Development of an ABM-based Radiation Emergency Response Simulation Applying an Exposure Model

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ABSTRACT

Although radiological emergencies are extremely rare, their consequences can be widespread and devastating, demanding thorough preparedness. Existing evacuation simulation studies, however, have been limited by their reliance on static analysis, which fails to realistically reflect dynamic factors such as resident movement or changing traffic conditions. To overcome these limitations, this study develops and applies a real-time exposure dose evaluation model that considers the dynamic movements of residents, utilizing the agent-based radiological emergency simulation platform, PRISM (Platform for Radiological Emergency Integrated Simulation Model). The core of this research is the integration of time-varying data on radioactive material concentration and ground deposition, derived from the HYSPLIT atmospheric dispersion model, into the PRISM platform. Based on this, a methodology was implemented to dynamically track and precisely calculate the cumulative dose for each resident (agent) moving along an evacuation route, accounting for external exposure (from ground and cloud shine) and internal exposure (from inhalation of radioactive materials).

The simulations conducted in this study not only present specific analytical results but also demonstrate the broader applicability of the developed model. The true value of this platform lies in its ability to provide policy insights by exploring the potential effects and unforeseen outcomes of complex emergency response strategies through various 'what-if' scenarios. For instance, decision-makers can use PRISM to quantitatively evaluate the trade-offs of different strategies by adjusting variables such as mass transit utilization rates, evacuation routes, and assembly point logistics. Furthermore, it moves beyond conceptually emphasizing the importance of a 'golden time' for evacuation by scientifically demonstrating how delays numerically impact the average and maximum exposure doses within a population, thereby providing an evidentiary basis for designing the most effective response procedures. In conclusion, the dynamic exposure dose evaluation simulation developed in this study is significant as a powerful analytical tool capable of predicting potential problems and comparing the effectiveness of various strategies in a realistic evacuation scenario. This research can contribute to enhancing national radiological emergency preparedness by providing the key insights needed to formulate more effective and optimal response strategies.

Keywords: Radiological Emergency, Agent-Based Model, Evacuation Simulation

I. INTRODUCTION

Although radiological emergencies are extremely rare, their consequences can be widespread and devastating, demanding thorough preparedness. The Fukushima Daiichi nuclear power plant accident, triggered by the 2011 Great East Japan Earthquake, was a pivotal event that underscored this risk to the world. It vividly demonstrated how minimizing radiation exposure and systematically evacuating residents are essential for protecting lives and safety, and it highlighted the importance of simulations to verify the practical effectiveness of theoretical plans and identify unforeseen problems in complex and uncertain emergency situations [1].

In response, research on exposure dose calculation and dispersion models for radiological emergency scenarios has been actively conducted. For example, Srinivas used sophisticated atmospheric dispersion models based on initial data from the Fukushima accident to assess the dispersion of radioactive materials within a $40\ km$ radius and the resulting public exposure [2]. Similarly, Marzo analyzed the extensive transport and deposition patterns of major radionuclides released into the atmosphere, supporting the scientific validity of the mandatory evacuation measures implemented at the time [3]. In fact, various investigations and studies after the Fukushima accident confirmed that, thanks to multi-layered protective measures such as prompt public evacuation and restrictions on contaminated food, the exposure levels of the general public were managed within international safety standards [4]. To date, no statistically significant increase in cancer incidence due to radiation exposure has been observed [5]; however, psychological and social impacts, such as long-term anxiety and social stigma, have been identified as significant health risk factors [6].

These real-world accident experiences and research findings re-emphasize the importance of regulatory guidelines for radiation exposure. Domestic regulatory guidelines, based on recommendations from international organizations such as the ICRP and IAEA, strictly manage the annual effective dose limit for the general public at $1\ mSv$ under normal circumstances [7]. However, in large-scale emergencies like the Fukushima accident, the reference dose for judging public evacuation and sheltering can be flexibly applied up to $20 - 50\ mSv$, considering the realistic exposure risk [8].

