Probabilistic Assessment of Radiation Exposure Risk Considering Shadow Evacuation Near a Nuclear Facility: Application of Evacuation Simulation and Level 3 PRA

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ABSTRACT

This study presents a novel probabilistic risk assessment of radiation exposure that incorporates the impact of "shadow evacuations" — voluntary evacuations by residents in the Urgent Protective Action Planning Zone (UPZ) — on prioritized evacuations from the Precautionary Action Zone (PAZ) during a nuclear emergency. In Japan, PAZ residents are expected to evacuate promptly before the release of radioactive material, while UPZ residents are generally advised to shelter indoors initially. However, uncoordinated UPZ evacuations can cause severe traffic congestion, potentially delaying PAZ evacuations and increasing radiation exposure. To quantify these effects, we combined evacuation simulations using PTV VISUM-SBA with radiological consequence assessments using the MACCS2 (v1.13) code. A densely populated area surrounding a representative Japanese nuclear facility was modeled, and Evacuation Time Estimation (ETE) were derived under varying UPZ shadow evacuation rates. As MACCS2 does not natively support detailed traffic flow modeling, we developed a method to translate simulation-based delays into phase-specific evacuation speeds, enabling realistic integration of congestion effects into Level 3 PRA. We also introduced a new risk metric, the Relative Population Dose (RPD), to capture changes in collective dose under different evacuation scenarios. The results indicate that increasing levels of UPZ shadow evacuation substantially delay PAZ evacuations, leading to elevated radiation risk depending on the timing of protective actions. Conversely, UPZ residents themselves experience lower exposure if evacuation occurs after the release has concluded, reinforcing the rationale behind Japan's current phased evacuation policies. These findings emphasize the critical need for real-time, risk-informed decision-making in emergency response planning.

Keywords: Level 3 PRA, Evacuation Simulation, Shadow evacuations, Emergency Preparedness and Response, ETE

I. INTRODUCTION

In the field of nuclear safety assessment, it is essential not only to evaluate system reliability and hardware integrity but also the effectiveness of protective actions for surrounding residents[1]. One critical behavioral phenomenon during nuclear emergencies is "shadow evacuation," where residents outside designated evacuation zones voluntarily evacuate, potentially causing severe traffic congestion and delaying priority evacuations[2].

In Japan, nuclear emergency planning zones are divided into the Precautionary Action Zone (PAZ, approximately 5 km radius), where residents must evacuate immediately before radioactive release, and the Urgent Protective Action Planning Zone (UPZ, approximately 30 km radius), where residents are initially instructed to shelter indoors[3]. However, spontaneous evacuation by UPZ residents can interfere with PAZ evacuations, creating a policy dilemma.

Level 3 Probabilistic Risk Assessment (PRA) is widely used to quantitatively assess risks to the public during nuclear accidents[4, 5]. While Level 3 PRA considers dispersion of radioactive materials and resulting health effects, conventional models simplify evacuation behavior with fixed parameters, failing to reflect real-world evacuation dynamics[6].

This study aims to evaluate how shadow evacuations by UPZ residents influence the evacuation performance and radiation exposure risk for PAZ residents. We integrate a traffic simulation model (PTV VISUM with Simulation-Based Assignment (SBA)[7]) with a Level 3 PRA tool (MACCS2[8]), allowing us to probabilistically assess the impact of evacuation behavior on radiation exposure. Compared to prior studies, this research:

- Develops a high-resolution method to reflect evacuation delay caused by shadow evacuations;
- Applies the analysis to a Japanese nuclear site with realistic demographic and infrastructural data;
- Provides policy-relevant insights into managing shadow evacuations under uncertainty.

This study builds on prior U.S.-based research[9, 10] but represents the first application of this integrated framework to a Japanese context, contributing to both methodological advancement and policy formulation.

II. METHODOLOGY

This study integrates traffic simulation with Level 3 PRA to evaluate radiation risk under different shadow evacuation scenarios. The methodology consists of three main components: evacuation simulation using VISUM-SBA, risk calculation using MACCS2, and definition of risk indicators.

II.1. Evacuation Simulation using VISUM-SBA

For ethical and security reasons, the name of the study area is not disclosed. This study does not aim to evaluate site-specific radiological risk, but to generalize how evacuation behavior influences radiation exposure risk. Accordingly, the analysis emphasizes causal mechanisms and structural patterns over region-dependent numerical values.

