Integration of Panic Models into Platform for Radiological Emergency Agent-based Integrated Simulation Model

Minho Hwang[a], Geon Kim[a], Joonseok Lim[a], Sungmin Han[a], Gyunyoung Heo[a*]
[a]Department of Nuclear Engineering, Kyung Hee University, Yongin-si, Republic of Korea

Abstract: The effectiveness of radiological emergency evacuation is crucial for public safety. Residents living near nuclear power plants begin evacuating immediately when a radioactive material leak is anticipated. Evacuation is the last strategy to protect lives, and governments conduct preemptive evacuation drills to develop strategies for mitigating damage in such situations. However, the behavior of evacuees during an actual incident may not be the same as in drills. The reality of an actual situation can instill significant fear in residents. We have introduced PRISM (Platform for Radiological Emergency Agent-based Integrated Simulation Model). PRISM provides insights into the evacuation behavior of residents living around nuclear power plants, utilizing an ABM (Agent-based Model). This study, recognizing the need to consider the complex behaviors of stressed individuals and crowds, enhances PRISM by integrating a panic model. The panic model targets the impact of human emotional responses on evacuation. This enhancement is expected to provide essential insights into potential bottlenecks and challenges that might occur during emergencies, empowering emergency planners to develop more effective evacuation routes. The panic model specifically illustrates how evacuees are influenced by the movements of the surrounding crowd. The previous version of the PRISM model was constrained by its approach of selecting the shortest path to the nearest shelter, often leading to bottleneck phenomena. By integrating the panic model, it becomes possible not only to modulate the panic states of evacuees, enhancing overall evacuation efficiency, but also to allow for a more realistic depiction of the effects of panic on decision-making and movement speeds. PRISM provides insights that can help establish emergency response strategies to reduce panic.

Keywords: Radiological emergency, Agent-based modeling, Panic, Evacuation strategy

1. INTRODUCTION

The IAEA has presented general requirements for evacuation in GSR PART 7 to minimize the damage from radiation accidents and provided guidelines to develop protective strategies based on these requirements. However, during a radiation emergency, evacuation involves multiple people moving to a single destination in the shortest time, rather than individuals moving to separate destinations. Various elements such as response facilities, relief supplies, and personnel are involved in evacuation during such emergencies [1], and it is important to consider that humans rely on emotional factors [2].

In agent-based simulations, human behavior reflects human sciences such as sociology and psychology, showing how they interact. This results in larger system outcomes through the simple behaviors of agents. Existing studies have simulated the evacuation process of residents during radiation emergencies using agent-based modeling (ABM). For example, Dubey et al. developed a cognitive agent-based simulation model to improve evacuation procedures in emergencies, mathematically abstracting agent behaviors and interactions to suggest optimal evacuation routes [3]. Ren et al. proposed a solution integrating atmospheric dispersion and radiation dose models to plan optimal evacuation routes within nuclear power plants [4].

While these studies have made significant contributions to evaluating and improving evacuation procedures during emergencies, there are several limitations. First, they often require large amounts of detailed data, making real-world application challenging. Second, they do not sufficiently consider psychological factors such as panic, failing to accurately reflect human behavior in actual situations. Third, existing traffic models do not adequately account for complex situations such as traffic congestion, which can hinder the optimization of evacuation routes.

The existing agent-based simulation developed in previous research [1,5,6], PRISM, shows the process of residents evacuating to shelters during a radiation emergency. When the simulation starts, evacuees are randomly generated based on Geographic Information System (GIS) data for each residential area and move to shelters. Previous studies have derived optimal evacuation outcomes through PRISM by mathematically abstracting and modeling the interactions of agents involved in emergencies. However, considering the interactions of agents for realistic evacuation outcomes complicates the simulation, showing different aspects from pre-trained results.