However, existing simulation studies to support the effective implementation of these regulatory guidelines and the establishment of practical evacuation strategies have mostly been based on static analysis, such as calculating exposure doses at fixed points or assuming individuals remain in a particular location. This has resulted in a clear limitation in realistically reflecting dynamic factors such as resident movement during evacuation, changes in traffic conditions, and real-time variations in the dispersion of radioactive materials.

This study aims to overcome these limitations by utilizing PRISM (Platform for Radiological Emergency Integrated Simulation Model), an agent-based radiological emergency evacuation simulation platform developed at Kyung Hee University [9]. The core objective of this study is to develop and apply a methodology for more precisely and dynamically calculating the short-term exposure doses that residents receive while being exposed to a constantly changing environment during evacuation. This is achieved by integrating time-varying data on radioactive material concentration and deposition, derived from the HYSPLIT atmospheric dispersion model, into the simulation. Through this, the study aims to quantitatively analyze the impact of evacuation start time on cumulative exposure dose, evaluate how different evacuation methods (e.g., private vehicles, walking, assembly buses) affect exposure risk, and ultimately provide concrete insights for formulating optimal evacuation strategies that can minimize the total exposure dose for the entire population under specific conditions.

II. METHODOLOGY

II.A. PRISM (Platform for Radiological emergency Integrated Simulation Model)

PRISM (Platform for Radiological emergency Integrated Simulation Model) is an integrated modeling framework developed with the goal of establishing effective radiological emergency preparedness and response (EPR) plans to minimize damage in the event of an emergency, such as a radioactive leak [9]. The core technology of this system is agent-based modeling (ABM). This approach defines various individual elements related to a radiological emergency scenario (e.g., residents, vehicles, radioactive materials, relief supplies, etc.) as 'agents' and the 'environment'. These agents then act autonomously according to predefined rules and interact with each other, thereby reproducing and predicting the complex macroscopic phenomena that arise.

PRISM is built and simulated based on Netlogo, a free and accessible software with an easy-to-use programming language. The model focuses on illustrating the emergency modeling process by simulating the complex interactions that occur during an emergency. Additionally, it incorporates the concept of system resilience, which is defined as the probability that the degree of system recovery (resilience (RES)) returns to its original or a targeted level (targeted recovery (REC^*)) within a required time (t) following a radiological accident. This resilience is assumed to be determined by the interaction between risk factors, such as radiological concentration, and infrastructure elements, like relief supplies (for instance, exposure dose increases with the concentration of radioactive material and decreases with the availability of relief supplies).

The specific procedure for PRISM is as follows: first, it performs environmental modeling of the target area's road network, buildings, and infrastructure resources using Geographic Information System (GIS) data. Second, it identifies and selects components such as protected populations, risk factors, and mitigation infrastructure according to the scope of the simulation. Third, it selects models for pathfinding, traffic flow, and atmospheric dispersion to realistically reflect the interactions between these elements. Finally, it runs multiple simulations repeatedly to quantitatively estimate the system's degree of recovery (REC) and resilience ($RES(t)$) over time.

II.B. Application of the Dispersion Model using HYSPLIT

To improve the accuracy of the radiological emergency evacuation simulation, this study needed to precisely simulate the movement, atmospheric dispersion, and surface deposition of radioactive materials over time. For this purpose, the study used the HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model, developed by the Air Resources Laboratory (ARL) of the U.S. National Oceanic and Atmospheric Administration (NOAA), to predict the spatiotemporal distribution of these materials [10]. The HYSPLIT model is a sophisticated atmospheric dispersion and trajectory prediction software designed to conduct detailed simulations of the transport, dispersion, and deposition of substances in the atmosphere across various time and space scales. Its key feature is the effective combination of a Lagrangian particle-tracking method and an Eulerian fixed-grid method to realistically simulate the behavior of air parcels and the pollutants they contain. It is widely used to predict how various atmospheric pollutants—like radionuclides, fine dust, hazardous chemicals, volcanic ash, and smoke—will travel, disperse, and deposit based on weather conditions after being released from a specific point. Running the model requires high-resolution gridded meteorological data (e.g., wind fields, temperature, precipitation) for the target area. Users can define the specific emission characteristics of the pollutant source (e.g., emission rate, time, and height) and can include a chemical transformation module to more accurately replicate changes in the real atmospheric environment.