A hybrid traffic model, VISUM-SBA, was selected to simulate evacuation from areas near a Japanese nuclear power plant. VISUM-SBA combines a macroscopic road network model (VISUM) with a simplified behavioral algorithm (SBA) to estimate Evacuation Time Estimations (ETE) under varying population and traffic conditions. The macroscopic model calculates traffic flow based on road capacities and demand, while SBA distributes departure times and route choices based on probabilistic rules. This hybrid approach enables efficient simulation of large-scale evacuations without requiring full microsimulation. The model estimates ETE for residents in both PAZ and UPZ zones. The population distribution was based on Japanese census data, mapped to concentric mesh zones. While the specific location is not disclosed, the characteristics of the study area are broadly consistent with those of a mid-sized Japanese municipality in a semi-urban region. The population density in the PAZ (0–5 km) and UPZ (5–30 km) zones ranges from approximately 500 to 2,000 persons per square kilometer. The local road network includes both arterial roads and residential streets, with daily traffic volumes on main evacuation routes ranging from a few thousand to over ten thousand vehicles per day. These conditions provide a representative context for testing the effects of evacuation behavior on radiation risk without relying on site-specific identifiers. Shadow evacuation rates for UPZ residents under various shadow evacuation rates (0% to 90%). Road network data were extracted from OpenStreetMap[11] and processed to represent realistic evacuation routes, considering road type, lane count, and signal locations.

Vehicle counts were estimated assuming a Vehicle Occupancy Rate (VOR) of 2. The simulation output includes time-dependent vehicle passage across the 30 km zone boundary. The departure time for both PAZ residents and shadow evacuees in the UPZ was assumed to be within 0 to 1 hour after the initiation of the evacuation order.

Figure 1 shows the cumulative evacuation rates for PAZ and UPZ residents under different shadow evacuation scenarios.

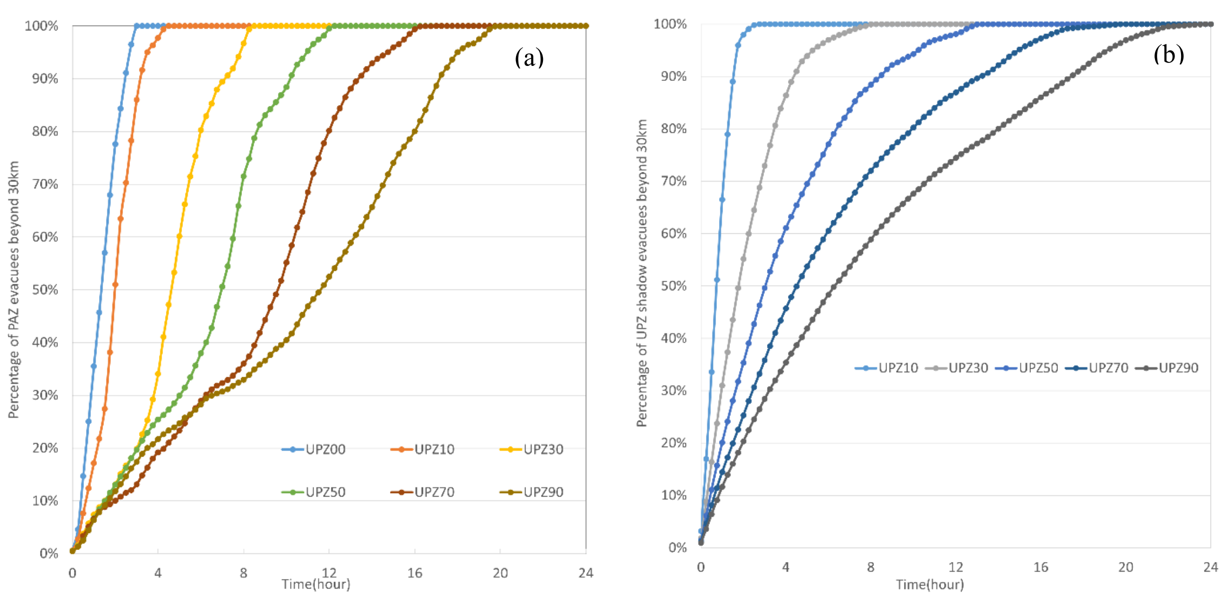

FIGURE 1. Cumulative evacuation rates of residents are beyond the 30 km zone under different shadow evacuation scenarios: (a) PAZ residents and (b) UPZ residents. Each curve represents a scenario with a different percentage of shadow evacuation in the UPZ, ranging from 0% to 90%. The data reflects traffic simulation results using VISUM-SBA.

II.2. Development of a New Method for Integrating ETE into MACCS2

In MACCS2, the analysis domain is divided into multiple spatial meshes to represent evacuation behavior. Each mesh is assigned a population, and since the size of the meshes is not uniform—outer meshes tend to have larger areas than central ones—meshes on the periphery generally contain more people, even when population density per unit area is assumed to be constant. Due to this spatial structure, evacuation tends to be completed earlier in the outer regions with larger populations, while the inner meshes, which contain fewer people, tend to remain until later in the process. As a result, the rate of increase in the evacuation completion ratio (ECR) tends to slow down over time.

In this study, significant inflection points in the ECR curve—approximately 28% for PAZ residents and 17% for UPZ residents—were used to define the timing of the first change in ESPEED1 (DURBEG). In addition, following the U.S. NRC's ETE guidelines[12], where the 90% Evacuation Completion Time (ECT) is considered a key benchmark, the midpoint of the evacuation period (DURMID) in ESPEED2 was set accordingly. The final evacuation speed (ESPEED3) was adjusted to align with the time when ECR reaches 100%. Meanwhile, the values of ESPEED1 and ESPEED2 were also modified based on the results of the evacuation simulation to ensure consistency with the traffic conditions observed in VISUM-SBA.

