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A risk-based method for planning of bus–subway corridor evacuation under hybrid uncertainties

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ABSTRACT

Emergencies involved in a bus–subway corridor system are associated with many processes and factors with social and economic implications. These processes and factors and their interactions are related to a variety of uncertainties. In this study, an interval chance-constrained integer programming (EICI) method is developed in response to such challenges for bus–subway corridor based evacuation planning. The method couples a chance-constrained programming with an interval integer programming model framework. It can thus deal with interval uncertainties that cannot be quantified with specified probability distribution functions. Meanwhile, it can also reflect stochastic features of traffic flow capacity, and thereby help examine the related violation risk of constraint. The EICI method is applied to a subway incident based evacuation case study. It is solved through an interactive algorithm that does not lead to more complicated intermediate submodels and has a relatively low computational requirement. A number of decision alternatives could be directly generated based on results from the EICI method. It is indicated that the solutions cannot only help decision makers identify desired population evacuation and vehicle dispatch schemes under hybrid uncertainties, but also provide bases for in-depth analyses of tradeoffs among evacuation plans, total evacuation time, and constraint-violation risks.

1. Introduction

Many large cities or conurbations all over the world are surrounded by commuter belts and connection corridors. Parallel roadway and transit lines are usually the main facilities to serve the travel demands from residential zones to employment centers, such as a Central Business District (CBD) [1,2]. Such commuting corridor networks for the cities with dense populations typically contain multiple public transportation modes, such as bus and urban rail. With the growing pressure on urban rail transit systems, potential risks in rail operation will therefore exist and may substantially disturb urban activities. When a rail incident occurs, consequent delay will be inevitable; this can result in adverse socioeconomic implications. For instance, commuters could be late for work or after-work appointments, and business travelers might miss important meetings. In fact, the scale and the impact of incidents may vary. The recent statistical data show that the passenger flow volumes in peak hours have reached more than 25,000 for a corridor line of Beijing urban rail transit; this means that if an incident happens to the line, the local authorities should be responsible for these commuters' delay during peak hours [3]. Although the probabilities of such incident/emergency occurrences are relatively low, their potential impacts on human society (e.g., healthy and economic aspects) justify the importance of evacuation planning corresponding to various emergency scenarios. In particular, under such a traffic corridor incident situation, most evacuees do not have access to private vehicles (e.g., car and taxi) and hence must be evacuated by well-coordinated public transit (bus and urban rail); this can largely alleviate the negative consequences in a safe and timely manner [4].

Over the past several years, the emergency evacuation planning has drawn significant interest and attention. Transportation engineers have also been involved in the development and application of modeling systems to support the development of evacuation plans [5–14]. Among different modes of transportation, the transit system plays a crucial role in all four phases of an emergency management process including mitigation, preparedness,

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response, and recovery. While it is generally acknowledged that public transit can serve as an essential emergency function, it was not until relatively recent years that applying public transit to emergency management gained the mainstream attention of emergency planners [15–17]. The success of using Amtrak in moving over 8000 citizens in anticipation of Hurricane Gustav demonstrated the substantial advantages of using public transit in evacuations [18]. Naghawi and Wolshon once conducted modeling studies of transit bus evacuation operations [19,20]. However, utilization of well cooperated and joint public transit among multiple transportation modes during evacuation events has not received enough attention in literatures [16,21]. Lack of incorporating multiple transportation modes of public transit in emergency plans can be attributed to the following facts: first, utilization of urban public transit need be primarily determined by scales and characteristics of the emergencies; and second, due to the attributes of the transit system itself, not every emergency can be warranted to use multiple public transit services for evacuation [21]. Therefore, it is desired to place more emphases on corridor-incident-based evacuation planning through utilization of well-coordinated public transit.

