Transportation Research Part C 90 (2018) 134–155

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Locating emergency vehicles with an approximate queuing model and a meta-heuristic solution approach☆

M. Altan Akdoğan, Z. Pelin Bayındır[1], Cem Iyigun*,[1]

Middle East Technical University, Dumlupinar Bulvari No:1, 06800 Cankaya, Ankara, Turkey

ARTICLE INFO

Keywords:
Emergency service vehicles
Vehicle location
Approximate queuing model
Order of districting
Genetic algorithm

ABSTRACT

In this paper, the location of emergency service (ES) vehicles is studied on fully connected networks. Queuing theory is utilized to obtain the performance metrics of the system. An approximate queuing model the (AQM) is proposed. For the AQM, different service rate formulations are constructed. These formulations are tested with a simulation study for different approximation levels. A mathematical model is proposed to minimize the mean response time of ES systems based on AQM. In the model, multiple vehicles are allowed at a single location. The objective function of the model has no closed form expression. A genetic algorithm is constructed to solve the model. With the help of the genetic algorithm, the effect of assigning multiple vehicles on the mean response time is reported.

1. Introduction

Emergency services (ES) are systems that exist to provide a rapid response to people in need of services such as rescue, fire fighting, on-site medical care or transportation to definitive care. ES are a system of components that are vital for its success, such as organizations, transportation and communication networks, emergency centers, trained professionals, and administrators. Having emergencies as the primary concern, the planning of such systems requires significant work to ensure the public receive the best possible care. The literature on emergency services covers important studies that change the dynamics of these systems. Green (2004) review some of the important studies in operational research and management science literature that lead to significant improvements in emergency responsiveness.

Planning of emergency service operations has gained significant importance as governmental authorities impose regulations on the performance metrics of these systems and as new technologies emerge in intelligent vehicle tracking systems. Qin (2012) propose control strategies for traffic signal timing regarding emergency vehicle transition at intersections. Employing novel models to plan emergency service systems stays important for cosmopolitan cities where population continues to increase and planning of these systems becomes harder. Working on these systems in a deeper and more realistic sense is crucial considering the implications on the ever-growing population. Besides the management of these systems, the planning of the physical infrastructure determines a major part in its performance.

In locating ES vehicles, there is more than one criterion to consider, each targeting different performance measures. These could include quantitative or qualitative concerns which give due regard to the view of the decision maker and/or regulations. Such criteria could be the utilization of vehicles, fraction of demand lost, mean response time of the system and investment or operational costs

☆ This article belongs to the Virtual Special Issue on “Advances in Modeling, Simulation and Optimization of Dynamic Network Traffic”.

* Corresponding author.
E-mail address: iyigun@metu.edu.tr (C. Iyigun).

[1] Contributed equally to this work.

https://doi.org/10.1016/j.trc.2018.01.014
Received 20 March 2017; Received in revised form 13 January 2018; Accepted 15 January 2018
0968-090X/

related to the system. Regarding the regulations, the mean response time of the system is the most important measure to be met by the operators of these services. For instance, one of the four national health service institutions of the United Kingdom, NHS (2015) requires 75% of life-threatening medical incidents to be responded to within 8 min. In the literature, there are models with different objectives where the mean response time takes the lead. Aringhieri (2017) perform a review of the vast literature on location planning in emergency medical services (EMS).

With the changing dynamics, the stochastic and dynamic nature of problem inputs such as demand, travel time, and incident handling time can begin to attract more attention in emergency vehicle location problems, depending on the nature of the problem. Gendreau (1971) extends the Double Standard Model (DSM) in Gendreau (1997) by relocating ambulances, where the DSM uses two different time thresholds for coverage. Liu (2016) propose a new double standard model with chance constraints for EMS vehicle allocation. Degel et al. (2004) extend the Maximal Covering Location Problem in Church (1974) with time-dependent variations for the ambulance location problem. Probabilistic models are developed to also consider changing conditions or inputs such as the availability of vehicles and travel times. Daskin (1983) introduces the Maximum Expected Covering Problem for the location analysis of public service facilities. The Maximum Availability Location Problem(MALP) is developed by ReVelle (1989), incorporating vehicle availability into the location problem. Beraldi (2009) use Two Stage Stochastic Programming in locating ambulances to cover demand with a specified reliance.

