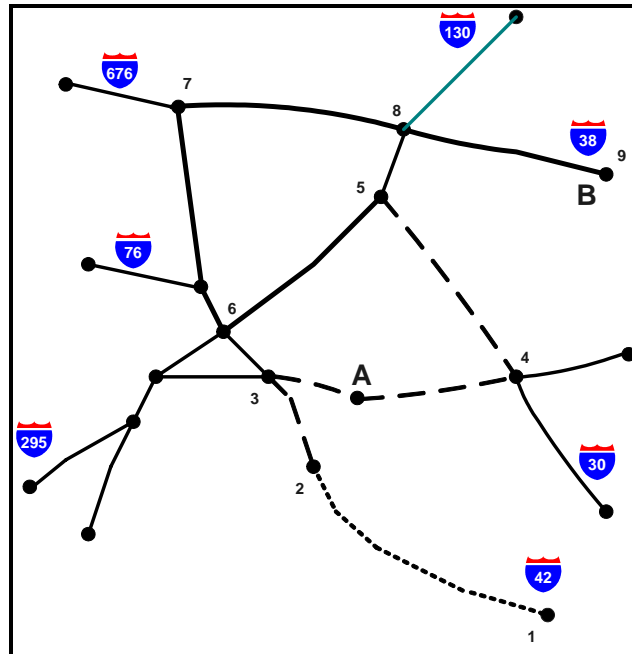

Figure 1 South Jersey roadway network

Table 2 Definitions of candidate control variables

Variables	Meaning	Type
x	The number of TFRUs in the depot.	Integer (1~9).
r	The number of TFRUs in the FSP.	Integer (0~4).

The incident duration is the time elapsed between the occurrence and the clearance of an incident, which can be divided into four components, detection time, dispatching time, travel time and clearance time. Since one of the critical tasks of an IMS is to clear the incident as quickly as possible, we choose average incident duration as the response variable, which is defined as the total incident duration during a simulation run divided by the total number of incidents that have occurred in the simulation run. The reasons for doing so are twofold. Firstly, the incident duration is an important measure for evaluating the effectiveness of an incident management system. The shorter is the incident duration, the smaller adverse impact this incident will cause. Secondly, the incident duration is easier to measure directly compared to the other measures, such as pollution, gas consumption and traffic delay.

Comparing to the depot option, FSP could save valuable detection, dispatching and travel time by cleaning incidents occurring along its patrol route, but it covers a smaller region. The goal of this study is thus to demonstrate the importance of these two distinct incident management strategies in terms of reducing average incident duration, and come up with a strategy to allocate limited resources between depot and FSP optimally to maximize the reduction in average incident duration.

3. Methodology

Response surface methodology is a collection of mathematical and statistical techniques that are useful for modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize the response (Myers and Montgomery, 1995). Most applications of RSM have three phases, which are summarized in Figure 2.
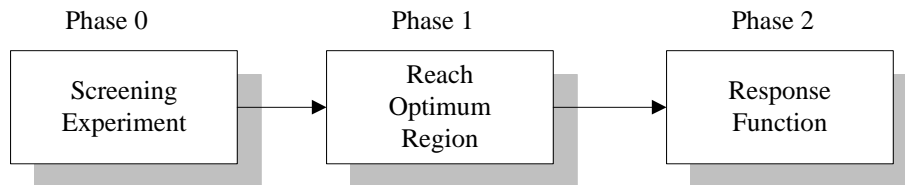
Phase 0	Phase 1	Phase 2
Screening Experiment	Reach Optimum Region	Response Function

Figure 2 Three Phases of RSM

To start the RSM procedure, an experiment is designed in a small sub-region of the input variable (i.e., factor) space, and a first-order linear model is used to represent

the data obtained from the response. Factorial or fractional factorial experiments are usually performed to fit this linear model. If the goal is to minimize the response, then a search along the estimated direction of the steepest descent is conducted. This method aims at climbing down the response surface rather than exploring the whole region, and its success depends on the assumption that the ultimate minimum can be reached via such a path of descent (Davies, 1956). Joshi et al. (1998) pointed out that the standard RSM approach uses a pure gradient search that can be prone to zigzagging and slow to converge. Moreover, there is no information available from previous iterations that could be successively employed to provide improved search directions, and the process is essentially memoryless. To enhance the performance of search process, they proposed a deflection strategy, which attempts to capture the second-order curvature effects over successive iterations. As the search moves down the surface, it is assumed that at some point, there will be an evident curvature, after which the response no longer improves or starts increasing. At this point, an accurate model approximating the true response function within a small region around the optimum is constructed.