To address this, the present study aims to observe the impact of panic on evacuation in the existing traffic model. Panic hinders the swift judgment of evacuees, making them act more cautiously and causing traffic congestion. This resulting bottleneck delays evacuation, requiring appropriate strategies. Traffic congestion induces stress in evacuees and can lead to secondary accidents such as traffic collisions. By enhancing the traffic model, a sensitivity analysis considering traffic congestion was performed. The most vulnerable road sections were identified by segmenting the roads with the highest traffic volume. Based on this, methods to improve the safety and comfort of evacuation through the integrated model are proposed.

2. PREVIOUS VERSION OF PRISM

PRISM, previously introduced as an ABM technique for radiation emergency evacuation simulations, operates by simulating the evacuation of residents to assembly points and shelters in the event of a radioactive material leak from a nuclear power plant. The interactions between residents and other agents are governed by behavior rules derived from various models, including path finding, traffic, dispersion, panic, infrastructure, and information dissemination models. Specifically, these interactions are characterized by attributes such as location, dose concentration, speed, and supply rate, which are dynamically computed by the models. The non-linear nature of these interactions during simulations is a hallmark of the ABM approach.

Previous studies have focused on updating the models embedded in PRISM [7]. For instance, the dispersion model has been enhanced by employing the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)software, transitioning from a Gaussian puff model to a Lagrangian model, thereby improving the depiction of actual weather conditions. Similarly, the path finding model, initially implemented using algorithms within NetLogo, has been optimized for speed by incorporating Python built-in functions. The current study is dedicated to updating the traffic model.

The traffic model simulates the behavior of evacuees as they navigate nodes along pre-calculated paths. The preceding traffic model utilized the Cellular Automata approach, which determined speed at each tick— the fundamental time unit of the simulation—and moved agents the corresponding distance per tick. However, this model exhibited limitations in accuracy, as it failed to account for inter-vehicle distances unless the vehicles were within a specific range, resulting in a fixed maximum speed. To mitigate this issue, we have adopted the Intelligent Driver Model (IDM) [8], which incorporates factors such as inter-vehicle distance and speed differentials between vehicles, thereby offering a more realistic simulation of driver behavior.

3. MODEL UPDATE

3.1. Intelligent Driver Model

IDM models how a specific vehicle maintains its distance and adjusts its speed while following the vehicle in front. To address the limitations of accurately reflecting driver behavior in real road situations, IDM provides a detailed description of driver responses, including speed selection, braking, and maintaining inter-vehicle distance, thereby reflecting the psychological state of the driver. This model considers both physical variables and driver preferences to determine vehicle driving behavior, as shown in Eq. 1.

$$a_\alpha = a_0 \left[1 - (\frac{V_\alpha}{V_0})^\delta - \frac{(S^*(V_\alpha, \Delta V_\alpha))^2}{S_\alpha} \right] \quad (1)$$

$$S^*(V_\alpha, \Delta V_\alpha) = S_0 + V_0 * T + \frac{V_\alpha * \Delta V_\alpha}{2\sqrt{ab}} \quad (2)$$

IDM determines the driver's acceleration, where a_α is the maximum acceleration, V_α is the current speed, V_0 is the desired speed of the driver, δ is the acceleration exponent, $S^*(V_\alpha, \Delta V_\alpha)$ is the safe distance function, S_α is the actual distance to the vehicle in front, and ΔV_α is the speed difference with the vehicle in front. In Eq. 2, the safe distance S^* is defined. Here, S_0 is the minimum distance at standstill, T is the safe time headway, and b is the driver's deceleration.

3.2. Panic Integrating

Panic-IDM (P-IDM) is a model that integrates the element of panic into the existing IDM [8]. This model simulates how drivers react under stressful conditions. Panic reflects the psychological stress experienced by drivers in emergency situations, directly influencing their acceleration and driving behavior. Panic is represented by a value between 0 and 1, indicating the intensity of panic. In P-IDM, the panic variable is included in the original IDM formula to adjust acceleration. The P-IDM, which incorporates the panic factor p, is defined in Eq. 3.

$$a_\alpha = a_0[1 - (\frac{V_\alpha * (1+p)}{V_0})^\delta - (\frac{S^*(V_\alpha, \Delta V_\alpha)}{S_\alpha})^2] \quad (3)$$

As the panic factor increases, drivers tend to drive more cautiously, leading to a decrease in acceleration [9]. This means that as panic increases, drivers aim to maintain a larger safe distance from the vehicle in front and respond with lower acceleration.

