Fundamental Building Blocks for Vehicle-Pedestrian Interaction in Emergency Evacuations

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ABSTRACT

Evacuations requiring large numbers of pedestrians to evacuate and potentially interact with vehicles are unique in the complexity of interactions that must be understood and in the potentially catastrophic consequences of poor management. On the pedestrian side alone, these events, which may result from a variety of causes including terrorist attacks, bomb threats, and building fires, require an understanding of individual and group social dynamics, a wide breadth of mobility levels, cultural tendencies, and many other factors. Past research, involving bimodal interactions, concentrate on intersections or pedestrian midblock crossings in non–emergency scenarios, but only rarely address panic-induced evacuations. Using an agent-based modeling approach, this study serves as a fundamental building block for establishing pedestrian behavior when navigating around vehicles during an evacuation. This model combines survey data with sociological and psychological factors obtained from the literature to capture the heterogeneous decision-making of the pedestrian evacuees. The model will include a range of evacuating agents and focus on the decisions of pedestrians interacting with a few vehicles to explore the basic bimodal dynamics that occur during emergency evacuations. Findings show that implementing diverse characteristics changes the pedestrian response in a panic-induced environment. This model lays the foundation for a fundamentally sound full-scale evacuation model.

ABOUT THE AUTHORS

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INTRODUCTION

The Nuclear Management and Resources Council (NUMAC) funded a 1989 study to identify and analyze the factors affecting emergency evacuations. This study found that between 1980 and 1987, "emergency evacuations of at least 100 people occur more than once a week, and major evacuations of more than 1,000 people occur more than three times per month in the United States" (Weston, 1989). A later study sponsored by the National Regulatory Commission (NRC), found that between 1990 and 2003, large-scale evacuations of greater than 1,000 people occurred approximately once every two weeks in the United States (Dotson, 2005). High profile events, such as the 1995 bombing of the Murrah Building in Oklahoma City (FBI, 1995), the massive power outage in New York City in 2003, and the 9/11 terrorists attacks in New York City and in Washington, D. C., are examples of devastating events requiring the need for emergency evacuations. From an evacuation standpoint, the common denominator between these emergency situations is the immediate evacuation of all occupants of the buildings and surrounding areas to flee from the destruction and the potential of further attacks. Vehicle-pedestrian interactions disrupt traffic flow of traffic, have a high probability of incidents and accidents, and potentially causing gridlock preventing effective emergency response, Following the 9/11 attacks, the U. S. Department of Transportation Federal Highway Administration (FHWA) produced a final report on managing pedestrians during the evacuation of metropolitan areas (Bolton, 2007). In this report, the term "pedestrian evacuation" describes masses of people who leave a suddenly dangerous area on foot in order to reach a safer place. It entails the combination of masses of people on foot along with the corresponding congestion of the evacuation of others in private vehicles, always or at times moving along the same routes" (p. iii).

Emergency management and planning personnel preparing for such events would benefit from a tool capable of accurately simulating human/vehicle interactions. This paper focuses on one critical aspect of such a simulation, the decisions that pedestrians make when encountering vehicles. Past research involving bimodal interactions of pedestrian and vehicles concentrate on these interactions at intersections or pedestrian midblock crossings in non–emergency scenarios, but only rarely address panic-induced evacuations. From a modeling perspective, in lieu of simulating pedestrians and vehicles through physics-based or grid-based models, this approach uses agent based modeling (ABM) to capture the pedestrians' (referred to as agents) decisions while evacuating. These decisions are based on that pedestrian's unique characteristics and response during stress-inducing events. ABM is a modeling approach that is capable of fully capturing the actions and interactions of autonomous agents to assess their effects on the overall system over time. This makes it is an appropriate method to explore how diverse characteristics change the pedestrians' responses and how these responses change the evacuation outcome overall. Of most interest is the implementation of a pedestrian's behavior when situations cause anxiety, high stress, and fear. For preservation of life, against normal inclinations, a person may make higher risk decisions to escape danger or conversely, engage in altruistic behavior to help someone else in need. With the application of sociological and psychological factors obtained from the literature, the authors incorporate the heterogeneous decision-making of the pedestrian evacuees. The model will include a number of evacuating agents and focus on the decisions of pedestrians interacting with stationary vehicles to explore the basic bimodal dynamics that occur during emergency evacuations.

