Level 3 PRAコードと避難シミュレーションの統合

リスク評価防災研究グループ

嶋田和真

目的：Level 3 PRAの避難モデルをより現実的に表現することで原子力防災に役立つ知見を得ること
→交通シミュレーションを用いて住民の詳細な避難行動をLevel3PRAに反映する

*本研究は発表者がUniversity of Illinois at Urbana-Champaign校に留学していた際の研究成果です。
*本発表はASRAM2020(Asian Symposium on Risk Assessment and Management)での発表が基になっております。

Level3PRAの避難モデル

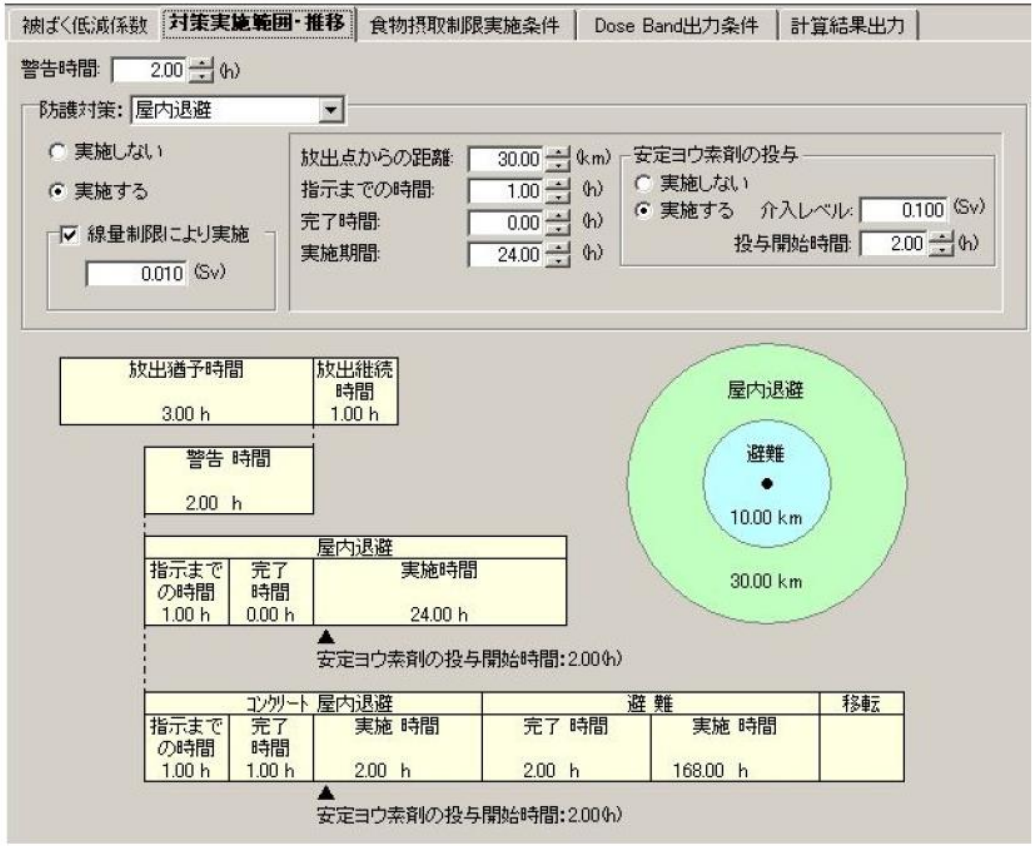


図 8-47　対策実施範囲、推移

Fig. GUI of OSCAAR: Set time and area of evacuation

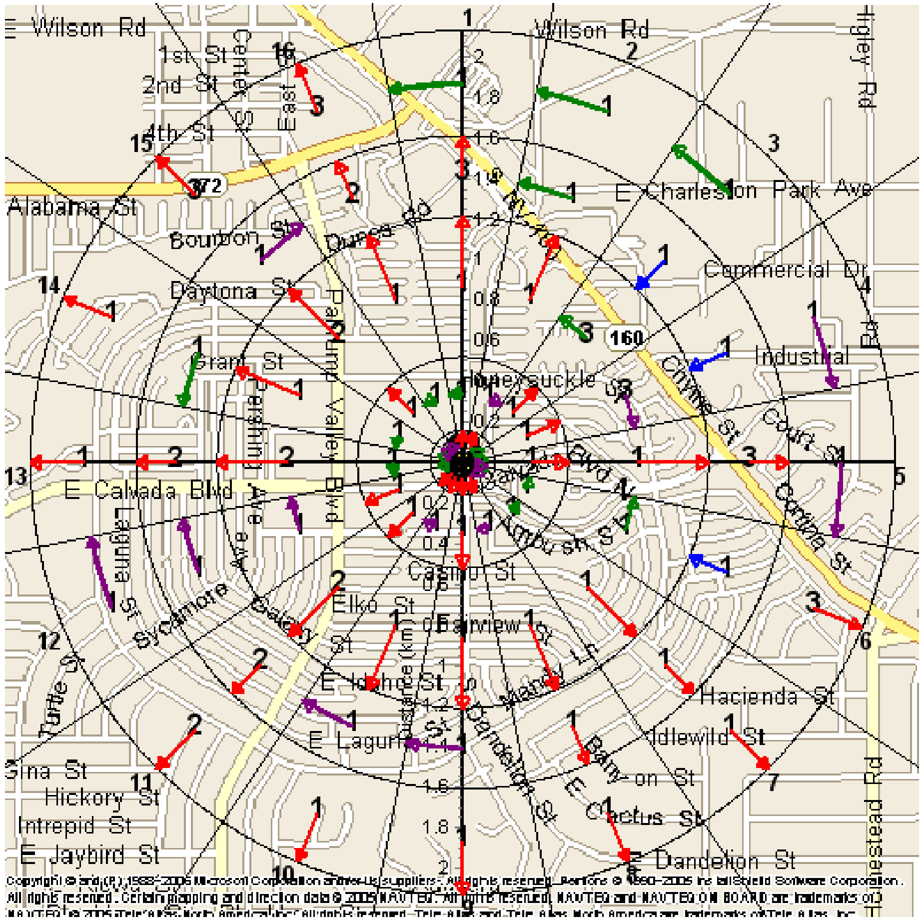
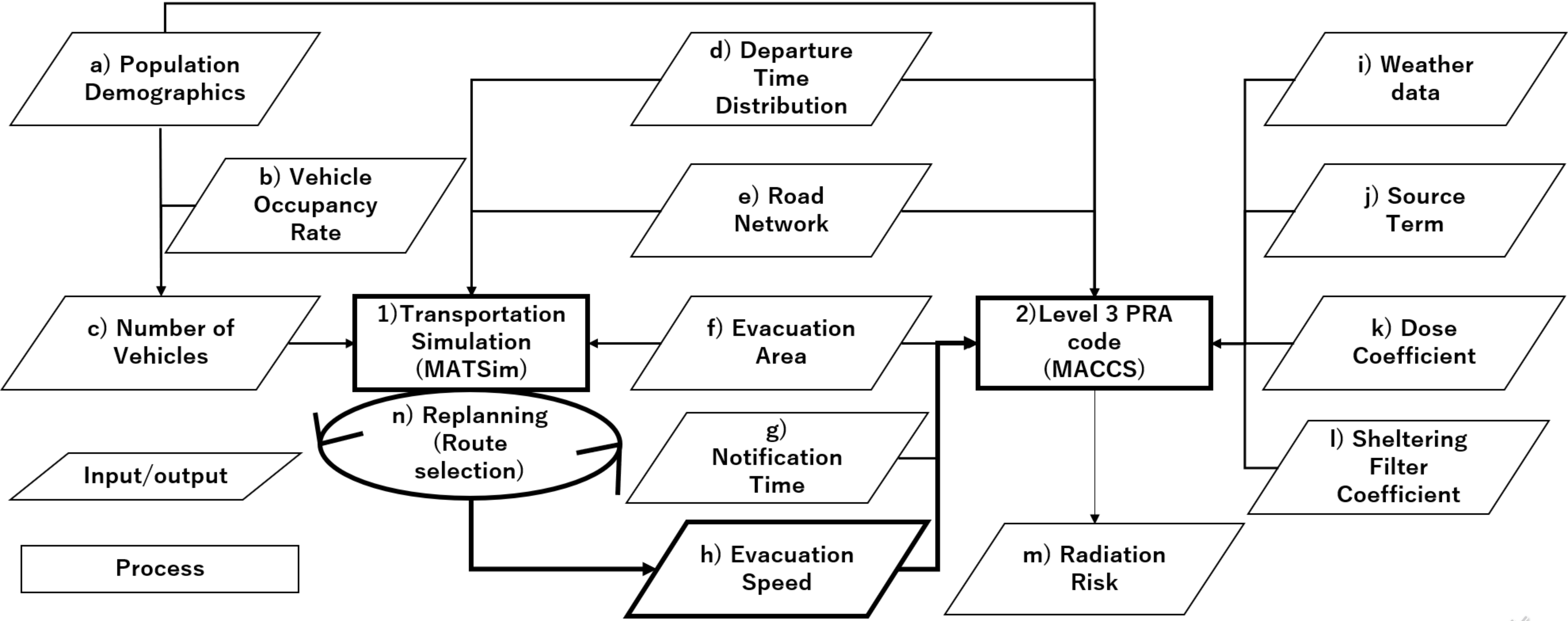