In our case, since all candidate independent variables are discrete and vary in a very small range, it is possible to use a surface to fit the whole variable space. The response data for combinations of various factors are collected using a simulation software package, which is developed at the Rutgers Intelligent Transportation Systems (RITS) Laboratory using C ++ programming language.

4. Simulation Model

The simulation model consists of three major modules: Incident Generation, Traffic Simulation and Incident Response Simulation. The relationships between these modules are shown in Figure 3.
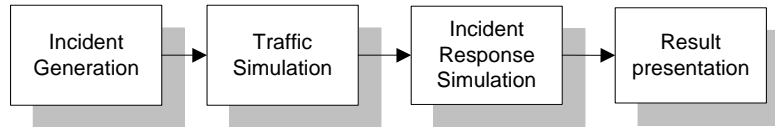

Figure 3 The simulation model

By assuming the interarrival times of incidents are independent and identically distributed exponential random variables (Richard *et al*., 1981), we generate incident arrivals in accordance with Poisson processes. Higher arrival rates represent worse traffic situations. The locations of the incidents are assumed to be randomly distributed among the nodes. For those incidents not located on any patrolling route, we introduce an extra detection time, which is assumed to be normally distributed with mean equal to fifteen minutes. Our traffic simulation module is developed based on the cell transmission model proposed by Daganzo (1994). We need to run traffic simulation for any newly occurred incident in order to obtain the link travel times under the impact of that incident. As it was mentioned earlier, an incident could be either cleared by the TFRU dispatched from a depot or the patrolling TFRU. The travel time t_t is shortest travel time from the current location of the TFRU to the site of incident based on the updated link travel times. Once

the assigned TFRU arrives at the incident site, it has to stay on the scene until the incident is cleared. After the incident is cleared, the assigned TFRU returns to the depot if it is dispatched from the depot, or resumes its patrolling service if it is a FSP TFRU.

After all of the incidents generated by the incident generation module are cleared, the average incident duration is calculated by dividing the sum of all incident durations by the total number of incidents generated.

5. Response Surfaces

Let y denote the response variable, the average incident duration in seconds. Let f denote the average number of incidents that might occur over the roadway network during a given time period. We assume there can be up to nine TFRUs in the depot and four TFRUs in the FSP due to the budget constraint. Note that the number of vehicles in the patrolling service could be zero, which means no patrolling service is available in the incident management system. We run simulations for incident frequency levels varying from one incident to nine incidents during the simulation period, which represents the scenarios from the light traffic condition to the heavy traffic condition. Fifty replications of each scenario are run, providing data points to develop the response surface.

5.1 Dispatching TFRU from Depots

We devote this section to examining the effects of depot, including the effects of the number of TFRUs, dispatching policies and the location of the depot.

Since the average incident duration decreases quickly as the number of TFRUs in the depot, x, increases, we are interested in the effects of x values at various traffic conditions. In the following tests, we do not consider the patrolling service, while the number of TFRUs and the frequency of incidents vary from one to nine. The total number of scenarios is 9×9. Fifty replications of each of the 81 scenarios are run, providing 4050 independent data points that are used to develop the response surface. The collected data demonstrates a negative exponential relationship between the average incident duration and the number of TFRUs. The average incident duration decreases very fast initially. But, as the number of TFRUs continues to increase, the rate of decrease slows down, and it does not decrease much after the number of TFRUs reaches five. From this observation, we assume that the average incident duration follows an exponential model which has the form, $y = ce^{g(x,f)} + d$, where $g(x,f) = k_x x + k_f f$, and c, d, k_x and k_f are the parameters need to be determined. Fitting a nonlinear regression model to data is slightly more involved than fitting a linear model. We use SAS$^{\text{TM}}$ (version 8.2) software to fit this model. Newton fitting algorithm is applied. After 12 iterations, the convergence criterion is met, and the estimated parameters and the goodness of fitness are shown in tables 3 and 4.