These parameter settings were determined approximately based on the results of traffic simulations and applied to MACCS2. Since these settings involve a degree of analyst discretion, future work should aim to develop more objective and automated methods for parameter estimation.

To bridge the gap between traffic simulation results and MACCS2 inputs, we developed a new approximation method that quantitatively relates ECT and ECR. Specifically, ECT_i for each concentric mesh cell i is computed using the following piecewise function based on its evacuation distance d_i, which represents the distance from mesh cell i to the designated evacuation destination:

(1) $if\ d_i \le ESPEED1 \times DURBEG$

$$ECT_i = \frac{d_i}{ESPEED1} \tag{1}$$

(2) $if\ ESPEED1 \times DURBEG < d_i \le ESPEED1 \times DURBEG + ESPEED2 \times DURMID$

$$ECT_i = DURBEG + \frac{d_i - ESPEED1 \times DURBEG}{ESPEED2} \tag{2}$$

(3) if $d_i > ESPEED1 \times DURBEG + ESPEED2 \times DURMID$

$$ECT_i = DURBEG + DURMID + \frac{d_i - (ESPEED1 \times DURBEG + ESPEED2 \times DURMID)}{ESPEED3} \tag{3}$$

Here, ESPEED1–3 represent evacuation speeds (km/h) for each phase, and DURBEG and DURMID are their respective duration periods (hours). To calibrate ECR_i in MACCS2 based on VISUM-SBA results, the following steps were performed: The ECR_i in MACCS2 is defined as a cumulative value representing the proportion of the population in mesh i that has relocated to the designated evacuation mesh over time.

(1) Data Acquisition： The d_i for each mesh and the corresponding ECR_i are extracted from the MACCS2 output, assuming a constant-speed NETWORK evacuation scenario.
(2) Calculation of ECT_i: Using the previously obtained distance d_i, ECT_i for each location is calculated by applying a predefined piecewise function.
(3) Data Structuring: The calculated ECT_i are paired with their corresponding ECR_i values to construct the ECT_i–ECR_i correspondence dataset for MACCS2.
(4) Graph Generation: To compare the results with the ETE obtained from VISUM, both the MACCS2-derived ECT_i and ECR_i values and the VISUM ETE results are plotted on the same graph.
(5) Adjustment of ESPEED3: The evacuation speed parameter for the third period in MACCS2 (ESPEED3) is iteratively adjusted to align the ECR_i curve with the ECR curve obtained from the VISUM ETE results.

Figure 2 compares the ETE results from VISUM-SBA and MACCS2. Under the 0% shadow evacuation scenario, VISUM-SBA produced a smooth ECR curve for PAZ residents, reflecting continuous vehicle flow. In contrast, MACCS2's curve exhibited stepwise increases due to mesh-based movement assumptions. While both models yielded similar 90% ETE values, MACCS2 showed more abrupt changes, particularly between 1.5 and 2.5 hours, highlighting the limitations of discrete spatial modeling. For the 90% shadow evacuation scenario, UPZ residents' ECR curves revealed greater discrepancy in the early phase (0–8 hours), with MACCS2 lagging VISUM-SBA. From 8 to 24 hours, the models aligned more closely, ultimately converging in final ETE. These results underscore the impact of initial evacuation speed settings and spatial granularity in MACCS2. While the developed parameter adjustment approach improved overall alignment, deviations in the mid-phase suggest areas for future refinement in evacuation modeling.