Fig. Evacuation route setting in MACCS

- OSCAAR(公開版）の避難モデルは避難中の移動を考慮しないモデル
- MACCSはメッシュ毎に避難経路を設定した避難（ネットワーク避難）が可能

＊避難速度を手動で入力する必要があるため、渋滞などの情報を明示的に表現できない。

Level 3 PRA codeと交通シミュレーションを統合するフレームワーク



K.Shimada, "Integration of Transportation simulation with a Level 3 PRA Code for Nuclear Power Plants", ASRAM 2020

テストケース：SOARA2017

- 米国NRCのSOARCA (State-of-the-Art Reactor Consequence Analysis) 2017 studyをテストケースとして採用（避難以外のパラメーターはSOARCA2017と同じ）
  - テネシー州Sequoyah原子力発電所、起因事象を地震に設定
- 避難行動のパラメーター設定に専門家判断
  - 例：EPZ(10mile以内）の速度を2mph
- 交通シミュレーションを用いることにより、Level3PRAの避難モデルをより現実的に表現

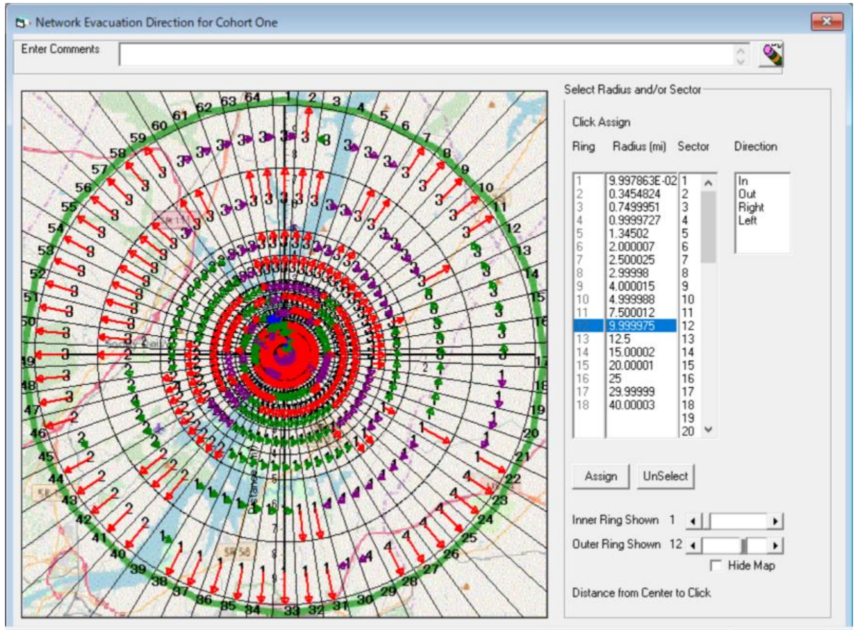


Fig. MACCSにおけるSequoyahのEPZ内の避難経路ネットワーク

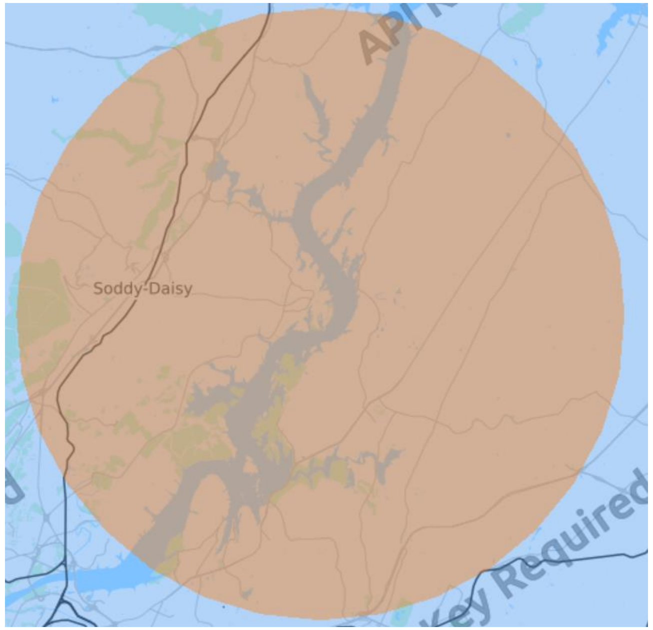
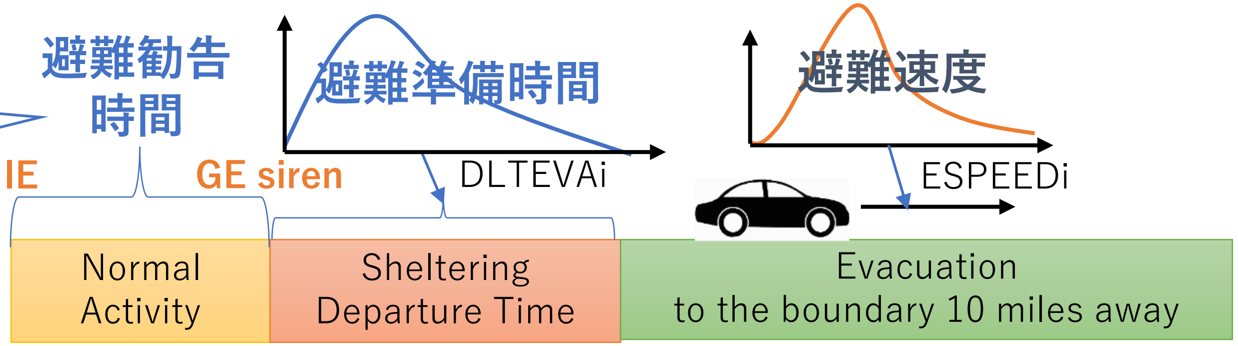