LITERATURE REVIEW

When modeling human crowd behavior, researchers typically focus on either collective crowd behavior or the individual human behavior (Sharbini & Bade, 2009). The model in this paper centers on human behavior and the decisions one makes in an emergency. It considers sociological and psychological factors obtained from the literature to capture the heterogeneous decision-making of pedestrian evacuees. Previous studies have modeled pedestrian and vehicle interactions during an evacuation but excluded the sociological and psychological aspects of decision-making. For example, Cova and Johnson (2002) used lane-based networks to determine the optimal evacuation routes for pedestrians and vehicles. The study used this approach to reduce traffic delays at intersections during an evacuation. Zhang and Chang (2011) utilized a node-link concept to represent the pedestrian and vehicle networks, and connectors to model turning movements at intersections. However, in both examples, full interaction of pedestrian and vehicles is avoided as the pedestrian and vehicle networks are separated.

Other studies that integrate the two modes of transportation model interactions when pedestrians cross the street at signalized and unsignalized intersections and at midblock crosswalks but are mostly concentrated in non-emergency setting (Boenisch & Kretz, 2009; Foster, Monsere, & Carlos, 2014; Helbing, Jiang, & Treiber, 2005; Li, Yan, Li, & Wang, 2012; Sun & Benekohal, 2003). For signalized intersections, the simulation models determine the ideal traffic signal timing plans for vehicles when considering the presence of pedestrians; pedestrian signals also optimize traffic and pedestrian flow through an intersection. Marisamynathan and Vedagiri (2014) developed a pedestrian delay model for signalized intersection crosswalks based on pedestrian crossing behavior by taking into account influencing factors such as pedestrian walking speed and pedestrian-vehicle interactions in crosswalks. For unsignalized intersections and midblock crossings, other studies focus on ascertaining the optimal gap acceptance for a pedestrian to cross the road based on the presence of an oncoming vehicle. For example, Wang, Wu, and McDonald (2012) used mathematical equations to model vehicle and pedestrian interaction behavior at unsignalized mid-block locations in an urban environment. The vehicle-pedestrian interaction sub-model is comprised of five modules that make up the vital components of their model framework: 1) pedestrians' gap acceptance, 2) pedestrian approaching the vehicle lanes, 3) pedestrians' on-road movement, 4) pedestrians' departing from vehicle lanes, and 5) vehicles' reaction to pedestrians. Another use of decision-making in a simulation model was done by Godara, Lassarre, and Banos (2007) where the researchers implemented behavioral rules for pedestrians using an agent-based modeling approach. Marked crosswalks are the attraction field and influence the behavior of pedestrians. If the attraction field is strong, i.e. the crosswalk is at a distance that attracts the attention of the pedestrian, he then crosses at the crosswalk to avoid a midblock crossing. However, for a weak attraction, the pedestrian may choose to cross midblock. On the sidewalk, the pedestrian chooses which direction to move depending on a vision radius and at the same time determines the best time to cross the street. The vision radius is significant as it directly effects the pedestrians' decision of using a crosswalk. Thus, as the vision radius extends, the strength of the attraction field increases and consequently, the chances of a pedestrian choosing the crosswalk increases as well. Similarly, a microscopic simulation for vehicle-pedestrian interaction at uncontrolled mid-block crosswalks called the Pedestrian Motorist Interaction Simulator (PMIS) considers multiple variables for pedestrians deciding when to cross the street faced with a conflicting scenario within the network. The decisions to cross are influenced by gap distance from a vehicle, which depends on pedestrian characteristics, roadway geometry, gap size, waiting time, and weather (Sun & Benekohal, 2003). These studies assist in advancing modeling and simulating decision-making during pedestrian and vehicle interactions, however, their primary focus is not on emergency scenarios.

In non-emergency or emergency scenarios alike, incorporating sociological and psychological attributes captures more realistic decision-making that drives the behavior of pedestrians and vehicle drivers. For the latter type of scenario, Pan, Han, Dauber, and Law (2007) categorized three characteristics that impact human behavior during emergency egress as: human physical, environmental, and psychological and sociological. According to Proulx (1993), "emergency decision-making differs from other types of decision-making in at least three ways: 1) higher stakes, 2) higher uncertainty, and 3) limited time" (p. 2). This paper serves as a fundamental building block for establishing pedestrian behavior when navigating around vehicles during an emergency evacuation with pedestrians and vehicles fully integrated on the network. At this preliminary stage, the model assumes that agents have full information about the emergency at hand and evacuates based on their own propensity to escape and their proximity to the origin of the emergency. Findings show that implementing diverse characteristics changes the pedestrian response in a panic-induced environment, possibly taking higher risks when faced with a crisis, and affecting the pedestrian's evacuation time. This model lays the foundation for a fundamentally sound full-scale evacuation model.