Table 3 Regression analysis results

Parameter	Estimate	Approx Std Error	Approximate 95% Confidence Limits	
c	3370.5	298.3	2776.6	3964.4
k_x	-0.9482	0.0455	-1.0388	-0.8575
k_f	0.2490	0.0100	0.2291	0.2690
d	3246.2	53.9343	3138.8	3353.6

Table 4 Goodness of fitness

Source	DF	Sum of Squares	Mean Square	F Value	Approx Pr > F
Regression	4	1.8288E9	4.572E8	910.70	<.0001
Residual	77	10312989	133935		
Uncorrected Total	81	1.8391E9			
Corrected Total	80	3.7624E8			

Similar to the R^2 value used to measure the quality of fit of linear regression models, we use psudo-R^2 value defined as follows to measure the goodness of our fitness:

$$R^2_{pseudo} = 1 - \frac{SS_{Residual}}{SS_{Total\ corrected}}.$$ (1)

Inserting the values presented in table 4 into equation (1) yields R^2_{pseudo} = 0.9726, which demonstrates the goodness of our fitted model. Thus, the model depicts the relationship between the average incident duration and the number of TFRUs in the depot and the incident frequency as

$$y = 3370.5e^{-.9482x + 0.2490f} + 3246.2.$$ (2)

Based on this model, we present in Figure 4 the three-dimensional graph of the average incident duration, with the number of TFRUs in the depot and the incident frequency as the independent variables. In Figure 4 we can see that the average incident duration decreases fast as the number of TFRUs increases. This decrease is much more

pronounced at higher incident frequency levels. Increasing the number of TFRUs beyond four does not help reduce the average incident durations.
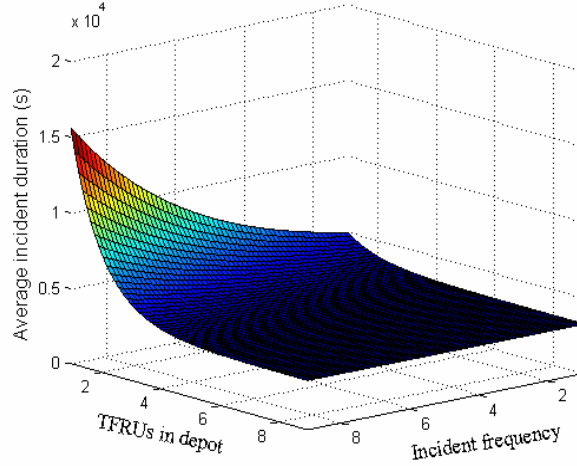

Figure 4 Response surface with incident frequency and response vehicles

Since relocating the depot is expensive and unrealistic in most situations, we do not select the location of the depot as an independent variable in our model. Still, we would like to investigate the importance of the depot location by comparing the response of the two possible depot locations: location A, which is in the center area of the roadway network, and location B, which is at the edge of the network. Locations A and B are marked out in Figure 1. For each location, we test four levels of incident frequency and change the number of response vehicles. The resulted model for location B is

$$y = 4843.2e^{-.9754x+0.2548f} + 3654.5 . \tag{4}$$

We compare the effect of these two depot locations in Figure 5, from which we can see that the average incident duration increases significantly if we move the depot from A to B, especially when the incident frequencies are high. This is because the average travel time from the center of the roadway network to the sites of incidents, which is distributed randomly over the network, is shorter than the average travel time from the edge of the network to the sites of incidents.
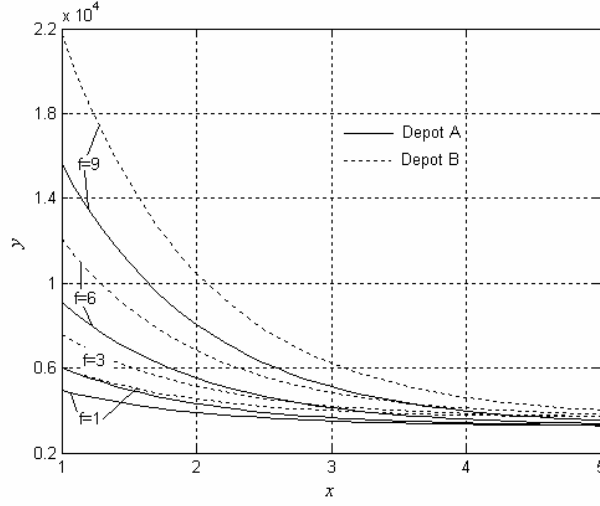
**Figure 5** Effect of the location of the depot

5.2 Effects of FSP

Currently, a typical patrol route in South Jersey covers all of I-76, I-676 and NJ42. To show the effect of the FSP, we change the number of TFRUs on this patrolling route, while keeping one available TFRU at the depot ($x = 1$). Similarly, we use nonlinear regression analysis and obtain another model to show the impact of the number of TFRUs in the FSP,

$$y = 1894.7e^{-.6537r+0.2438f} + 5320.0.$$ (5)

The response surface of TFRUs in the FSP and the incident frequency is depicted in Figure 6 (a). The 2-D curves for specific *f* values are shown in Figure 6 (b). The average incident duration decreases significantly when the number of TFRUs used by FSP increases, especially in the cases with high incident frequency level. This demonstrates the importance of FSP in the incident management systems.