Fig. 交通シミュレーション（MATSim）のSequoyahのEPZ内の避難経路ネットワーク

避難モデルの設定

起因事象から緊急事態宣言のサイレンが鳴るまでは165分と設定（SOARCA）



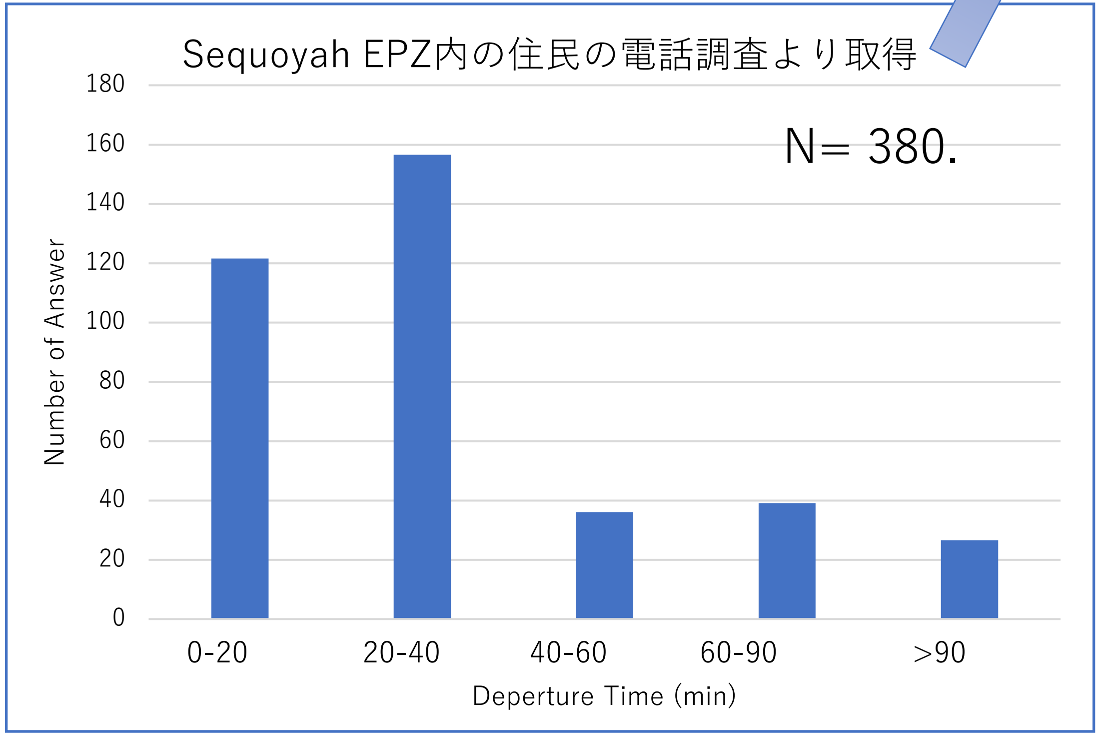