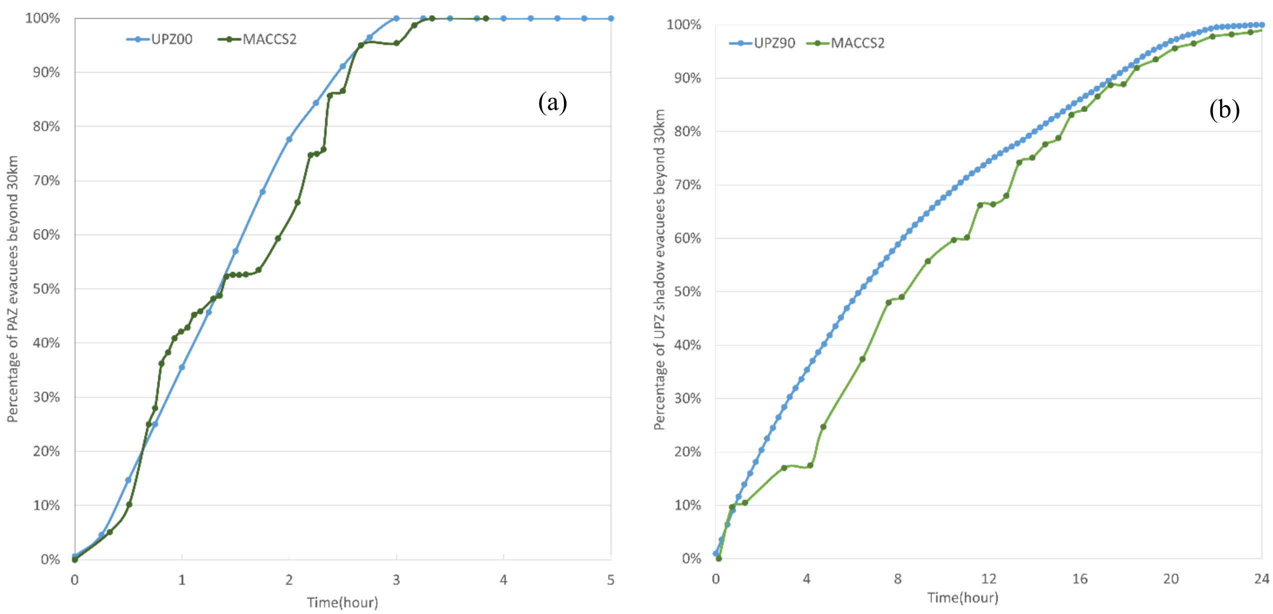

FIGURE 2. Comparison of evacuation completion rates between PAZ and UPZ residents using VISUM-SBA and MACCS2 simulations:(a) PAZ evacuation under 0% shadow evacuation scenario, and(b) UPZ evacuation under 90% shadow evacuation scenario.

II.3. MACCS2 inputs Configuration

The MACCS2 (v1.13) input configuration in this study followed the default settings from Sample Problem A as described in NUREG/CR-6613, except where it was modified for this analysis. Spatial mesh boundaries were adjusted to clearly delineate the PAZ (0–5 km) and UPZ (5–30 km) zones, following Japan's nuclear emergency response guidelines.

Meteorological sampling was configured using the "Stratified Random Samples for Each Day of the Year" option with 1,460 samples. The weather dataset from the Surry site, included in MACCS2's default input, was used without modification.

Radiation dose assessments were conducted using the EARLY module for the following four cohorts: PAZ evacuees, UPZ evacuees, UPZ shelterers, and non-evacuating residents outside 30 km. The proportions of Cohorts 2 and 3 were varied to simulate different shadow evacuation scenarios.

Evacuation modeling in MACCS2 used dynamic speed settings derived from VISUM-SBA results. While the definitions of ESPEED1–3 and DURBEG/DURMID are provided in the previous section, we note here that these parameters were carefully calibrated based on traffic patterns observed in the VISUM-SBA simulation. Specifically, DURBEG and DURMID were determined so that their combination with corresponding speeds reproduces realistic evacuation distances and timings. Although in several scenarios the product of ESPEED1 and DURBEG is approximately 30 km, this reflects the intended evacuation distance for PAZ residents and is not arbitrary. Phase-specific congestion effects are then captured through adjustments to ESPEED2, ESPEED3, and the respective durations. The evacuation speeds and durations were scenario-specific and are summarized in Tables 1 and 2. In the MACCS2 configuration, the evacuation start time for the PAZ cohort (Cohort 1) and the shadow evacuee cohort from the UPZ (Cohort 2) was also set to be the same.

To reflect realistic evacuation delays under varying traffic conditions, this study did not use the MACCS2 default evacuation speed of 1.8 m/s (6.48 km/h), which is uniformly applied across all time periods in the Surry site sample input. Instead, speeds were adjusted based on VISUM-SBA simulation results. As shown in Table 1, the initial speed (ESPEED1) for PAZ residents was set as high as 40.4 km/h in the baseline scenario (UPZ00), reflecting the assumption that they can evacuate promptly before plume release when no shadow evacuation occurs.

As the shadow evacuation rate in the UPZ increases, traffic congestion worsens, leading to a general decline in ESPEED1, ESPEED2, and ESPEED3 for both PAZ and UPZ residents. This trend is evident across the scenarios in Tables 1 and 2. Additionally, longer travel times in congested conditions necessitate extended phase durations (DURBEG and DURMID), resulting in increased total evacuation time. These speed and duration parameters were systematically varied for shadow evacuation rates of 0%, 10%, 30%, 50%, 70%, and 90%, and used in MACCS2 to evaluate radiation risk for both PAZ and UPZ populations. |

In the evacuation simulation, the endpoint of evacuation was defined as the central area of a real city located more than 50 km from the release point, based on actual designated evacuation destinations.

In contrast, for the MACCS2 network evacuation modeling, the evacuation destination was defined as a point beyond 100 km from the release point. This is because in MACCS2, once evacuees reach the destination, further dose calculation ceases, potentially underestimating the actual exposure if the destination is too close to the source. Therefore, a more distant endpoint was used to capture a more conservative dose estimate.

