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Traffic evacuation simulation based on multi-level driving decision model

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ABSTRACT

Traffic evacuation is a critical task in disaster management. Planning its evacuation in advance requires taking many factors into consideration such as the destination shelter locations and numbers, the number of vehicles to clear, the traffic congestions as well as traffic road configurations. A traffic evacuation simulation tool can provide the emergency managers with the flexibility of exploring various scenarios for identifying more accurate model to plan their evacuation. This paper presents a traffic evacuation simulation system based on integrated multi-level driving-decision models which generate agents' behavior in a unified framework. In this framework, each agent undergoes a Strategic, Cognitive, Tactical and Operational (SCTO) decision process, in order to make a driving decision. An agent's actions are determined by a combination, on each process level, of various existing behavior models widely used in different driving simulation models. A wide spectrum of variability in each agent's decision and driving behaviors, such as in pre-evacuation activities, in choice of route, and in the following or overtaking the car ahead, are represented in the SCTO decision process models to simulate various scenarios. We present the formal model for the agent and the multi-level decision models. A prototype simulation system that reflects the multi-level driving-decision process modeling is developed and implemented. Our SCTO framework is validated by comparing with MATSim tool, and the experimental results of evacuation simulation models are compared with the existing evacuation plan for densely populated Beijing, China in terms of various performance metrics. Our simulation system shows promising results to support emergency managers in designing and evaluating more realistic traffic evacuation plans with multi-level agent's decision models that reflect different levels of individual variability of handling stress situations. The flexible combination of existing behavior and decision models can help generating the best evacuation plan to manage each crisis with unique characteristics, rather than resorting to a fixed evacuation plan.

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1. Introduction

Life-disrupting disasters are an inevitable threat and challenge to human society. Geophysical, biological, chemical or nuclear threats result in great loss of life and economic damages every year. While such eventualities may not be preventable, their reliable prediction could lead to mitigation of casualties. In case of impending disaster events, efficient mass evacuation is necessary. Unfortunately, studies such as Pel et al. (2012) have pointed out the increasing difficulty and time consumption inherent in mass evacuation, due to rising urban populations and density of development, as well as growing road infrastructure. Recent large-scale disasters required mass evacuation responses. For example, the number of people evacuated in the Sichuan earthquake was over 200,000 (Cui et al., 2012) and that in the Fukushima Daiichi nuclear reactor failure reached 300,000 (Thielen, 2012). These emphasize the important tasks in emergency management of moving people in highly populated areas away from disasters rapidly and safely from the scene of such disasters.

Large-scale evacuation, involving hundreds of thousands of motorists on the road, poses a tremendous challenge to emergency response planners. Federal, state, and local departments responsible for developing evacuation plans must enable as many people as possible to flee to safety under pressure, considering both the time it takes for evacuation and the psychological states of people such as anxiety or nervousness. This challenging and complex task is dependent upon elements which include timing between warning and response, procedure for dissemination of information and instructions, availability of planned evacuation routes, traffic flow conditions, dynamic traffic control measures, evacuation time estimates, etc. It also relies on uncontrollable factors, determined in natural and social environments, such as economic conditions and mass psychology (Dash and Gladwin, 2007). During a disaster, individuals seek to save their own lives and social cohesion is tested. Decisions are made without regard to any previous plan for response. During a disaster, although every detail of an evacuation plan affects the evacuees, it is unrealistic to expect such a plan to be fully and perfectly executed.

Agent-based simulation, that represents evacuees as agents and models their behaviors and decisions in a global traffic environment, is an effective tool to help in the exploration of reasonable scenarios. Many simulation models have been applied in Intelligent Transportation System software (Fellendorf, 1994; Fellendorf and Vortisch, 2010; Smith et al., 1995; Halati et al., 1997; Balmer et al., 2009; Cameron and Duncan, 1996). However, the emergency management decision-making mechanism differs from that of normal situations (Murray-Tuite and Wolshon, 2013) where traffic activities are repetitive (e.g., morning and afternoon rush hours, etc.). Decisions under these circumstances usually aim at an efficient utilization of the traffic system. While a wrong decision may lead to a traffic jam, it is less likely to result in tragedy. Emergency evacuation, as an extraordinary measure under dire conditions, can cause more chaos. Studies have pointed out the significant impact of heterogeneity of evacuees' behaviors on the evacuation effectiveness such as delayed clearance time (e.g., Murray-Tuite and Mahmassani, 2003; Yin et al., 2014). Thus, in order to be an effective decision-making tool for both emergency managers and transportation planners, an agent-based simulation tool should provide the capability to model evacuees' driving behaviors and diverse psychological states that may affect the driving behavior decisions during evacuation. The simulation tool can provide response planners with knowledge and capabilities to identify the most plausible scenarios relevant to the disaster characteristics for both planning and execution.

The evacuation behavior of evacuees consists of multiple types and levels of planning and decision making, before or during an evacuation. Before evacuation, they must decide on their necessity to evacuate, on their instructed destination, and on their time of departure. During evacuation, they must choose a route to their destination and they must consider events, such as a traffic jam. While driving their vehicles, they must decide whether to follow a car ahead of them or to change lanes. A driver's response depends on multitude of decisions that select one from these various behaviors, observed external factors, and the evacuation contexts. Car following and lane changing behaviors for example, while affecting evacuation clearance time (Tu et al., 2010), are not as critical as decisions of destination and route choice in a large-scale evacuation. Some psychological conditions, such as panic, may be highly critical during no-noticed evacuations. In multi-agent evacuation simulation system, ESCAPES (Tsai et al., 2011), fear felt by an individual agent due to the uncertainty of emergency situation and concerns of one's safety is modeled. They propose an emotional model to simulate agent's decision making and behaviors in airport evacuation scenarios that are influenced by the inherited fear from other agents. In pedestrian evacuation, panic causes people to exhibit more irrational behaviors driven by short-term personal interests, due to the reduced attention and fear in emergency situations, and to exhibit nervousness, resorting to other people's behaviors, i.e., herding phenomenon (Helbing et al., 2002).

In this paper we propose a *multi-level agent driving decision framework* for traffic simulation to support emergency evacuation planning. We further show how this framework enables the simulation of complex and realistic agents' driving behaviors during emergency situations. We have designed and implemented a traffic simulation system based on this framework and have tested it under various emergency scenarios in order to identify traffic jam locations and to help develop strategies for selecting shelters. Our system employs microscopic traffic models where a single vehicle-driver is represented by an agent. Multi-level decision models, including strategic, cognitive, tactical and operational levels are proposed for each agent to simulate the evacuation. Each agent's decisions, ranging from those of pre-evacuation activities and choice of evacuation route, to decisions as to following or overtaking, can thus be captured and dealt with, out of a wide spectrum of behaviors.

The paper is organized as follows. Related work is discussed in Section 2. The proposed framework and the system architecture for evacuation decision support are discussed in Section 3. Section 4 includes definitions of agent and driving