Fig. Sequoyah EPZ内の住民の避難準備時間（夜間）

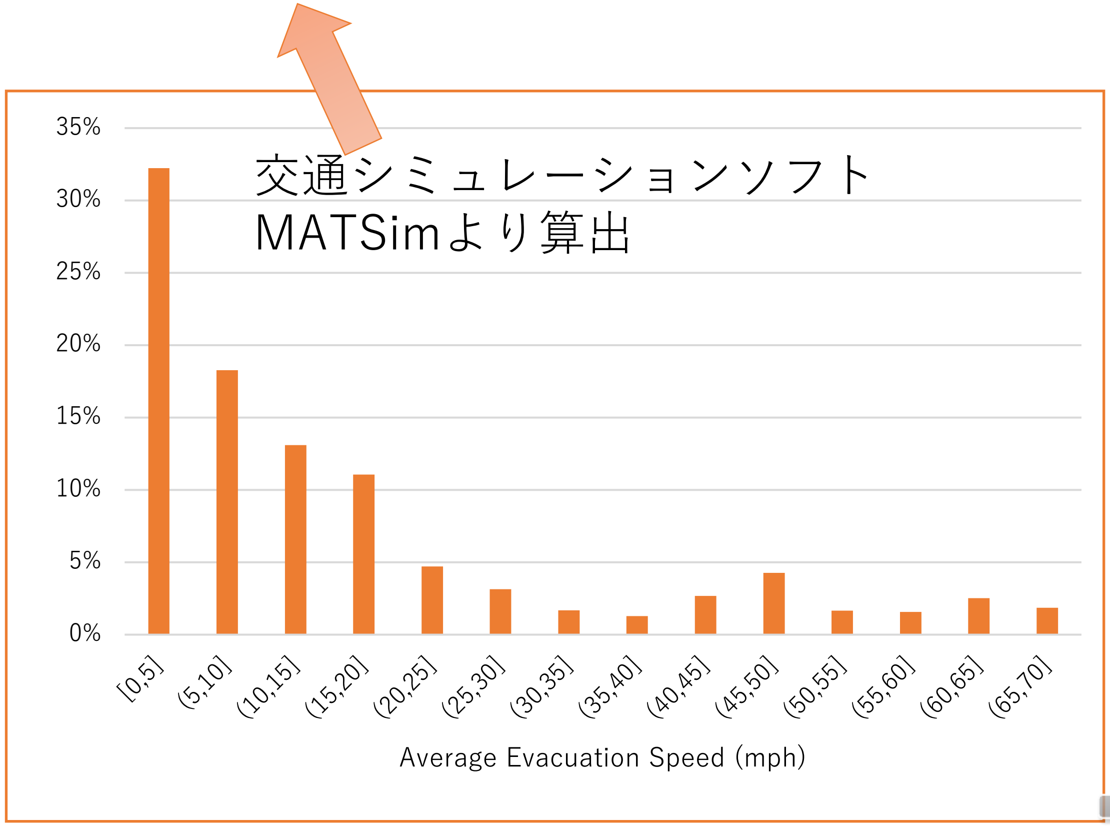
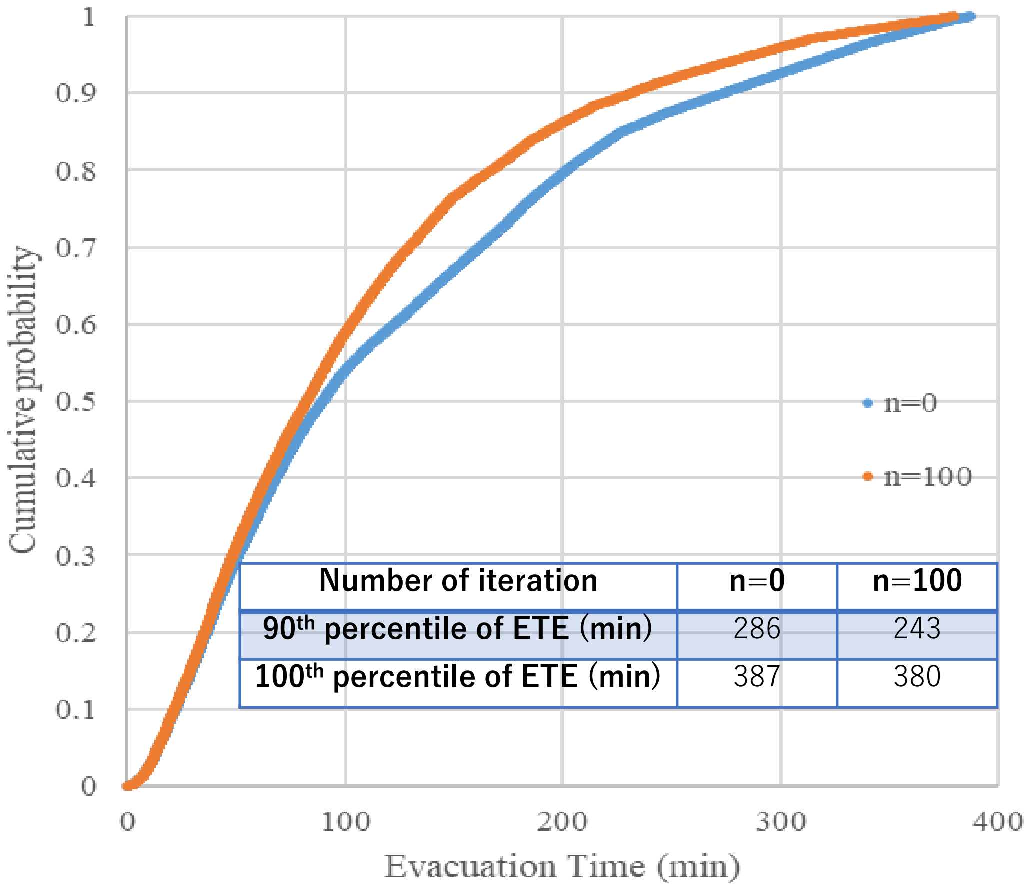