The outputs of the HYSPLIT model include detailed analytical data that can be verified against actual environmental measurements, such as the pollutant's expected trajectory over time, its atmospheric concentration at specific locations and altitudes, and the amount of surface deposition per unit area. These results serve as a critical scientific foundation for various research and practical applications, including environmental impact assessments, backtracking of atmospheric pollution sources, support for developing rapid response strategies in emergencies, and related policymaking. In this research, the hourly data on the spatial distribution and deposition of radioactive materials calculated by HYSPLIT is used as input for the PRISM evacuation simulation model to enhance the accuracy of real-time exposure dose assessments along the evacuees' routes.

II.C. Exposure Dose Calculation

In this study, the exposure dose for evacuees is dynamically calculated within the PRISM simulation based on the location and time of each agent (evacuee). Based on the hourly atmospheric concentration and ground deposition data of radioactive materials derived from the HYSPLIT model, the dose assessment methodology for the primary exposure pathways considered in this study—external exposure and internal exposure (inhalation)—is as follows.

II.C.1. External Exposure Dose Calculation

The two primary external exposure pathways considered in this study are: (1) gamma radiation from radioactive materials deposited on the ground (ground-shine external exposure), and (2) gamma radiation from airborne radioactive materials (cloud-shine external exposure). The external exposure dose from these pathways is calculated by applying the Dose Conversion Factors (DCFs) provided in the U.S. Environmental Protection Agency's (EPA) "Federal Guidance Report No. 15." [11] Based on the hourly ground deposition and atmospheric concentration data derived from the HYSPLIT model, the hourly effective dose for each evacuee is calculated using the following formulas.

1. External Exposure Dose from Ground Deposition ($H_{ext,G}$)

$$H_{ext,G} = DCF_{ext,G} \times C_G \times t \tag{1}$$

2. External Exposure Dose from Airborne Concentration ($H_{ext,A}$)

$$H_{ext,A} = DCF_{ext,A} \times C_A \times t \tag{2}$$

In the formulas above, $H_{ext,G}$ and $H_{ext,A}$ represent the effective external exposure doses (in Sv) from the ground deposition and airborne pathways, respectively. The dose conversion factors used in the calculation, $DCF_{ext,G}$ and $DCF_{ext,A}$, are the external exposure dose coefficients for radionuclides deposited on the ground (in Sv/s per Bq/m^2) and for airborne radionuclides (in Sv/s per Bq/m^3), respectively. C_G, calculated from the HYSPLIT model, is the concentration of radioactive material deposited on the ground surface (in Bq/m^2), while C_A represents the atmospheric concentration near the ground at a height of 1 meter (in Bq/m^3). Finally, t denotes the exposure time in seconds.

II.C.2. Internal Exposure Dose Calculation

The internal exposure pathway considered in this study is the inhalation of airborne radioactive materials through the respiratory tract. The Committed Effective Dose Equivalent from inhalation is calculated using the Inhalation Dose Coefficients provided in the U.S. EPA's "Federal Guidance Report No. 11" [12].

The hourly effective dose from inhalation is calculated by multiplying the atmospheric concentration of the radioactive material, the individual's breathing rate, and the nuclide-specific dose coefficient, as shown in the following formula:

$$H_{int,inh} = DCF_{int,inh} \times C_A \times BR \times t \tag{3}$$

In this formula, $H_{int,inh}$ is the committed effective dose equivalent from inhalation (in Sv). The dose coefficient for the inhalation of a specific nuclide is represented by $DCF_{int,inh}$ (in Sv/Bq), and C_A is the atmospheric concentration of the radioactive material calculated by HYSPLIT (in Bq/m^3). Furthermore, BR is the breathing rate for a standard adult (for which this study applies a rate of $0.02\ m^3/s$), and t denotes the exposure time in seconds.