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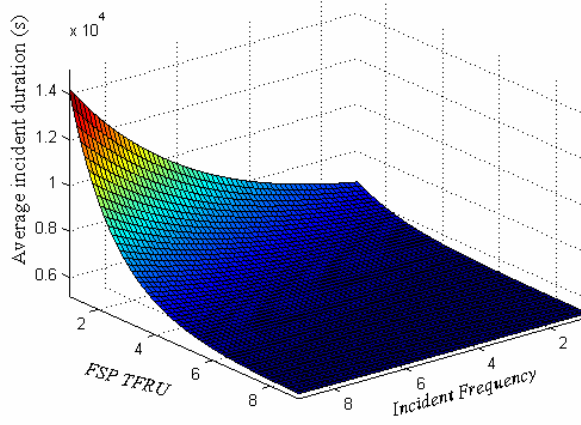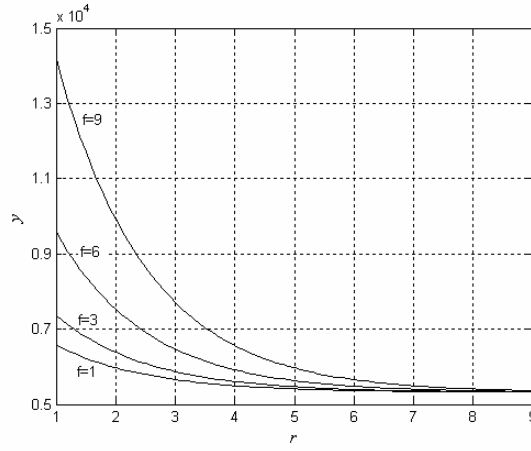
(a) Response surface

(b) Curves for specific f values.

Figure 6 Response surface of FSP and incident frequency with $x = 1$

In our single patrol route case, we also check the effect of the length of the patrolling route on the incident duration. We compare three patrol routes, which are illustrated in Figure 1 and the realistic patrol route. The short patrol route is depicted in dotted line, from node 1 to node 2. The patrol route with middle length extends the patrol route to node 5, which is the combination of the dotted line and dashed line. The longest patrol route extends the middle length route along node 5, 6, 7, 8, to 9. We evaluate the performance of different patrol routes under the same traffic condition with $f = 6$, while keeping one service vehicle available in the depot. We increase the number of TFRUs assigned to these patrol routes from one to nine, and the curves of average incident clearance duration for each route are shown in Figure 7. It can be seen that, for the scenario considered in this study, the longer patrol route results in shorter average incident clearance duration. And, the current typical patrol route is a reasonable choice, which is outperformed only by the longest patrol route chosen in our simulation studies.
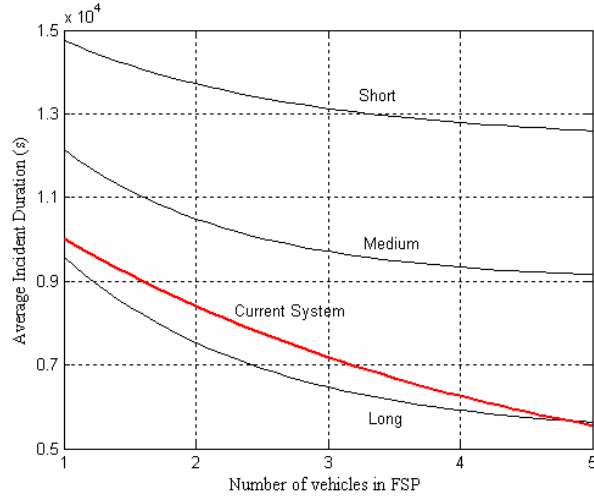
Figure 7 The effect of patrol route length

5.3 Combination of FSP and Depots

In this section, we demonstrate the combined impact of the number of TFRUs in the depot and the number of TFRUs on the current patrol route on the average incident duration. We use the model

$$y = ce^{g(x,r,f)} + d \qquad (6)$$

to fit our data, where $g(x,r,f) = k_x x + k_r r + k_f f + k_{xr} xr$ and k_{xr} is the parameter of the interaction of TFRUs in the depot and FSP. Same as previous sections, we use Newton fitting algorithm. After 17 iterations, the convergence criterion is met. The values of estimated parameters and the goodness of fitness are summarized in Tables 5 and 6.