Fig. 避難車両の平均速度の分布

結果：避難経路の変更による被ばくリスク低下

- MATSimの避難経路選定機能より、避難距離が最短の場合(n=0)と避難時間の合計が最小となる避難経路を選んだ場合(n=100)と比較
  - 避難完了時間低下、平均避難速度上昇、**被ばくリスクは約30%低下**



Number of iteration	n=0	n=100
90th percentile of ETE (min)	286	243
100th percentile of ETE (min)	387	380

Fig. 累積の避難完了時間

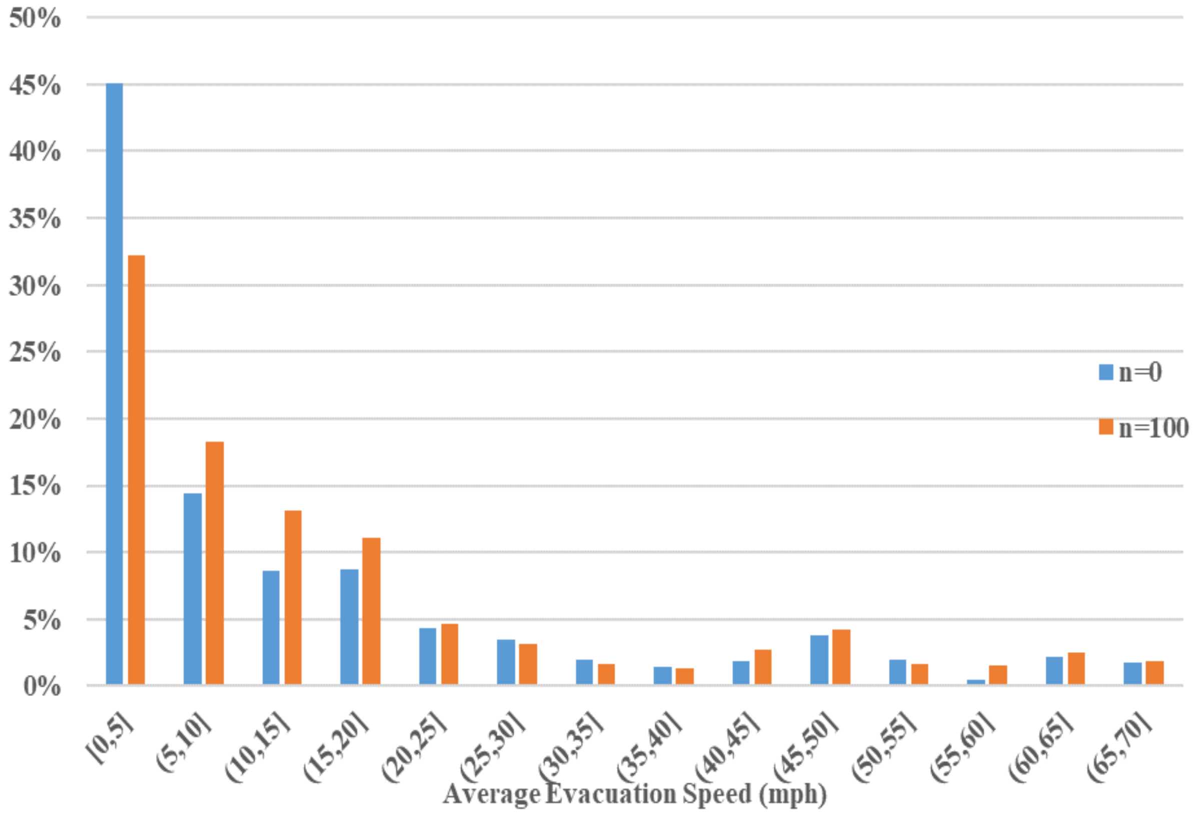


Fig. 平均避難速度の分布

繰り返し計算回数 n = 0：最短距離、 n = 100：最短時間

考察：避難経路の変更による渋滞の緩和

- 最短時間になる経路を選んだ場合（n＝１００）では、北東方向への避難車両が増加

　→北への避難を促進することで渋滞緩和の可能性

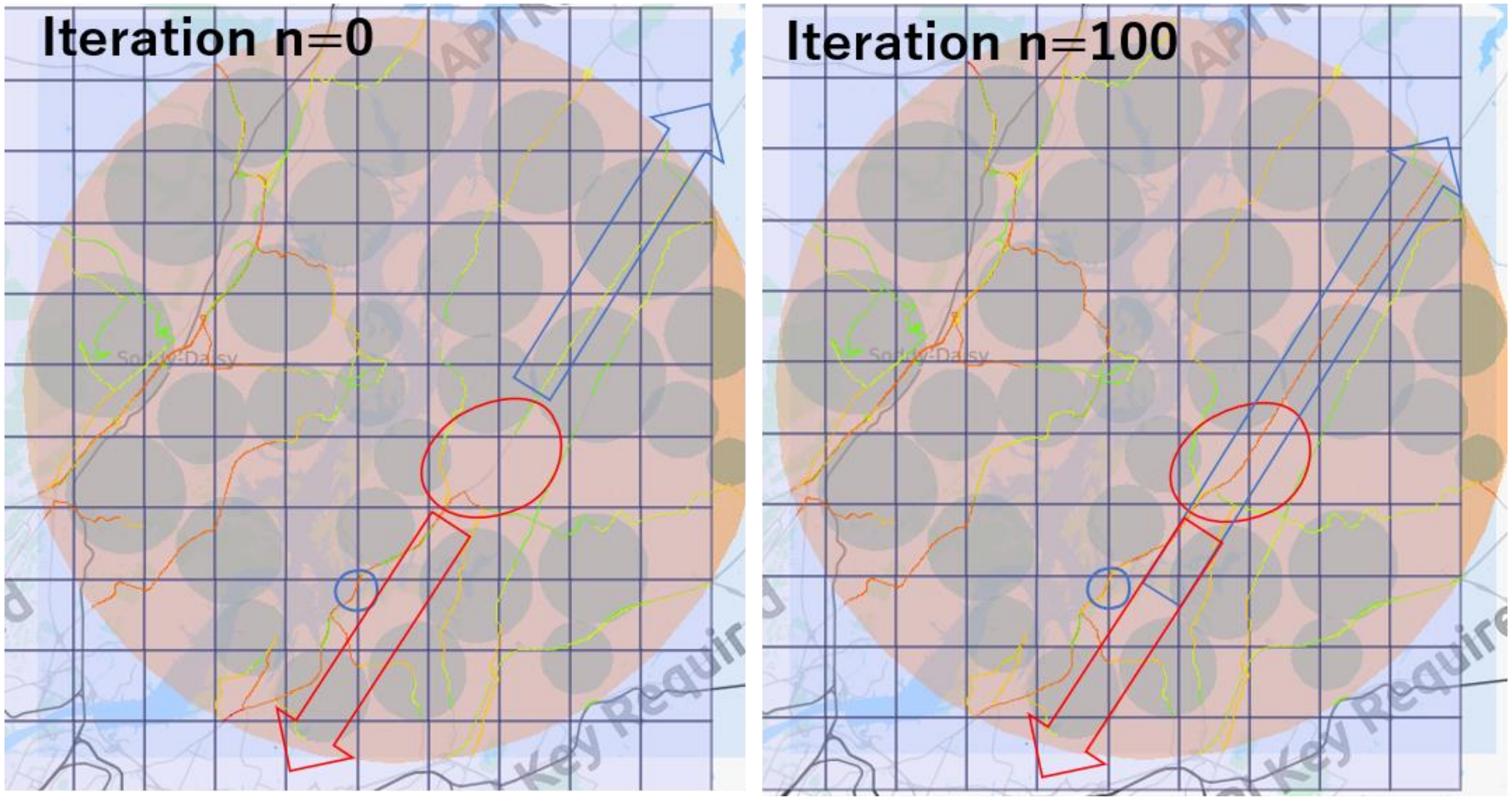


Fig. Road utilization map (Number of Replanning iterations Left: n = 0, Right: n = 100)

まとめと今後の展開

- Level3PRAの避難モデルをより現実的に表現するために交通シミュレーションを活用
- テストケースとして米国NRCのSOARCA2017を採用
- これまでは明示的に評価できなかった避難経路等の避難行動の違いによる被ばくリスクの変化を評価

- OSCAARの避難モデルを改良
- 日本の原子力発電所周辺地域に対して避難シミュレーションを実施し、OSCAARの避難モデルに入力
- 日本の原子力防災に役に立つ知見を取得

Appendix

1) Transportation simulation

- **M**ulti-**A**gent **T**ransport **Sim**ulation (MATSim) is selected [17]

  (i) MATSim is an **open-source** framework for implementing large-scale agent-based transportation simulations

  (ii) MATSim can simulate **millions of agents** with a manageable level of computational cost.