II.C.3. Total Effective Dose and Dynamic Accumulation

An evacuee's total effective dose is the sum of the doses from the previously defined external and internal exposure pathways. The total hourly effective dose rate (H_{total}), expressed in Sv/h, is calculated by summing the external dose from materials deposited on the ground ($H_{ext,G}$), the external dose from airborne materials ($H_{ext,A}$), and the internal dose from inhalation ($H_{int,inh}$):

$$H_{total} = H_{ext,G} + H_{ext,A} + H_{int,inh} \tag{4}$$

II.D. HYSPLIT Input Settings

To reproduce the release of radioactive materials into the environment and their atmospheric dispersion during the Fukushima Daiichi nuclear power plant accident, this study applied the 'Source Term 6 (JAEA-Katata-3h)' data, provided by NOAA (from the official HYSPLIT website), as the core source term (release scenario) for the HYSPLIT atmospheric dispersion model [13]. This source term, developed by Katata by compiling numerous field measurement data, accident progression analyses, and meteorological simulation results after the accident, provides highly detailed characteristics of the released radionuclides, including their form, the temporal variation of their release rates, and features corresponding to major physical events at different times during the accident (e.g., hydrogen explosions, pressure venting).

The most critical release information reflected in the 'Source Term 6 (JAEA-Katata-3h)' data is the distinction between I-131 and Cs-137, and the separate input for the 'gas' and 'particle' forms of each nuclide. Specifically, for I-131, both its gas and aerosol (particulate) forms were estimated and input at a rate of $3.4 \times 10^{12}\ Bq/h$ during the accident, while the particulate form of Cs-137 was applied with a release rate of $6.4 \times 10^{11}\ Bq/h$. This distinction in release forms is intended to reflect the actual differences in the behavior of radionuclides in the atmosphere—for example, gaseous iodine has much greater mobility and faster deposition characteristics, whereas particulate radioactive materials are more affected by their relatively heavier mass, slower dispersion, and surface deposition. Notably, I-131 is crucial for assessing initial atmospheric dispersion and rapid human exposure effects after the accident, while Cs-137 is a key factor in evaluating more long-term soil deposition and external exposure.

II.E. PRISM Exposure Calculation Implementation

To dynamically calculate the exposure dose for each agent within the PRISM simulation, the spatiotemporal concentration and deposition data from the HYSPLIT model are imported and processed. The detailed methodology is as follows:

First, the HYSPLIT simulation results are exported as .shp (shapefile) format using its built-in 'ESRI Generate' function. To capture the dynamic changes in the radioactive plume, data is extracted at one-minute intervals. This process generates separate datasets for ground surface deposition (C_G) and atmospheric concentration at a 1-meter height (C_A). This results in a total of six distinct data sets, accounting for the different nuclides and their forms:

- Cs-137 (Ground deposition)
- Cs-137 (Air concentration)
- I-131 particle (Ground deposition)
- I-131 particle (Air concentration)
- I-131 gas (Ground deposition)
- I-131 gas (Air concentration)

Each shapefile contains concentration data in a contour format, where the 'CONC' attribute field stores the value as a power of 10 (logarithmic scale). Within the PRISM environment, which is built on NetLogo, the gis extension is utilized to import this data. The 'gis:feature-list-of' function reads the contour features from each shapefile for each time step. The corresponding concentration values are then mapped onto the simulation's grid cells, known as 'patches'.