Queuing Theory is used to assess performance measures in probabilistic facility location-allocation models as well. In this study, we focus on the models that incorporate Markovian property. Larson (1974) was the first to use Queuing Theory in location models. The Hypercube Queuing Model (HQM), proposed by Larson, analyses vehicle location-allocation and districting in emergency response units operated as server-to-customer services. HQM is used to observe the steady-state probabilities of the system and to obtain various performance measures such as travel times and work-loads. The developed model is not used in an optimization approach. Sacks (1994), Brandeau (1986), Iannoni (2007), and Takeda (2007) use HQM as a tool to measure the performance of EMS systems. In the studies of Iannoni (2007) and Takeda (2007), service time variations resulting from the variations in travel times to the demand location are considered insignificant with respect to the sum of variations in set-up time, on-scene service time and travel time back to the vehicle location. Mendonca (2001) extend HQM for different service rates for each server in the system, but keep it the same for intra-district or inter-district responses for the same servers, where HQM is constructed with independent service times from the locations of the calls and responding server. They do not district the regions but assign different service rates for each vehicle. The focus of the study is not to optimize server locations but to assess the mean response time of the system. Halpern (1977) states that the estimations for service times in the study of Mendonca (2001), where variations in the travel times are considered to be of second order, give questionable results where travel time is a significant part of the service time. Morabito (2008) use HQM by defining specific service rates for each server and compare results with a homogeneous service rate assumption.

Iannoni (2008) use a genetic algorithm to find the locations for EMS servers, allowing only one server at a single location while using service rates specific to servers. Iannoni (2009) and Iannoni (2011) use HQM in an optimization environment for location and districting decisions of EMS servers on highways with alternative objectives. Geroliminis (2009) extend HQM and develop a Spatial Queuing Model (SQM) by defining non-identical service times for servers that take into account the demand call's characteristics (inter-district or intra-district response). Order of districting structure is employed to approximate the queuing system by determining a level for responding to demand. This structure deals with the observed busyiness of the system. The level of order of districting implies the order of the farthest vehicle that would respond to a demand call in the system. For example, fixing the order of districting as 3 assumes that a demand call is satisfied by at most the third closest vehicle to the demand region. The assumption is that the fourth closest vehicle never responds to this demand call. This means that order of districting uses an assumption about the observed operational practices without taking into account the traffic intensity of the system. This structure is used to generate rates in SQM. In Geroliminis (2009), the order of districting level is set to a single level of 3 considering the spatial structure of the network without a performance analysis of higher levels. The model also relaxes the predefined server location in HQM. It is used to find the location of a predefined number of service patrol vehicles at possible server locations on a freeway to minimize response time of the system. Dispatching preferences are also not predefined in advance. A heuristic solution approach consisting of a random search followed by the steepest decent method is used to find a near optimal solution. In a different study, Geroliminis (2011) work on a large scale system to deploy emergency response mobile units. They first district the area and find the optimal locations in these districts with the help of a genetic algorithm.

Approximation algorithms are another research approach in the location analysis of ES vehicles. Boyaci (2015) propose approximation algorithms for large scale networks with spatially distributed demand. They propose an Aggregate HQM that is used with a partitioning algorithm to find optimal server locations. Atkinson (2008) propose ad hoc heuristics to assess the probability of loss using algorithms based on the hypercube queuing model. Budge (2009) propose an algorithm to find the dispatch frequencies of vehicles. What sets this apart from previous studies is they allow the locating of multiple vehicles at a single location. Estimation errors are reported on frequencies and utilizations of vehicles. Neither of the studies in Atkinson (2008) and Budge (2009) considers an optimization problem. Different than the above studies, Zhang (2016) focus on the travel time which is an important parameter in location problems and they work on the approximation of the distribution of emergency vehicle travel time.

Our study specifically aims to develop a model to locate a given number of emergency vehicles under a coverage criterion while minimizing the mean response time of a system based on stochastic processes. In this study, we extend the work in Geroliminis (2009), where a single vehicle is allowed at a single location and service times are identical for demand calls from the different regions. Different than Geroliminis (2009), we consider the case where multiple vehicles are allowed and service rates are call-specific, which means that they are specific to the location of demand and the servers.

To deal with the optimization problem at hand, one needs to have a performance evaluation (i.e. a mean response time) under a