4. RESULTS

The impact of panic on the traffic model was analyzed by conducting simulations. The simulations were run 1,100 times, with the panic value increasing from 0 to 1 in increments of 0.1, and each simulation was performed 100 times. In each simulation, 5,000 agents were generated simultaneously and moved to the nearest shelter. The shelters were set at highway entrances approximately 5 km away from a nuclear power plant (as shown in Fig. 1). Fig. 2 shows the simulation time for each panic value, with the scatter plot illustrating the results, and the red line indicating the average time. It is evident that the simulation time increases as the panic value rises. Fig. 3 displays the average speed of agents corresponding to each panic value, indicating a decrease in average speed as panic increases. Table 1 presents the specific values corresponding to each panic level and the percentage increase or decrease compared to a panic value of 0. These results align with the mathematical formula of P-IDM, which predicts a reduction in speed as panic increases. Panic not only delays evacuation but also suggests that, although the current PRISM does not include traffic accidents, additional accidents could be caused by psychological stress. This highlights the need for infrastructure improvements or the dispersion of evacuation routes to reduce panic.

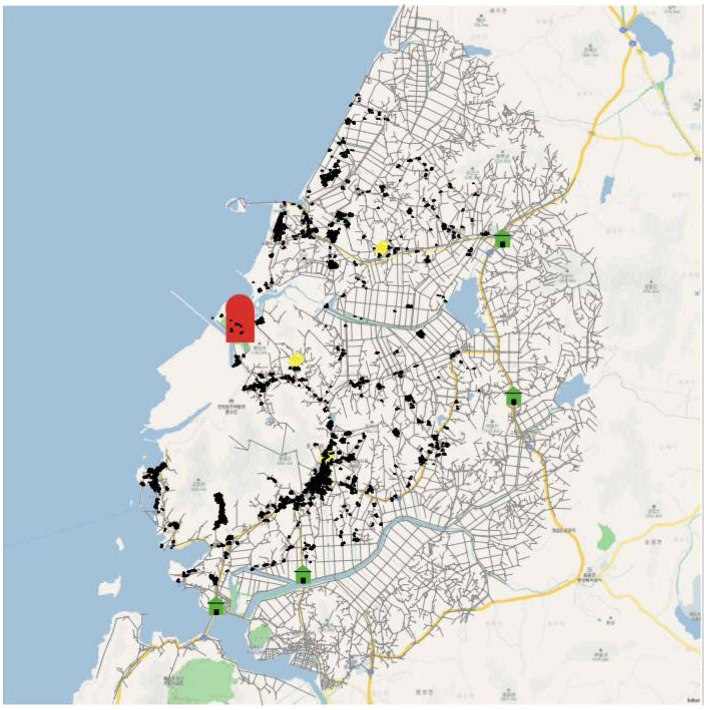

Figure 1. Simulation Execution Screen

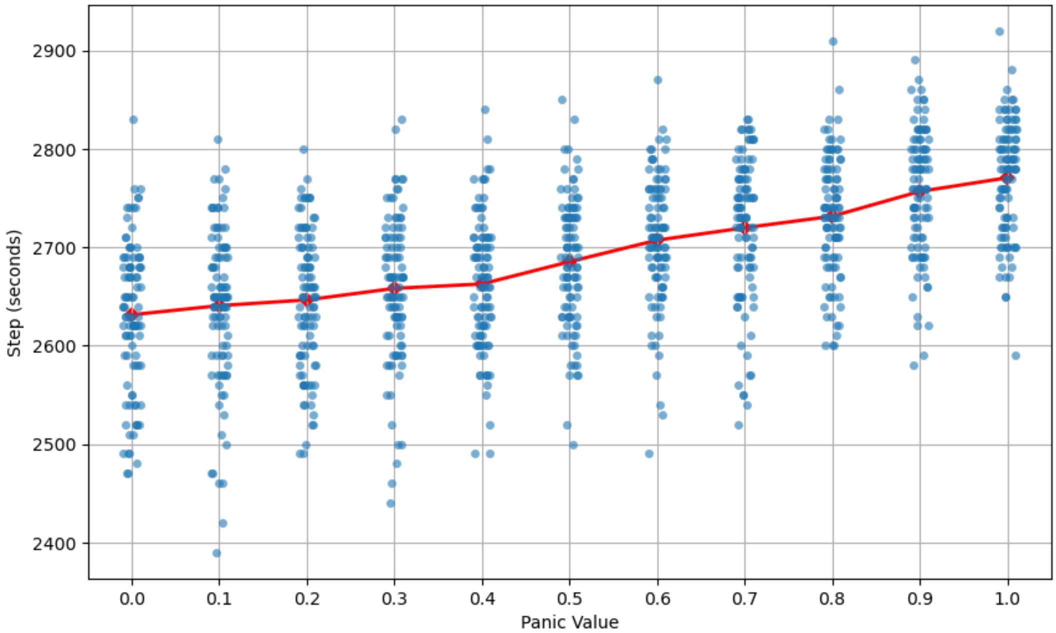

Figure 2. Average evacuation time

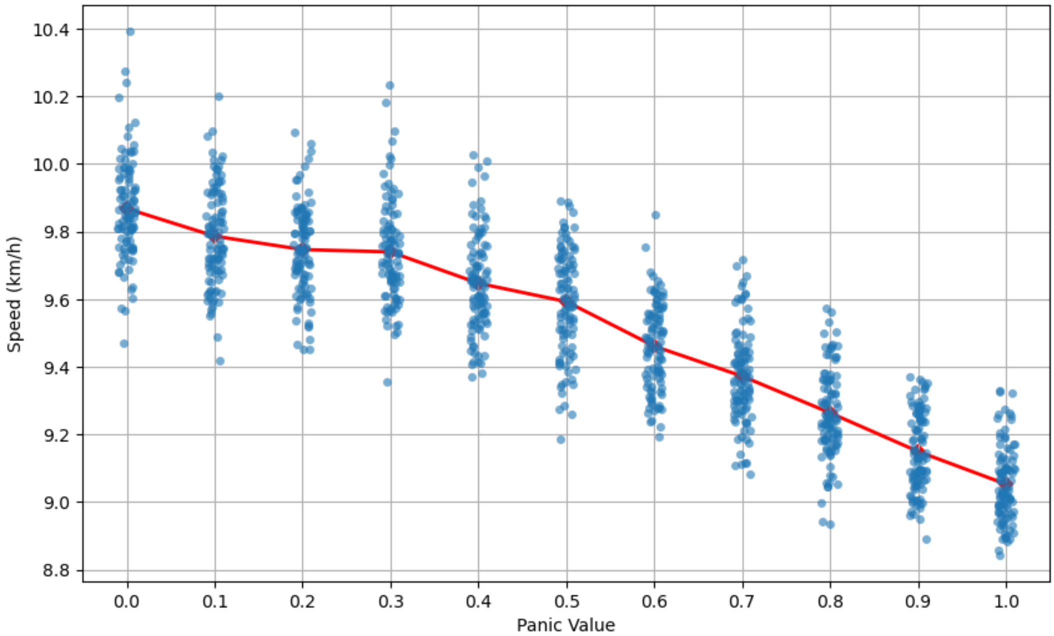

Figure 3. Average speed

Table 1. Change According to Panic

Panic	Step (sec)	Mean Speed (km/h)	Step Change (%)	Speed Change (%)
0	2631.3	9.868	0	0
0.1	2640.6	9.786	0.353	-0.826
0.2	2646.4	9.746	0.220	-0.406
0.3	2658.1	9.740	0.442	-0.070
0.4	2662.6	9.647	0.169	-0.953
0.5	2685.2	9.593	0.849	-0.561
0.6	2707.1	9.461	0.816	-1.375
0.7	2719.7	9.372	0.465	-0.938
0.8	2731.4	9.264	0.430	-1.157
0.9	2756.6	9.150	0.923	-1.231
1	2770.5	9.053	0.504	-1.058