METHODOLOGY

The model simulates evacuating pedestrians with an emphasis on the decisions made when fleeing across a road using the crosswalk or navigating through stationary vehicles on the road. The agents must avoid other agents and the vehicles. The analysis then explores the impacts of agents' decisions about crossing points. The authors chose the agent based modeling (ABM) approach to capture the actions and interactions of agents that are autonomous and heterogeneous, as well as have learning capabilities, are adaptive, and can modify their behavior (North & Macal, 2007). In addition, this approach allows the modeler to define behavior at the individual agent level to observe emergent global behavior. In simulations representing evacuations, ABM is an appropriate fit to observe the effect that individual behavior and decision-making has on the overall evacuation as it allows for independent and varying agent attributes and interactions using the aforementioned characteristics.

Model Description

The model was developed using the NetLogo tool (Wilensky, 1999). The simulation is a basic evacuation of 200 agents traveling from a hazardous area by way of crossing a road to a safe area in a parking lot a distance away (see **Error! Reference source not found.**). At the beginning of the run, each agent is random placed in the evacuation area then walks toward a preferred location in the parking. The authors simplified the pedestrian behavior in order to explore the pedestrian-vehicle dynamics. We assume that the pedestrian agents suffer no visual impairments and have a generalized sense of when to cross the street. The agents travel at varying speeds from one to five (1 = slow walk, 2 = medium walk, 3 = fast walk, 4 = faster jog, 5 = fastest run). However, an agent's speed does not increase or decrease in the simulation. The attribute analyzed in this paper is the risks levels of the pedestrian agent. If an agent is a risk-taker, represented as a red dot, he jaywalks (crosses the road without using the crosswalk) and navigates around the vehicles, while the non-risk-taker will use the crosswalk to avoid the vehicle interaction. However, if the crosswalk is too crowded, some agents will increase their risk level and cross elsewhere. The road is a two-way, four-lane road, with a number of vehicles dispersed throughout the lanes and a midblock crosswalk. For a percentage of non-risk takers, if the crosswalk is too crowded, a possibly exists that a non-risk taker becomes a risk-taker and decides to jaywalk. For simplicity, the vehicles on the road are stationary and only the decision-making of the pedestrian is explored.

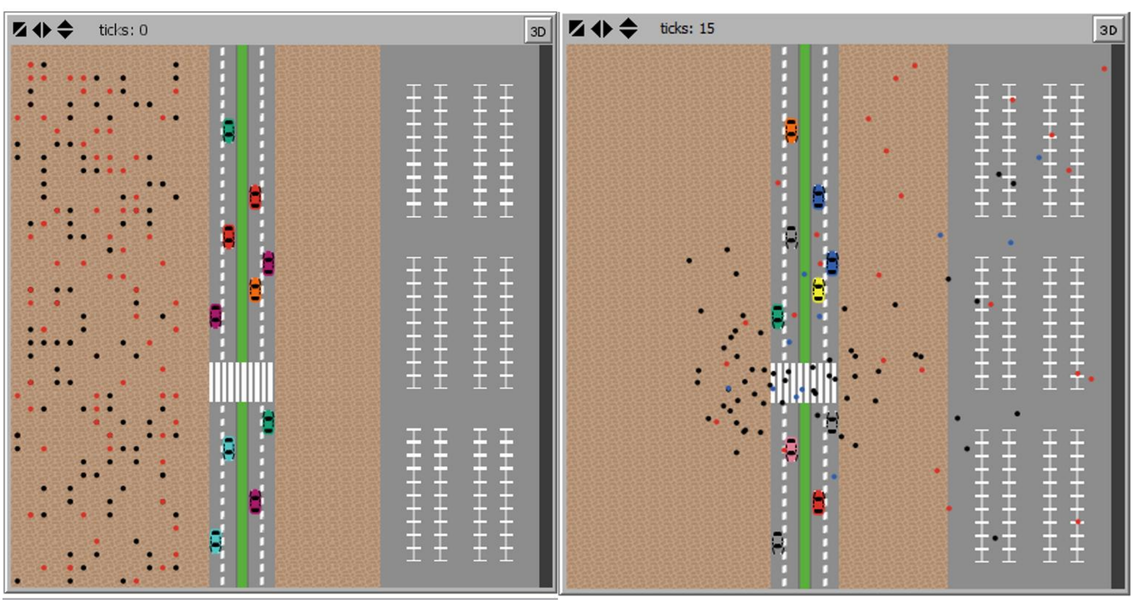

Figure 1. NetLogo Model

Results

The software tool Behavior Space that accompanies NetLogo was used to perform experimental runs on the model. Due to the stochastic nature of the simulation, the authors varied the input parameters. The percentage of risk-takers ranged from 0 to 100 increasing at increments of 10%, and the number of agents (evacuating population) ranged from 50 to 500 also increasing at increments of 10. Future versions of the model will consider all permutations of the variables to experiment with different test cases. The experiment completed 5,060 runs, recording the results of the dependent variable, evacuation time, for each run. The results show that as the percentage of risk-takers increases, the evacuation time decreases; as the population increases, the evacuation time increases (see Figure 2). These obvious results indicate that the model is performing as expected, serving as an initial verification step of the model code.