Table 1. Evacuation Speeds and Durations for PAZ Residents

Scenario	ESPEED1 (km/h)	ESPEED2 (km/h)	ESPEED3 (km/h)	DURBEG (h)	DURMID (h)
UPZ00	40.4	5.5	2.0	0.75	1.75
UPZ10	20.2	6.4	1.0	1.5	1.5
UPZ30	8.1	3.2	1.0	3.8	3.0
UPZ50	6.7	1.8	0.5	4.5	5.3
UPZ70	5.1	1.4	0.5	6.0	6.8
UPZ90	5.1	0.9	0.5	6.0	10.8

Table 2. Evacuation Speeds and Durations for UPZ Residents

Scenario	ESPEED1 (km/h)	ESPEED2 (km/h)	ESPEED3 (km/h)	DURBEG (h)	DURMID (h)
UPZ10	25.0	20.0	5.0	0.5	1.0
UPZ30	18.3	5.3	2.0	0.5	4.3
UPZ50	9.2	2.8	1.0	1.0	8.0
UPZ70	6.1	1.8	1.0	1.5	12.5
UPZ90	3.1	1.5	1.0	3.0	15.5

II.4. Radiation Risk Metrics

Radiation risk was quantified using the Population Dose (PD), defined as the product of average effective dose and population size (person-Sv). A new normalized indicator, Relative Population Dose (RPD), was introduced to evaluate the risk reduction effect of evacuation. RPD is defined as the ratio of PD under evacuation to PD under 7-days indoor sheltering. RPD > 1 indicates evacuation increased exposure; RPD < 1 indicates risk reduction.

This modeling framework enables probabilistic assessment of evacuation behavior's impact on radiation exposure, considering both traffic congestion and meteorological variability.

III. RESULTS AND DISCUSSION

III.A. Results of PAZ residents

Using MACCS2 simulations, this study evaluated radiation risk for PAZ residents under varying shadow evacuation rates by UPZ residents. The RPD was used to compare evacuation scenarios against a baseline of 7-days indoor sheltering. Figure 3 illustrates the RPD of PAZ residents under both average (Mean) and worst-case (Max) meteorological conditions. In this study, the "worst-case meteorological condition" refers to the condition under which the collective dose to the population becomes the highest among the meteorological scenarios considered. It does not necessarily correspond to extreme values of individual weather variables such as wind speed or precipitation but rather reflects the atmospheric conditions most conducive to maximizing radiological exposure.

III.A 1. Pre-Release Evacuation

When evacuation began before the release of radioactive plumes (i.e., in the negative X-axis region), a general reduction in radiation exposure risk for PAZ residents was observed. Under scenarios where the shadow evacuation rate of UPZ residents was 10% or lower, PAZ residents could evacuate without encountering the plume, resulting in an RPD of 0. This was due to minimal traffic congestion, allowing timely evacuation.

However, when the shadow evacuation rate exceeded 30%, delays in PAZ evacuation occurred, preventing completion before plume arrival and making it difficult to avoid exposure.

In the Max case (Figure 3(b)), the RPD values were higher compared to the Mean case (Figure 3(a)), indicating that shadow evacuations by UPZ residents significantly affect the effectiveness of pre-emptive evacuation of PAZ residents. This result highlights the critical role of UPZ shadow evacuation behavior in determining the evacuation success and radiation risk for PAZ residents.

III.A 2. Evacuation During Release (0–1 Hour)

When evacuation was initiated during plume release (0–1 hour), RPD values for PAZ residents exceeded 1 in both Mean and Max cases once the shadow evacuation rate reached approximately 30%. This implies that exposure doses during evacuation could surpass those from 7 days of sheltering in place.

A sharp increase in radiation dose was observed for PAZ residents under scenarios with shadow evacuation rates above 30%, due to evacuation congestion delaying PAZ movement and increasing exposure during plume passage. These results highlight the critical importance of evacuation timing, as well as the influence of UPZ residents' unplanned evacuation on PAZ evacuation strategy.

Although the RPD values did not show significant differences between the Mean and Max meteorological conditions, this should not be interpreted as an indication that the radiation dose received during evacuation is insensitive to weather conditions. Here, RPD is defined as the ratio of the collective dose under the evacuation scenario to that under the full indoor sheltering scenario. Since the denominator—the collective dose from indoor sheltering—varies between meteorological conditions, the apparent similarity in RPD values reflects the relative relationship between two distinct group dose estimates rather than absolute insensitivity. Therefore, the results should be interpreted with caution. Nevertheless, these findings reinforce the importance of initiating evacuation prior to plume release under any meteorological condition.

III.A 3. Post-Release Evacuation (After 1 Hour)

When evacuation began after the plume release (>1 hour), RPD values for PAZ residents remained relatively constant, regardless of the UPZ shadow evacuation rate. Since exposure occurred primarily during indoor sheltering before evacuation, the act of post-plume evacuation had limited additional impact.

Differences in ECT had only minor effects on additional exposure from surface-deposited radionuclides. Notably, there was little difference between the Mean and Max cases, suggesting that post-release weather variations had limited influence. Therefore, route selection and destination planning are more critical than speed in reducing radiation exposure in this phase.

III.A 4. Evacuation Time and Radiation Risk Correlation

Even under a high shadow evacuation rate of 90% among UPZ residents, the *ECT* for PAZ residents remained around 20 hours (see Figure 1(a)). Since RPD = 1 corresponds to the dose from 7 days of indoor sheltering, post-plume evacuation can still reduce exposure.