The simulation progresses in discrete time steps, where each 'tick' represents 10 seconds of real time. As an agent moves across the grid, the simulation identifies the patch the agent occupies at each tick. The exposure dose for that 10-second interval is then calculated using the concentration values stored in that specific patch. The total dose is computed by applying Equations (1), (2), and (3), where the time variable, t, is set to 10 seconds. This calculated dose is then added to the agent's individual cumulative dose variable. This process repeats every tick, allowing for a dynamic accumulation of the total effective dose based on the agent's unique trajectory through the evolving radiological environment. The Dose Conversion Factors used for the calculations are as follows:

- $DCF_{ext,G}$:
  - Cs-137: 7.85×10^{-18}
  - I-131: 2.44×10^{-16}

- $DCF_{ext,A}$:
  - Cs-137: 3.89×10^{-16}
  - I-131: 1.69×10^{-14}

- $DCF_{int,inh}$:
  - Cs-137: 8.63×10^{-9}
  - I-131: 8.89×10^{-9}

III. RESULTS

Utilizing the dynamic exposure dose evaluation simulation developed in this study, we quantitatively analyzed the effects of two primary research objectives on total exposure dose: the evacuation method and the evacuation start time. The simulation was conducted with a population of 5,000 agents, and to ensure the statistical reliability of the results, a total of 50 simulation runs were performed for each scenario.

A. Analysis of Exposure Dose by Designated Assembly Point Radius

The first simulation analyzed the impact of the designated walking distance to assembly points on residents' cumulative exposure dose and evacuation efficiency. In this simulation, it was assumed that residents not designated to walk to an assembly point would evacuate using their private vehicles. Two scenarios were compared, and the results are presented in Figure 1. In the figure, the solid and dashed lines represent the mean cumulative exposure dose from 50 simulation trials for each scenario, while the shaded areas represent the standard deviation. It is also important to note that the average cumulative exposure dose shown in the graph was calculated only for individuals who received a non-zero dose.

- Scenario 1: Only residents living within a 500m radius of an assembly point walk to it and then evacuate by bus.
- Scenario 2: Only residents living within a 300m radius of an assembly point walk to it and then evacuate by bus.

As shown in Figure 1, the '300m Scenario' (orange dashed line) tended to record a higher average cumulative exposure dose than the '500m Scenario' (blue line) throughout the simulation. However, an important additional finding is that despite the higher dose, the 300m scenario achieved a faster overall evacuation completion time.

This trade-off can be attributed to several complex factors. First, residents in the narrower 300m zone, covering a shorter distance, may have arrived at the assembly points almost simultaneously. This could have created a bottleneck, increasing the waiting time for buses and thereby raising the exposure dose for those individuals. Second, this outcome could also be influenced by the direction of the radioactive plume's dispersion. It is possible that, due to the specific simulated path of the plume, the 300m-radius assembly points were coincidentally located in areas with a relatively higher concentration of contamination.

In conclusion, this analysis clearly demonstrates that a potential trade-off can exist between the speed of evacuation completion and the minimization of individual exposure doses. This presents a critical policy dilemma when establishing radiological emergency response plans. Therefore, the value of an agent-based simulation platform like PRISM, as utilized in this study, is further highlighted. It allows decision-makers to run various 'what-if' scenarios—such as optimizing the utilization rates of buses and private cars or adjusting the catchment radius of assembly points—to gain key insights into optimal response strategies that can effectively minimize both total evacuation time and total exposure dose under given conditions.