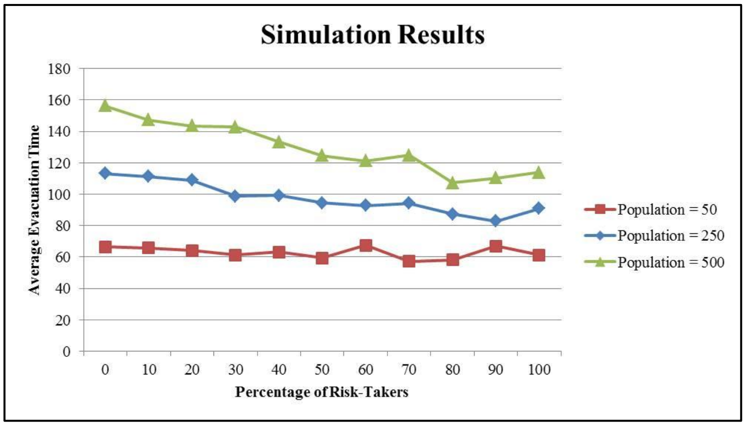

Figure 2. Subset of Simulation Results

Furthermore, we acknowledge that this initial model is simple in the sense that only two independent variables are tested, percentage of risk-takers and population. However, evaluating the results from the regression analysis for the 5,060 runs, our model explains approximately 80% ($r^2 \approx 0.8$) of the variance in the data, verifying that the development of the model is headed in the right direction. More detailed regression analysis will be conducted on future expansions of the model that will include additional parameters, which are discussed in the conclusions.

CONCLUSIONS

This simplified simulation demonstrates the influence of adding just one human characteristic of risk taking into the model. With this implementation the interactions and evacuation times showed significant differences verifying the importance of incorporating human attributes to evacuation models specific to pedestrian and vehicle interactions. An obvious omission to this study is the movement of the vehicles, which is a natural progression for expansion of the model. Moving vehicles will introduce a layer of complication with interactions when having to not only addressing pedestrian decisions but also decisions of the vehicle driver. In addition, when keeping with the human attribute of risk-taking, the jaywalking pedestrian now faces the decisions of crossing the street, based on the level of risk, whether to cross after a vehicle has passed or risk crossing in front of an approaching vehicle. Certainly, vehicle characteristics of speed and distance come into play as well.

As previously mentioned, agents are modeled with varying levels of mobility representative of fully mobile adults, the mobility challenged, and children,. To expand the model, agents will change their speed, 1) based on their desire to flee faster from an emergency, 2) move faster to avoid an oncoming vehicle, or 3) to slow down to allow a vehicle to pass. Lastly, an important element of effectively modeling crowds is the incorporation of small groups within the crowd and how decisions are altered depending on the group dynamics (Elzie, Frydenlund, Collins, & Robinson, 2015).

The current stage of development considers decision-making specific to one's own preference and personal characteristics. Future work will extend this basis by incorporating individual behavior due to the observation of other evacuees. One's decisions and behaviors are influenced by the responses and actions of others in the crowd surrounding them, even without full knowledge of the emergency. "We do things for which we have no basis in evidence. Indeed, we do them knowing we have no evidence; and sometimes, despite this, we are even the first in the group to do them" (Epstein, 2013, p. 2). This could lead to non-adaptive crowd behavior, such as stampeding, pushing, and trampling, causing panic in the crowd due to people reacting based on others actions and not necessarily based on the actual reason for the emergency. Conversely, modeling altruistic behavior captures ones propensity to act selflessly and help others in an emergency. Both types of behaviors to consider for future work.

Overall, the inclusion of physical and sociological/psychological attributes are important aspects of modeling pedestrian and vehicle driver decisions during an emergency and would allow for a complete model. This paper introduces a fundamental building block to begin the process of creating a robust and realistic model for bimodal emergency evacuations to provide a useful for disaster management and local emergency personnel.

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