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Freeway service patrol deployment planning for incident management and congestion mitigation

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ABSTRACT

This paper investigates the problem of deploying freeway service patrols to detect, respond to and clear traffic incidents in two settings, deterministic and stochastic. The deterministic setting assumes that there is only one scenario of incident occurrence and, in the stochastic counterpart, there are many scenarios, each of which occurs with a probability. The main objective of both problems is to minimize the total incident response time. Rather than minimizing the expected total response time, the stochastic model minimizes the expected total response time over the high-consequence scenarios instead. In both settings, the deployment problem can be formulated as a mixed-integer nonlinear optimization problem, a hard class of problem to solve. To obtain solutions in a reasonable amount of time, three heuristic algorithms are proposed. In particular, one makes use of the dual information, another employs a neighborhood search technique and the third uses simulated annealing, a meta-heuristic algorithm. Numerical experiments based on data from Sioux Falls demonstrate that all three algorithms provide solutions with a significant reduction in total response time without using an excessive amount of CPU time.

1. Introduction

Traffic congestion is one of the most severe problems that threaten the economic prosperity and the quality of life in many societies. There are two main types of congestion, recurring and incident-related. Recurring congestion occurs on a regular basis, e.g., due to insufficient road capacity during peak hours. On the other hand, incident-related congestion happens when an incident such as an accident or a stalled car brings traffic to a crawl. In 2005, about 25% of congestion in the US is incident related (FHWA, 2005).

In practice, alleviating incident-related congestion often involves detecting, responding to and removing the traffic incidents with the goal of restoring the road or highway capacity as safely and quickly as possible (see, e.g., Logi and Ritchie, 2002; Zhang and Taylor, 2006; Lan and Huang, 2006). One key component in incident management to integrate the three activities (detecting, responding and removing incidents) is freeway service patrols (FSP). Such a program divides a network of freeways into a set of non-overlapping patrol beats, each of which consists of connected freeway segments (very often both directions) between 10 and 20 miles long. A number of tow (or FSP) trucks are then assigned to patrol each of these beats. As they travel back and forth along their beats, these trucks will stop to clear any incident they encounter. Clearing an incident requires, e.g., changing flat tires, offering gasoline to stranded motorists, and removing vehicles that

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cannot be made operational to designated areas (Petty, 1997). Each FSP truck essentially functions as an emergency response unit that detects, responds to, and clears the incidents without being dispatched by a central command or headquarters.

Across the US, the number of municipalities or agencies with a FSP program is significant. With an annual budget of more than $40 millions, the one in California employs 300 tow trucks and covers 1400 miles of freeways in eight cities/areas. The program in Florida is smaller. It has an annual budget of approximately $15 millions and uses 111 tow trucks to patrol approximately 1025 miles of freeways in six districts. Most of these programs design their beats and allocate FSP trucks manually. As a result, some programs are cost effective and some are not. When the travel time and fuel savings are considered as benefits, the overall benefit/cost (B/C) ratios for the programs in California and Florida are 5 and 26, respectively (see, e.g., Skabardonis et al., 1998, Hagen et al., 2005). However, the B/C ratio of the program that covers I-75 and SR 924 in District 6 of Florida Department of Transportation is less than one.

Planning FSP programs typically consists of two components, designing patrol beats and assigning tow trucks to them. Traditionally, FSP services are provided by local transportation authorities, such as state departments of transportation, but implemented by private contractors. Given the available funding for the FSP program within a local authority, the total fleet size can be determined by considering potential contracted cost for each truck. The subsequent decisions involve beat design and fleet allocation. A good beat design and fleet allocation can allow a FSP program to significantly reduce the level of incident-related congestion, fuel consumption, and the likelihood of secondary accidents. However, with the astronomical number of combinations to investigate and evaluate, it is generally impossible to manually design a FSP program with, e.g., the largest B/C ratio, in a timely manner. When investigated, the literature on FSP does not offer much assistance. The number of articles addressing FSP is relatively few. Some focus on evaluating FSP system configurations using simulation (e.g., Pal and Sinha, 2002; Ozbay and Bartin, 2003) or developing tools to estimate the benefits of expanding FSP services (e.g., Davies et al., 2004; Khattak et al., 2004; Edara and Dougald, 2007). Others (e.g., Petty, 1997, Yin, 2006, Yin, 2008, Geroliminis et al., 2006) only address the fleet allocation component of FSP planning. In related areas, articles such as Sherali and Subramanian (1999), Ozbay et al. (2004) and references therein discuss location-allocation models for locating emergency response vehicles and determining optimal strategies for locating and dispatching them. These models are not applicable because FSP trucks are not dispatched. Instead, they are mobile emergency response units that independently roam the freeways to detect, respond to, and clear traffic incidents. Similarly, articles on vehicle routing (see, e.g., Toth and Vigo, 2001 and references cited therein) deal with designing the optimal set of routes to serve a given set of customers with the objective of minimizing, e.g., the number of required vehicles, distance traveled, and required labor. On one hand, these objectives are not well suited for FSP for they do not directly lead to a reduction in the level of incident-related congestion, and it is not straight forward to convert the FSP problem into routing problems that consider customers at nodes. On the other hand, searching techniques for finding improved routes in the vehicle routing literature are useful in patrol beat design.

This paper addresses the two interrelated components in planning a FSP program, namely beat design and fleet allocation, in a single integrated model. Assuming deterministic travel time and number of incidents, Section 2 presents a mixed-integer nonlinear program for optimal beat design and fleet allocation. As formulated, the model is large, highly nonlinear and non-convex, making it difficult to obtain an optimal solution. Three heuristic algorithms are thus proposed in Section 3, one making use of the dual information associated with constraints in a relaxed model, another employing a neighborhood search technique (Ahuja et al., 2002) and the third applying a meta-heuristic algorithm known as simulated annealing (e.g., Kirkpatrick et al., 1983). The latter two are implemented in VB.NET framework and the former uses GAMS or General Algebraic Modeling System (Brooke et al., 1992). A numerical example is provided in Section 4 to demonstrate the effectiveness of the formulations and solution algorithms. With insights obtained from the deterministic FSP planning model, Section 5 presents a scenario-based stochastic program for FSP that takes into account the randomness in incident occurrence and its impact on travel times. The stochastic program can be solved by the three heuristic algorithms with some minor modification, which is demonstrated using another numerical example. Conclusions and recommendations for further research are offered Section 6.

2. Deterministic FSP planning model

We let a directed graph, $G(N,A)$, represent a network of freeways, where N and A are the sets of nodes and links in the network. For each link $(i,j) \in A$, t_{ij} and f_{ij} denote respectively the average time it takes a FSP truck to patrol link (i,j), and the total number of incidents on the link during the planning horizon. A typical planning horizon is one year. In this and the next two sections, assume that both t_{ij} and f_{ij} are deterministic and the numbers of patrol beats, B, and tow trucks, V, where $V \geqslant B$, are given. There are two main sets of decisions in developing a FSP plan. One is deciding which freeway segments to be covered by each beat (beat design) and the other is the numbers of FSP trucks to assign to each beat (fleet allocation). Mathematically, let x_{ij}^{b} be a binary variable indicating whether link (i,j) is covered by beat b (i.e., 1 = yes; 0 = no), and v_b, an integer variable, be the number of FSP trucks assigned to beat b. Below is an optimization problem that determines a beat design and fleet allocation with the objective of minimizing the overall average incident response time. We refer to this problem as the deterministic FSP planning problem or DFSPP.