Moreover, there are a number of complexities embedded within evacuation management systems. Thus, the corresponding uncertainties associated with the evacuation-planning-based modeling efforts are far beyond the capabilities of conventional optimization techniques [22]. Significant contributions have been made by many researchers in addressing system uncertainties [23–29]. For example, Janacek [25] focused on the uncertainty in the vehicle evacuation time in the road network due to unpredictable circumstances, and proposed an approach for tackling the uncertainty based on the theory of fuzzy sets. Yao [26] considered evacuation via surface transportation networks in an uncertain environment, and developed a robust optimization approach based programming model for dealing with demand uncertainty, where hard constraints were guaranteed within an appropriate uncertainty set. Bish and Sherali [24] provided an aggregate-level modeling framework that offered strategic flexibility and utilized a lexicographic objective function that represented a hierarchy of relevant evacuation-based goals; meanwhile, the models with and without congestion in relation to tractability, normative optimality, and robustness under demand uncertainty were compared in the study. However, less attention has been paid to those complexities in traffic corridor incident based evacuation modeling. There is a demand for studies that incorporate various uncertain inputs associated with their complex interactions within a general system management framework to generate robust decision support for evacuation planning with utilization of well-coordinated public transit. These uncertainties may not only be presented as uncertain inputs in terms of travel time, number of evacuees, evacuation capacity and roadway flow, but also be involved in an optimization process under multiple uncertainties, which is more challenging for evacuation decision-making.

Previously, a number of inexact optimization techniques have been developed for dealing with uncertainties for transportation planning, such as stochastic mathematical programming (SMP), fuzzy mathematical programming (FMP), and interval mathematical programming (IMP) [30–38]. Among these programming methods, IMP can be an available alternative because (1) it allows uncertainties to be directly communicated into the optimization process for resulting solutions, (2) it does not lead to more complicated intermediate models, and thus has a relatively low computational requirement, and (3) it does not require distributional information for model parameters, which is particularly meaningful for practical applications since it is typically much more difficult for planners/engineers to specify distributions than to define fluctuation intervals [22,39,40]. However, when parameters in the right-hand sides of constraints are highly uncertain and can be specified with known distribution functions, it may lead to limited practical applicability of the IMP method. For instance, the roadway flow capacity in the constraint's right-hand side may be available to be presented as probability distribution function, so that the congestion risk related to vehicle flow can be reflected. Under this situation, development of a sound optimization tool that can reflect such a complexity of system uncertainty is desired. The chance-constrained programming (CCP) method can effectively reflect the risk of violating (or reliability of satisfying) system constraints under uncertainty [41,42]. The chance-constrained programming method does not require that all of the constraints be totally satisfied. Instead, they can be satisfied in a proportion of cases with given probabilities [43]. Previously, a number of research works for chance-constrained programming methods were undertaken [34,41,42,44–46]. However, few studies have been done to address the uncertainties in the public transit based emergency evacuation management system, which links chance-constrained programming with interval mathematical programming methods.

The objective of the study is to develop a planning model using an interval chance-constrained integer programming (EICI) method to response to the subway incident. The EICI model will collaborate with multiple public transportation modes to address a bus–subway corridor based evacuation problem. Furthermore, the proposed method will couple chance-constrained programming with an interval integer programming model framework. Thus, the EICI method can deal with interval uncertainties that cannot be quantified with specified distribution functions; meanwhile, it can also reflect stochastic features of roadway flow capacity, and thereby help examine the related violation risks of constraints. The developed model will then be applied to an evacuation case study based on bus–subway the corridor incident. Interval solutions will be analyzed and interpreted to generate multiple decision alternatives under various system conditions, and thus help decision makers to identify desired population evacuation and vehicle dispatch schemes under hybrid uncertainties.

2. Methodologies

2.1. Statement of problems

In a typical bus–subway corridor network, transit lines together with parallel roadways provide travel services for commuters [1,47]. Generally, the urban rail system uses its independent facilities while the buses share the same roadway network with the private cars. As for those commuters, they can choose any travel modes in the corridor network. However, due to congestion on roads and travel-time reliability of urban railway systems in the morning and evening rush hours, the rail transit may play a large part in serving commuting travel demand. When an emergency occurs in the rail system, preconceived evacuation strategies should contribute to alleviation of the negative consequences, where the role of buses is critical for supporting the transit-dependent travelers in the evacuation. For example, if a non-notice incident happens to a subway station, the passengers have to get off the train at the nearest turning-back station and make extra transfers to their destinations. Generally, an effective evacuation plan which should be carried out immediately may include: first, shuttle buses can be assigned to provide service between the stations with turning-back lines (Option A), and second, passengers can also switch to buses; however, under such situation, extra buses may be required to satisfy the dramatically increasing travel demand. Furthermore, the incident-based evacuation practices for large crowds are subject to extensive uncertainties, which further complicate the problem. They are ubiquitous in many system components and may affect processes of data investigation, modeling computation, and results