The results show that increased shadow evacuation significantly affects PAZ residents' risk, mainly by delaying their evacuation. Thus, emergency planning must account for the impact of UPZ residents' spontaneous evacuation on PAZ evacuation efficiency and radiation exposure.

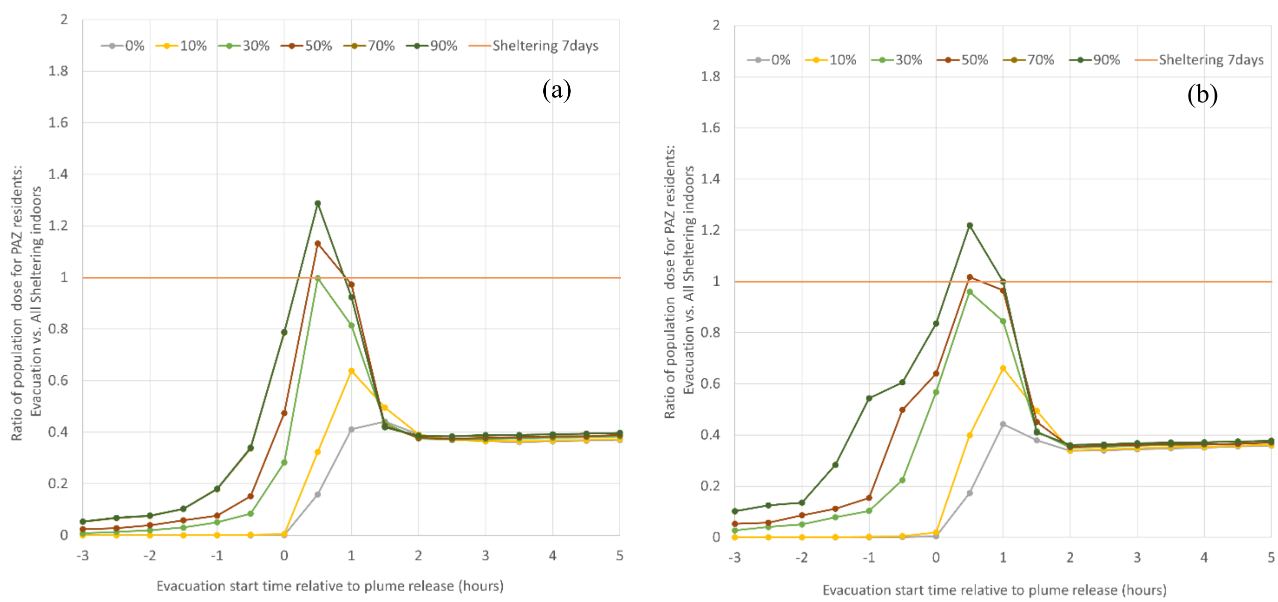

FIGURE 3. Relative Population Dose (RPD) for PAZ residents under two meteorological conditions based on MACCS2 output: (a) average condition (Mean), and (b) worst-case condition (Max). Each line represents a different shadow evacuation rate in the UPZ, showing the relative radiation dose from evacuation compared to a baseline of 7-days indoor sheltering (RPD = 1).

III.B. Results of UPZ residents

Under Japan's nuclear emergency guidelines, UPZ residents are advised to shelter indoors before plume release and evacuate based on post-release ambient dose rates. In this study, the remaining population in the UPZ—those who do not evacuate under each scenario—is assumed to shelter in place indoors for 7 days. The RPD in this section is calculated based on the collective dose of the entire UPZ population, and not on individual exposure levels. As shown in Figures 4(a) (Mean) and 4(b) (Max), the RPD remains at 1 when all residents shelter indoors. However, when evacuation is implemented, the RPD varies depending on the evacuation timing and the shadow evacuation rate. These variations are especially pronounced in the Max case, where meteorological conditions tend to amplify exposure differences. This highlights the importance of evacuation timing and the effect of traffic-induced delays on the overall population dose.

III.B.1. Pre-Release Evacuation

In the Mean case (Figure 4(a)), when UPZ residents began shadow evacuation before plume release (i.e., negative X-axis), the RPD generally decreased compared to the shelter-in-place scenario. Notably, evacuating more than 3 hours prior to release led to lower RPDs, especially with higher shadow evacuation rates.

However, one hour before release, scenarios with a 90% shadow evacuation rate resulted in higher RPDs than those with 30%, due to severe congestion delaying evacuation. This inversion indicates that excessive shadow evacuation can increase risk by preventing timely evacuation.

Figure 4(b) (Max case) further reveals that even when evacuation began three hours prior, high shadow evacuation rates (≥70%) could still lead to RPD >1, highlighting the dominant influence of adverse weather. The Max results consistently show higher RPDs than Mean, stressing the impact of meteorological variability and plume behavior under congested conditions.

III.B.2. Evacuation During Release (0–1 Hour)

Evacuation during plume release led to a rapid increase in exposure, especially with higher shadow evacuation rates. In the Mean case, RPDs exceeded 1 at 50% shadow evacuation and reached over 1.4 at 90%. The Max case showed even more severe outcomes, with RPDs reaching up to 3 under a 90% shadow evacuation rate.

