ARTICLE IN PRESS

Safety Science xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Safety Science

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

Operating strategies of buses for mass evacuation

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ARTICLE INFO

Keywords:
Evacuation
Bus-based evacuation planning
Radiological emergency
Uncertainty

ABSTRACT

Appropriate bus operating strategies are essential for mass bus dependent evacuation after a disaster strikes. Due to limited availability of buses, buses need to be run continuously, i.e., making multiple trips. It is important to find the efficient operating strategies of buses, including the number and sequence of trips. In order to find the optimal operating strategies, mathematical models have been developed. These models help the emergency manager in determining: (i) the minimum number of buses that must be available at respective depots in order to carry out the evacuation within the available time (ii) the optimal operating strategies of buses in order to minimize the overall evacuation time and (iii) perturbations required in these strategies on account of changes in the evacuation ecosystem due to uncertainties. To test the efficacy of these developed models, a case of a radiological accident is presented.

1. Introduction

Evacuation time estimate (ETE) is considered an important component in emergency resource planning. ETEs are required to develop efficient traffic management and the best response actions during emergencies. The evacuation time depends on many factors including traffic routing, signalization, population needing evacuation, weather condition and time of the day the emergency occurred (Urbanik, 2000). In order to reduce the evacuation time and thus, make the evacuation process effective, various traffic management strategies have been proposed in the literature. These strategies include contraflow, assigning traffic control personnel, and changing signal timings (Murray-Tuite and Wolshon, 2013). Generally, the models used in developing these strategies assume that personal vehicles are used as the mode of transport for evacuation. However, emergency transportation must also be provided to people who do not have access to personal vehicles during emergency. This aspect of evacuation planning has not been studied much (Nawaz et al., 2016). The importance of this aspect of evacuation planning was realized only after Hurricane Katrina (2005). During the hurricane it was observed that there was unnecessary delay in the evacuation process solely because personal vehicles were causing excess congestion on various road segments (Kulshrestha et al., 2011). It was also observed that a number of buses were flooded due to lack of well designed plan for buses during evacuation. Further, evacuation by personal vehicles is logistically complex and expensive (Deghdak, 2016). Therefore, public transit should be encouraged as the choice of transportation over personal vehicles during evacuation. In this paper, we develop a methodology for bus based evacuation plans.

Bus-based evacuation planning consists of a set of geographically scattered demand points i.e. pickup points from where people need to be transported in buses to a safe destination. These pickup points are subjected to time constraints, i.e., the time by which all people present at a given pickup point must be shifted to safe destinations within a specified time available for safe evacuation. Due to different geographical locations of these pickup points, they may have different values of the time available.

In case of limited availability of fleet of buses (which is generally the case), buses are required to run continuously, i.e., make multiple trips between pickup points and their respective safe destination (used interchangeably with shelter). Due to the requirement of multiple trips, it is important to develop optimal operation strategies of the buses in operation. Several deterministic models have been developed in the past (Bish, 2011; Dhingra and Roy, 2015; Kulshrestha et al., 2011) to make these strategies for sequencing bus trips. Various objective functions have been used to determine the optimal operating strategies. Table 1 lists the models developed by different authors and their respective objectives of the evacuation process.

Margulis et al. (2006) develop a deterministic model for evacuation using buses. They consider a scenario of flooding in which the objective is to maximize the number of people evacuated in a given time. However, the limitation of their model is that it can be applied to small areas only. Sayyady and Eksioglu (2010) formulated a similar model with an objective of minimizing the total evacuation time. However, the limitation of their model is that it takes initial trip assignment as an input,

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https://doi.org/10.1016/j.ssci.2018.07.007
Received 30 June 2017; Received in revised form 17 April 2018; Accepted 8 July 2018

Please cite this article as: Bolia, N.B., Safety Science (2018), https://doi.org/10.1016/j.ssci.2018.07.007

Table 1
Objective considered in past for bus-based evacuation planning.

Objective for allocation	Paper
Minimize total evacuation time	Sayyady and Eksioglu (2010)
Maximize number of people evacuated	Margulis et al. (2006)
Minimize operational cost of evacuation	Dhingra and Roy (2015)
Handling Uncertainty in travel time, demand	Goerigk et al. (2015)

something not always justified.

In most of the models, evacuation problem is generally formulated from the perspective of transportation modelling and traffic assignment with no resource scarcity (Dhingra and Roy, 2015). These models do not incorporate factors related to constraints on available time, resource availability and variability of risk. Dhingra and Roy (2015) try to incorporate these aspects in their work and find the optimal allocation of limited resources with the given time constraint. However, their model mainly tries to minimize the operational cost of evacuation rather than minimizing exposure time to the disaster. Another limitation is that being probabilistic, their model may dispatch a bus to a pickup point that is already evacuated.