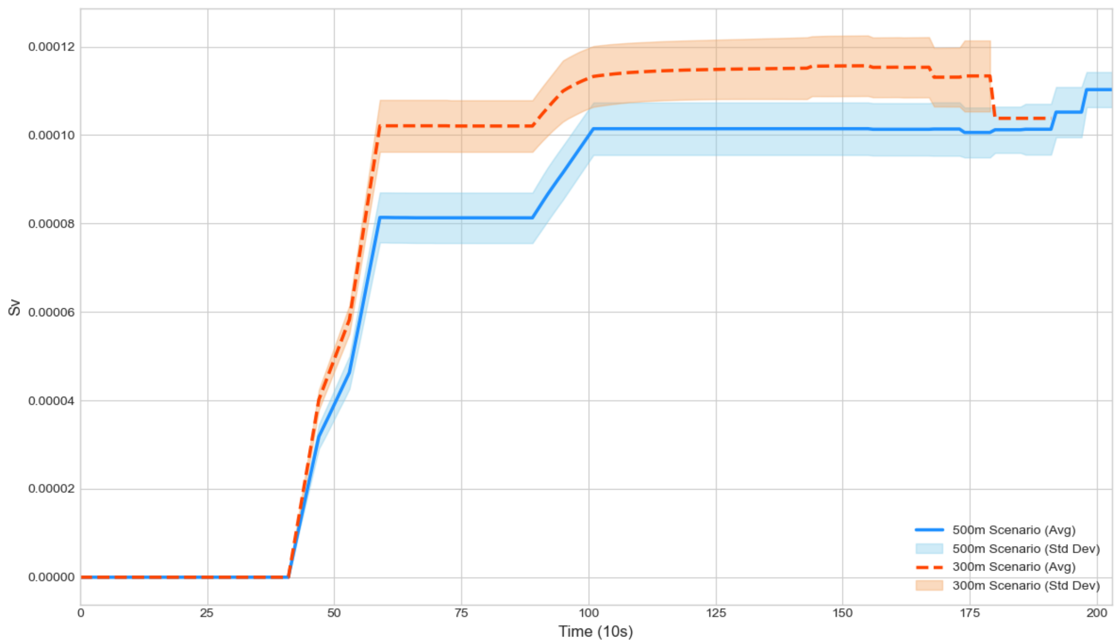

FIGURE 1. Comparison of cumulative exposure dose by assembly point radius scenario

B. Analysis of exposure dose by evacuation start time

The second simulation evaluated the impact of the delay between the disaster warning and the actual start of evacuation on exposure dose. The evacuation start time was varied from 10 to 30 minutes in two-minute intervals. Figure 2 shows the distribution of final cumulative exposure doses, with the results grouped according to each specific delay time. The mean, maximum, and minimum cumulative exposure doses for each scenario were analyzed, with the results shown in Figure 2.

The analysis shows a general trend of increasing average cumulative exposure dose (blue line) as the evacuation start time is delayed. The average dose, which was approximately $4.3 \times 10^{-5}\ Sv$ for a 10-minute delay, increased to about $6.0 \times 10^{-5}\ Sv$ with a 30-minute delay.

Particularly noteworthy is the change in the maximum dose (green line). The maximum exposure received by any single individual increased more sharply with delays. The maximum dose rose from approximately $7.0 \times 10^{-5}\ Sv$ at a 10-minute delay to a peak of nearly $1.2 \times 10^{-4}\ Sv$ at a 28-minute delay. This implies that delaying evacuation not only raises the average population dose but also significantly elevates the risk of severe exposure for certain individuals. Furthermore, the widening range between the minimum and maximum values indicates that longer delays lead to greater disparity in exposure outcomes among the population. This result scientifically substantiates that securing a 'golden time' for evacuation through prompt decision-making and public action is critical to minimizing casualties in a radiological emergency.