5. CONCLUSION

This paper explores the enhancement of the PRISM to more accurately simulate evacuation behavior during radiological emergencies by integrating a panic model. The original PRISM focused on optimizing evacuation routes by mathematically abstracting the movement of residents; however, it did not adequately account for the impact of panic, a critical factor in real-world scenarios. By incorporating the panic model, this study provides a more realistic representation of the psychological responses of evacuees, particularly how these responses influence traffic congestion and evacuation efficiency.

The findings indicate that as panic levels increase, both evacuation times and traffic congestion worsen, highlighting the potential for bottlenecks and accidents during an emergency. This suggests the necessity for infrastructure improvements and the dispersion of evacuation routes to mitigate the effects of panic. The insights gained from this study are expected to contribute significantly to the enhancement of emergency response strategies, ultimately improving the effectiveness of evacuation plans in radiological emergencies.

Acknowledgements

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korean government(MSIP:Ministry of Science, ICT and Future Planning) (No. NRF-2021M2D2A1A02044210).

References

[1] Kim, G., & Heo, G. (2023). Agent-based radiological emergency evacuation simulation modeling cons idering mitigation infrastructures. Reliability Engineering and System Safety, 233, 109098. https://doi. org/10.1016/j.ress.2023.109098
[2] Cao, M., Zhang, G., Wang, M., Lu, D., & Liu, H. (2017). A method of emotion contagion for crowd ev acuation. Physica A: Statistical Mechanics and its Applications, 483, 250-258. https://doi.org/10.1016/ j.physa.2017.04.137
[3] Dubey, R. K., Sohn, S. S., Hoelscher, C., & Kapadia, M. (2019). Cognitive agent-based simulation mo del for improving disaster response procedures. Preprint. Retrieved from https://www.researchgate.net/ publication/336230112
[4] Ren, Y., Zhang, G., Zheng, J., & Miao, H. (2024). An integrated solution for nuclear power plant on-si te optimal evacuation path planning based on atmospheric dispersion and dose model. Sustainability, 1 6, 2458. https://doi.org/10.3390/su16062458
[5] Hwang, M., Kim, G., Lim, J., & Heo, G. (2023). Platform for radiological emergency agent-based inte grated simulation model to optimize evacuation planning. In Proceedings of the Asian Symposium on Risk Assessment and Management (ASRAM2023) (ASRAM2023-031), 04-06 December 2023, Hong Kong, P.R. China.
[6] Kang, S. W., Park, J., Kim, G., Heo, G., & Jang, S. (2023). Proposed methodology to estimate the off-s ite emergency response convocation time during multi-unit accident management using an agent-based model. In Transactions of the Korean Nuclear Society Autumn Meeting, 26-27 October 2023, Gyeong ju, Korea.
[7] Hwang, M., Kim, G., & Heo, G. (2023). Platform for radiological emergency agent-based integrated si mulation model updated for relief process. In Transactions of the Korean Nuclear Society Autumn Me eting, 26-27 October 2023, Gyeongju, Korea.
[8] Tanveer, H., Mubasher, M. M., & Jaffry, S. W. (2020). Integrating human panic factor in intelligent dr iver model. In Proceedings of the IEEE International Conference on Intelligent Transportation Systems (ITSC) (pp. 1-8). https://doi.org/10.1109/ITSC45102.2020.9286433
[9] Liu, A., Ma, S., Chen, Z., Zhang, K., Yang, Y., & Guo, Y. (2022). Study on the Influence of Driver An xiety on Driving Behavior During Car-Following. *International Journal of Scientific Advances (IJSCI A)*, 3(4), 544-546. https://doi.org/10.12345/ijscia.v3i4.303