The highest risk scenario occurred under specific winter morning meteorological conditions: wind speed of 2.5 m/s, Pasquill–Gifford stability class F, and wind direction directly impacting densely populated areas. These stable atmospheric conditions promoted ground-level plume retention and high localized radiation concentrations.

Thus, evacuating during plume release, particularly under high congestion and unfavorable weather, significantly increases UPZ residents' radiation risks. This finding underscores the need for cautious evacuation timing in emergency plans.

III.B.3. Post-Release Evacuation (After 1 Hour)

Post-release evacuation generally led to decreasing RPDs over time, regardless of shadow evacuation rate. This was attributed to accumulated exposure during sheltering, which was then mitigated by evacuation. Higher shadow evacuation rates further reduced collective doses by shifting more residents from sheltering to evacuation.

However, practical challenges such as shelter capacity and route congestion must be considered; maximizing evacuation participation does not automatically minimize risk.

In the Max case, trends diverged from the Mean case: RPDs remained above 1 at three hours post-release across all evacuation rates, indicating potential risk from premature evacuation before plume clearance. These results highlight the importance of verifying plume passage using real-time dose rate monitoring before initiating evacuation.

Given that current guidelines recommend evacuation only in high-contamination zones, more realistic modeling reflecting heterogeneous behavior and localized contamination is essential for future Level 3 PRA applications.

It should be noted that while RPD is used as a common metric in both PAZ and UPZ analyses, the underlying assumptions and cohort compositions differ between the two zones. Specifically, the population size, evacuation behavior, and sheltering assumptions are distinct. Therefore, direct comparison of RPD values across Figure 3 (PAZ) and Figure 4 (UPZ) should be made with caution, as they do not represent equivalent baseline conditions. Additional context is necessary for meaningful interpretation of relative values between the zones.

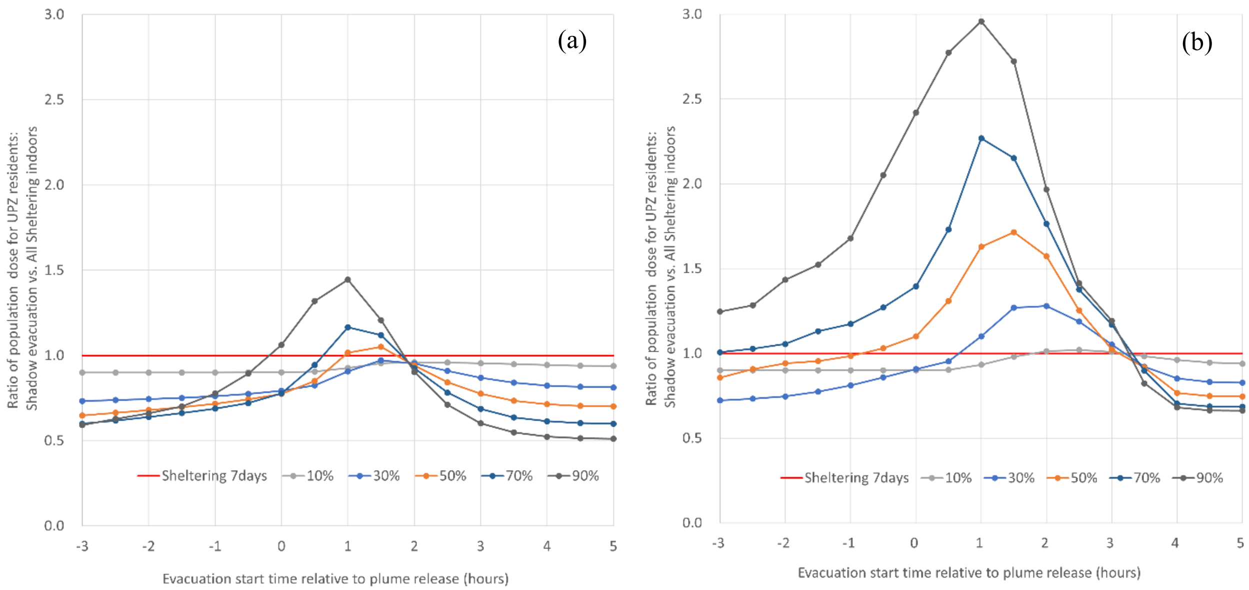

FIGURE 4. Relative Population Dose (RPD) for UPZ residents under two meteorological conditions based on MACCS2 output: (a) average condition (Mean), and (b) worst-case condition (Max). Each line represents a different shadow evacuation rate in the UPZ, showing the relative radiation dose from evacuation compared to a baseline of 7-days indoor sheltering (RPD = 1).

IV. CONCLUSION AND FUTURE WORK

This study integrated a traffic simulation model (PTV VISUM-SBA) with a Level 3 Probabilistic Risk Assessment tool (MACCS2) to evaluate how shadow evacuations by UPZ residents affect the radiation exposure risk of both PAZ and UPZ populations during a nuclear emergency in Japan. A new risk indicator, the Relative Population Dose (RPD), was introduced to quantify the relative effectiveness of evacuation versus sheltering.