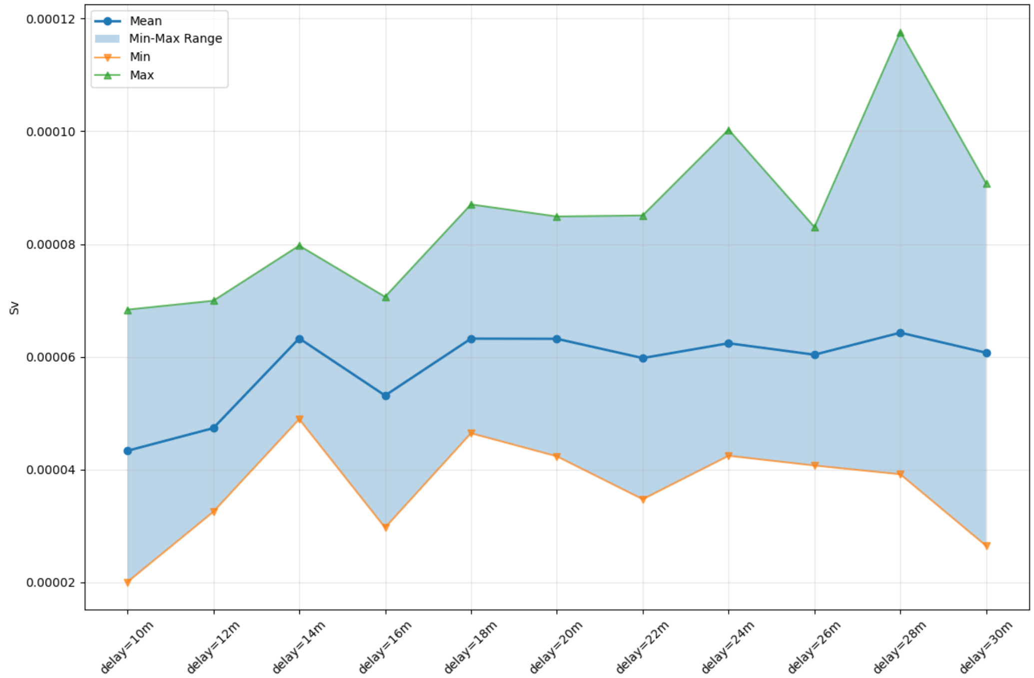

FIGURE 2. Distribution of final cumulative exposure dose by evacuation start delay

IV. CONCLUSIONS

This study developed and applied a real-time exposure dose evaluation model that considers the dynamic movements of residents during a radiological emergency, utilizing the agent-based radiological emergency evacuation simulation platform, PRISM. To overcome the limitations of existing static analysis models, this study integrated time-varying data on radioactive material concentration and ground deposition, derived from the HYSPLIT atmospheric dispersion model, into the simulation. Based on this, a methodology was implemented to dynamically track and precisely calculate the cumulative dose for each resident (agent) moving along an evacuation route, accounting for external exposure (from ground and cloud shine) and internal exposure (from inhalation of radioactive materials).

By using the developed simulation to quantitatively analyze the effects of evacuation method and start time on total exposure dose, significant policy implications were identified. First, the analysis of evacuation methods revealed that simply increasing the proportion of mass transit, such as buses, does not always guarantee an optimal outcome. A trade-off was observed where the scenario with a 500 m walking radius to assembly points resulted in a lower average cumulative exposure dose but a longer overall evacuation time compared to the 300 m radius scenario. This suggests that complex factors, including the assembly point radius, bottlenecks from bus waiting times, and the dispersion path of the radioactive plume, can create a policy dilemma between the goals of evacuation efficiency and exposure dose minimization.

Second, the analysis of evacuation start time delays clearly confirmed a trend of increasing average and maximum exposure doses as the time between the disaster warning and the actual start of evacuation grew longer. The average exposure dose increased from approximately $4.3 \times 10^{-5}\ Sv$ for a 10-minute delay to about $6.0 \times 10^{-5}\ Sv$ for a 30-minute delay, while the maximum individual exposure dose rose even more sharply. This result scientifically substantiates that securing a 'golden time' for evacuation through prompt decision-making and public action is the most critical factor in minimizing casualties during a radiological emergency.

However, this study has the following clear limitations. First, there is a temporal mismatch between the hourly data provided by the HYSPLIT atmospheric dispersion model and the 10-second timestep of the PRISM simulation. Calculations were performed by interpolating the hourly data, which may limit the model's ability to precisely reflect rapid, real-time changes in concentration. Second, the current model assumes that residents immediately evacuate outdoors and does not consider an 'indoor sheltering' scenario, where individuals might wait inside before evacuating. As indoor sheltering provides significant radiation shielding, its omission may act as a factor that overestimates the actual exposure dose.