We believe what is needed instead is an integrated approach to find the optimum number of buses required, their deterministic sequencing operating strategies for different pickup points, given their respective time constraints. Overall, in this study, therefore, effort has been made to develop models for bus operating strategies for mass transit dependent people with resource and time constraints. These proposed models determine the schedule of buses from the depot and subsequent trips of those buses from the shelters to the pickup points. These models can provide the schedule of buses for both, small scale and large scale problems, and require acceptable computational times. To illustrate this, we consider a large scale evacuation problem that needs to be carried out by a fleet of buses. A case study of nuclear accident is used to test the efficacy of the developed model. However, the approach developed is general enough to be valid for cover other kinds of disasters where only a certain time window is available to complete the evacuation.

In case of an emergency, there are various types of uncertainties that arise and need to be incorporated while developing operating strategies for buses. As per Kulshrestha et al. (2011) there can be two types of uncertainties that may affect the schedule of buses: demand side uncertainty and supply side uncertainty. The former one includes uncertainty in the total number of evacuees, location of evacuees, and in the decision to evacuate or not. On the other hand, supply side uncertainties include reduction in link capacity, limited network connectivity, bus breakdown and availability of drivers. Goerigk et al. (2015) propose a robust optimization model to handle these kinds of uncertainties. However, they have not incorporated a constraint on the available time. Therefore, using that as a starting point, we develop a mathematical model to find the minimum change in schedule of the buses required to incorporate uncertainty.

Thus, the model developed in this study can help the emergency manager in the following ways:

- Determine the minimum number of transit vehicles required to evacuate all the transit dependent people.
- Determine the optimal operating strategies of buses in order to minimize the overall evacuation time.
- Calculate the maximum number of round trips any bus can make from pickup points to safe shelters within a given available time.
- Handle uncertainties and provide solutions in acceptable computational time.

The rest of this paper is structured as follows: Section 2 presents details about the bus-based evacuation problem. Mathematical modeling and formulation of bus operating strategies models has been presented in Section 3. The developed solution methodology has been applied to a case study of a nuclear accident in reactors of Kakrapar nuclear plant, Gujarat (India) in Section 4. Results and discussion are presented in Section 5. Section 6 provides a discussion on the insights and usefulness of the models. Section 7 concludes the paper along with some directions for possible future extension of this work.

2. Bus-based evacuation problem

Due to the warning of a disaster, authorities want an area to be evacuated. People present in the given area need to be evacuated to safe destinations. A transportation mode will be required in case the safe destination is far away. There may be people who rely on public transport to reach the safe destination. Therefore, evacuation planning for transit dependent people is required. The bus-based evacuation problem consists of finding the sequence of trips to be followed by the buses in order to evacuate endangered people within the available time. Bus-based evacuation consists of a set of bus yards (where buses are initially located), a set of pickup points and a set of safe destinations i.e. shelters. Buses go from the yard to the pickup points, where evacuees are gathered to board the buses. Buses take them to safe shelters from the pickup points. As stated in Section 1, due to high demand and limited number of buses, multiple trips of buses might be required. This means that once a bus reaches the shelter, it may have to come back to the same or any other pickup point in order to rescue more people. Fig. 1 shows the pictorial view of bus-based evacuation procedure. In the figure, a bus of yard 1 goes to the pickup point *P1*. From P1, it goes to shelter *S1*. Thereafter, it goes to *P3* from shelter *S1*. Likewise, other buses follow their own sequence of pickups. This process keeps on continuing until the demands from all pickup points are fulfilled.

The initial step in solving the bus-based evacuation problem is to know all the pickup points in the hazardous areas and the respective value of demand at those points. Once demand is known, possible shelter sites are identified, and the respective routes to those shelters should be computed. Afterwards, the number of buses available at different depots should be confirmed. By choosing an appropriate objective, the optimal operating strategies can be developed (more details in Section 3). Fig. 2 shows the various steps involved in the bus-based evacuation problem.

3. Mathematical modelling and formulation

Several inputs are required for developing the bus-based evacuation problem. Fig. 3 shows the inputs and outputs of bus-based evacuation models. Based on the scenario, an appropriate objective function should be considered. In order to determine optimal operating strategies for the buses, three mathematical models M1, M2, and M3 have been developed.

As stated earlier in Section 1, the purpose of these models is:

- Model M1 finds the minimum number of buses that must be available at different yards in order to carry out the evacuation in required time.
- Model M2 gives the required sequence of the trips of each bus in order to achieve the desired objective.
- Model M3 is for incorporating uncertainty related to bus failure and change in severity of accident.

The details of the models are explained below. The following assumptions have been made in developing these models:

- The initial locations of different yards (from where buses will be used for evacuation) are known.
- Buses with varying but known capacities will be used for evacuation.