The results demonstrate that shadow evacuation rates exceeding 30% significantly delay PAZ evacuation, leading to increased exposure risk, especially if evacuation occurs before or during the radioactive release. For UPZ residents, early evacuation can be effective under favorable conditions, but under adverse weather scenarios—such as stable atmospheric conditions and low wind speeds - high shadow evacuation rates can lead to elevated radiation doses, with RPD values exceeding 3 in extreme cases.

These findings highlight the complex, nonlinear relationship between evacuation timing, traffic congestion, and plume dynamics. They support Japan's current emergency response guidelines, which recommend pre-release evacuation for PAZ residents and indoor sheltering for UPZ residents until environmental radiation dose rates justify relocation. Managing shadow evacuation is critical not only for protecting PAZ residents but also for ensuring UPZ residents do not inadvertently increase their own exposure.

This study contributes to nuclear emergency planning by providing a quantitative framework to assess behavioral impacts on evacuation efficiency and public radiation risk. It underscores the importance of incorporating dynamic traffic modeling, and behavioral uncertainty into future Level 3 PRA applications.

Future work will focus on enhancing the realism and robustness of evacuation and risk modeling.

First, sensitivity analyses will be conducted on key traffic simulation parameters, including the distribution of evacuation start times, the vehicle occupancy rate (VOR), and the number of iterations for route assignment in VISUM-SBA. These factors could significantly influence Evacuation Time Estimation (ETE) and evacuation completion dynamics. This task is considered to have the greatest immediate impact on the calculated radiation risk, particularly through changes in evacuation delay and congestion. While sensitivity analysis in VISUM-SBA is technically feasible, performing it within MACCS2 presents a challenge due to its limited support for parameter uncertainty.

Second, future improvements will include integrating road hazard data such as blocked roads, reduced speed zones, and malfunctioning traffic signals, using disaster hazard maps. This task is technically feasible in principle and has been applied by the authors in prior U.S.-based studies using tools such as FEMA's HAZUS. However, the lack of equivalent geospatial hazard evaluation tools in Japan currently limits the ability to apply this method to domestic nuclear sites.

Third, more realistic behavioral rules for UPZ residents will be incorporated. Rather than assuming uniform shadow evacuation rates, future models will introduce Operational Intervention Levels (OILs) to trigger evacuation decisions based on real-time spatial dose rate measurements. Although MACCS2 supports protective action decisions based on cumulative dose (e.g., 7-day exposure), it does not natively support dose-rate-based evacuation logic. Implementing this capability would require model adaptation, such as estimating dose rates from integrated dose thresholds.

These developments aim to improve the generalizability and practical value of Level 3 PRA by more accurately capturing the dynamic and uncertain nature of evacuation behavior under nuclear emergency scenarios.

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REFERENCES

[1] IAEA, Preparedness and Response for a Nuclear or Radiological Emergency, 2015.
[2] P.B. Kevin Weinisch, The impact of shadow evacuation on evacuation time estimates for nuclear power plants, Journal of Emergency Management 13(2) (2015) 145-158.
[3] Nuclear Regulation Authority, Nuclear Emergency Response Guideline, 2019.
[4] J. Hirouchi, M. Watanabe, N. Hayashi, A. Nagakubo, S. Takahara, Effects of different accident scenarios and sites on the reduction factor used for expressing sheltering effectiveness, Journal of radiological protection : official journal of the Society for Radiological Protection (2025). https://doi.org/10.1088/1361-6498/adba6e.
[5] N.E. Bixler, S.-y. Kim, Performing a multi-unit level-3 PSA with MACCS, Nuclear Engineering and Technology 53(2) (2021) 386-392. https://doi.org/https://doi.org/10.1016/j.net.2020.07.034.
[6] JAEA, User's manual for the OSCAAR code package, 2020.
[7] PTV Group, PTV Visum. https://www.ptvgroup.com/en/products/ptv-visum, 2025.
[8] U.S.NRC, Code Manual for MACCS2, Users Guide 1998.
[9] K. Shimada, T. Sakurahara, S. Reihani, Z. Mohaghegh, Integration of transportation simulation with a level 3 PRA code for nuclear power plants, in: Proceedings of Asian Symposium on Risk Assessment and Management 2020 (ASRAM 2020)
[10] K. Shimada, T. Sakurahara, P. Farshadmanesh, S. Reihani, Z. Mohaghegh, Integration of Level 3 probabilistic risk assessment for nuclear power plants with transportation simulation considering earthquake hazards, Annals of Nuclear Energy 197 (2024) 110243. https://doi.org/https://doi.org/10.1016/j.anucene.2023.110243.
[11] Open Street Map Fundation, Java Open Street Map. https://josm.openstreetmap.de/, 2025.
[12] U.S.NRC, Criteria for Development of Evacuation Time Estimate Studies, NUREG/CR-7002 (2011).