Despite these limitations, the dynamic exposure dose evaluation simulation developed in this study is significant as a powerful analytical tool that overcomes the shortcomings of static analysis, allowing for the quantitative comparison and assessment of various strategies in a realistic evacuation scenario. The findings of this research provide a scientific basis for determining optimal evacuation start times and transportation mode mixes. Furthermore, by laying the groundwork for incorporating more detailed protective actions like indoor sheltering, this study can contribute to formulating more effective emergency response strategies and enhancing national radiological emergency preparedness.

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REFERENCES

[1] Ten Hoeve, J. E., & Jacobson, M. Z. (2012). Worldwide health effects of the Fukushima Daiichi nuclear accident. Energy & Environmental Science, 5(9), 8743-8757.
[2] Srinivas, C. V., Rakesh, P. T., Hari Prasad, K. B. R. R., Venkatesan, R., Baskaran, R., & Venkatraman, B. (2014). Assessment of atmospheric dispersion and radiological impact from the Fukushima accident in a 40-km range using a simulation approach. Air Quality, Atmosphere & Health, 7, 209-227.
[3] Marzo, G. A. (2014). Atmospheric transport and deposition of radionuclides released after the Fukushima Dai-chi accident and resulting effective dose. Atmospheric Environment, 94, 709-722.
[4] Yamashita, S., Suzuki, S., Suzuki, S., Shimura, H., & Saenko, V. (2018). Lessons from Fukushima: latest findings of thyroid cancer after the Fukushima nuclear power plant accident. Thyroid, 28(1), 11-22.
[5] Sakai, A., Nakano, H., Hashimoto, K., Okazaki, K., Nagao, M., Shimabukuro, M., ... & Yasumura, S. (2025). Changes in peripheral blood test results among adults in the six years following the Great East Japan Earthquake: the Fukushima Health Management Survey. Fukushima journal of medical science, 24-00041.
[6] Harada, N., Shigemura, J., Tanichi, M., Kawaida, K., Takahashi, S., & Yasukata, F. (2015). Mental health and psychological impacts from the 2011 Great East Japan Earthquake Disaster: a systematic literature review. Disaster and military medicine, 1, 1-12.
[7] Protection, R. (2007). ICRP publication 103. Ann ICRP, 37(2.4), 2.
[8] Ishikawa, T. (2020). Individual doses to the public after the Fukushima nuclear accident. Journal of Radiation Protection and Research, 45(2), 53-68.
[9] Kim, G., & Heo, G. (2023). Agent-based radiological emergency evacuation simulation modeling considering mitigation infrastructures. Reliability Engineering & System Safety, 233, 109098.
[10] Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J., Cohen, M. D., & Ngan, F. (2015). NOAA's HYSPLIT atmospheric transport and dispersion modeling system. Bulletin of the American Meteorological Society, 96(12), 2059-2077.
[11] Eckerman, K. F., & Ryman, J. C. (2019). External exposure to radionuclides in air, water, and soil (No. EPA 402-R-19-002). Oak Ridge National Lab., TN (United States).
[12] Eckerman, K. F., Wolbarst, A. B., & Richardson, A. C. (1988). Limiting values of radionuclide intake and air concentration and dose conversion factors for inhalation, submersion, and ingestion: Federal guidance report No. 11 (No. EPA-520/1-88-020). Environmental Protection Agency, Washington, DC (USA). Office of Radiation Programs; Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).
[13] Katata, G., Chino, M., Kobayashi, T., Terada, H., Ota, M., Nagai, H., ... & Sanada, Y. (2015). Detailed source term estimation of the atmospheric release for the Fukushima Daiichi Nuclear Power Station accident by coupling simulations of an atmospheric dispersion model with an improved deposition scheme and oceanic dispersion model. Atmospheric chemistry and physics, 15(2), 1029-1070.