Table 5 Fitting results

Parameter	Estimate	Approx Std Error	Approximate 95% Confidence Limits	
c	4725.1	289.3	4156.7	5293.5
k_x	-0.8543	0.0331	-0.9192	-0.7894
k_r	-0.1681	0.0301	-0.2273	-0.1089
k_f	0.2462	0.00606	0.2342	0.2581
k_{xr}	-0.1071	0.0262	-0.1587	-0.0556
d	3329.3	29.7064	3270.9	3387.6

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Table 6 Goodness of fitness

Source	DF	Sum of Squares	Mean Square	F Value	Approx Pr > F
Regression	6	1.034E10	1.7232E9	1493.53	<.0001
Residual	480	1.275E8	265631		
Uncorrected Total	486	1.047E10			
Corrected Total	485	2.1111E9			

Using the values in Table 6, equation (1) yields $R^2_{pseudo} = 0.94$, which demonstrates that the model fits the data very well. Thus, the resulted model depicted the combined effect of FSP and depot is

$$y = 4725.1e^{(-0.8543x-0.1681r+0.2462f-0.1071xr)} + 3329.3. \tag{7}$$

If the number of TFRUs in the depot and FSP are allowed to increase freely, Figure 8 shows the response surface when $f = 3$. Increasing the number of TFRUs in the depot or increasing the number of TFRUs in the FSP reduces the average incident duration significantly.
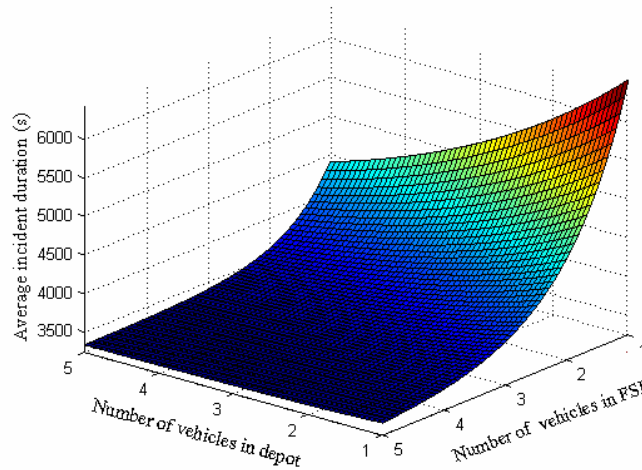
Figure 8 Response surface of FSP and TFRU with f=3

In practice, due to budget limitations, the total number of TFRUs is almost fixed. With limited resources, decision-makers need to choose between keeping TFRUs waiting at the depot or running along the patrol route to improve the performance of the incident

management systems. If we let v denote the total number of TFRUs the TMC can afford due to the budget constraints, and r of them are supposed to be assigned to the patrol service, then the number of TFRUs left in the depot is $x = v - r$. Increasing the number of TFRUs in the depot would force TMC to downsize the FSP fleet. In equation (6), the average incident duration is an increasing function of the value of $g(x, r, f)$. Smaller $g(x, r, f)$ leads to shorter incident duration. If we keep $v = 15$, it can be seen that $g(x, r, f)$ reaches its minimum value neither at $x=0$ nor $x=v$. This shows that both FSP and depot are important incident management approaches. Assigning all of the available TFRUs to the depot or FSP leads to longer incident durations.

6. Discussion

This paper presents a methodology combined with computer simulation and response surface methodology to address how to use existing resources efficiently to minimize the average incident durations. The results demonstrate that both depot and FSP are important to the incident management systems. For the depot service, besides the number of TFRUs, the locations of the depot and the dispatching policies also have significant effects on the average incident duration. In a transportation network with randomly distributed incidents, the depot should be close to the center of the network as possible. Patrolling service plays an important role in the incident response, especially when the incident frequency is relatively high. For a fixed number of FSP vehicles, longer patrolling route gives better results, since longer routes cover larger service areas. If the total number of TFRUs assigned to depot and FSP remains constant, then the decision makers need to determine an optimal allocation of the total response vehicles between these two options.

The approach discussed in this paper, which combines computer simulation and RSM techniques together, has many potential applications in practice. After the response surface is constructed, it is easy to find the best strategies for various scenarios. For example, for the sample network presented in the previous sections, it is easy to obtain the optimum number of TFRUs in depot and FSP, while avoiding running time-consuming simulation in the future.

Acknowledgement

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