- The MATSim **Evacuation extension**
  - A function of **automatically generating destinations** representing an arrival point at the intersection between the boundary of the evacuation area and the roads when the user sets the evacuation area [18]

[17] Horni, A. The Multi-Agent Transport Simulation MATSim. 2016, London: Ubiquity Press.
[18] Gregor Lämmel,, Hybrid Multimodal and Intermodal Transport Simulation Case Study on Large-Scale Evacuation Planning. Journal of the Transportation Research Board, 2016

a) Population/Demographics

- SOARCA selected **Sequoyah NPP site**[11]
  - **Sequoyah** is in Tennessee
- To discuss Evacuation effect in Emergency Prepared Zone: EPZ, we set population data **within 10 miles.**

  Population≒100,000

Table 5-1 Cumulative population and population density for selected distance intervals surrounding Sequoyah Unit 1

Distance (miles)	Radial Interval Population (2015)	Cumulative Population (2015)	Interval Population Density (persons per square mile)
0-1	236	236	75
1-2	2,418	2,654	257
2-5	24,427	27,081	370
5-10	70,650	97,731	300
10-15	182,548	280,278	465
15-20	202,733	483,011	369
20-30	210,758	693,770	134
30-40	214,990	908,760	97
40-50	197,435	1,106,196	69

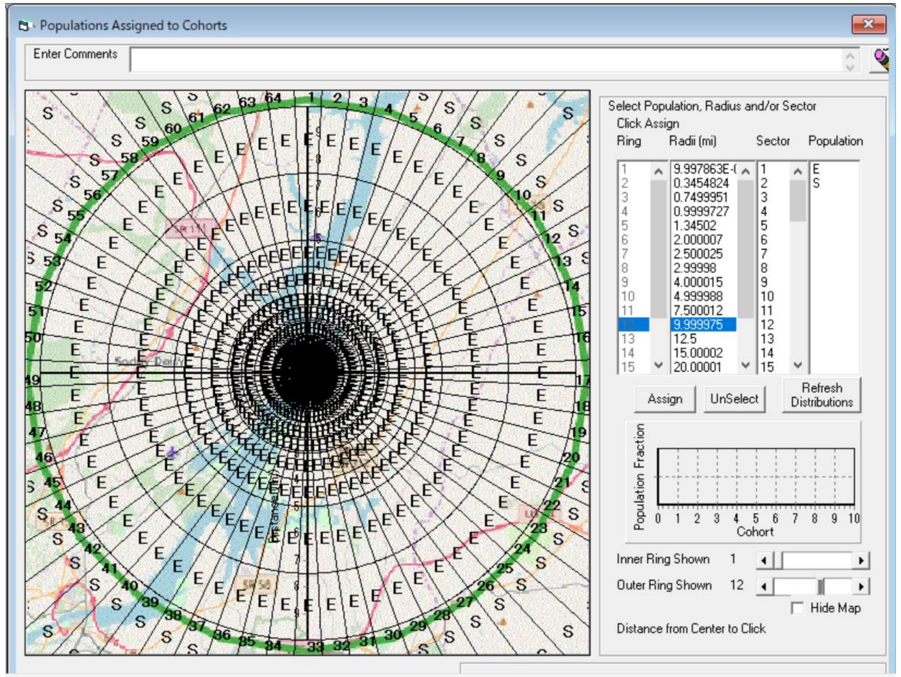


Fig. Concentric mesh of population in MACCS around Sequoyah NPP

[11]U.S.NRC, State-of-the-Art Reactor Consequence Analyses (SOARCA) Project; Sequoyah Integrated Deterministic and Uncertainty Analyses. 2017

b) Vehicle Occupation Rate
c) Number of Vehicles

- To MATSim
  - The number of vehicles is estimated from the population data.
- The number of passengers per vehicle (**Vehicle Occupancy Rate; VOR**) is provided,
  - As the default value, **VOR = 2.11** is used based on the results of a **telephone survey** of residents in the EPZ of Sequoyah NPP [19]
  - The number of vehicles in our base case = 46,316.

[19]ARCADIS, Evacuation Time Estimates for Sequoyah Nuclear Power Plant Plume Exposure Pathway Emergency Planning Zone., 2012

e) Road Network

- In MATSim, the road network is created using OpenStreetMap [20].
- In MACCS, **four directions** are set for each **concentric mesh**
  - In this research, the evacuation route described in SOARCA report is used as input to MACCS.

[20]Java Open Street Map. Available from: https://josm.openstreetmap.de/.

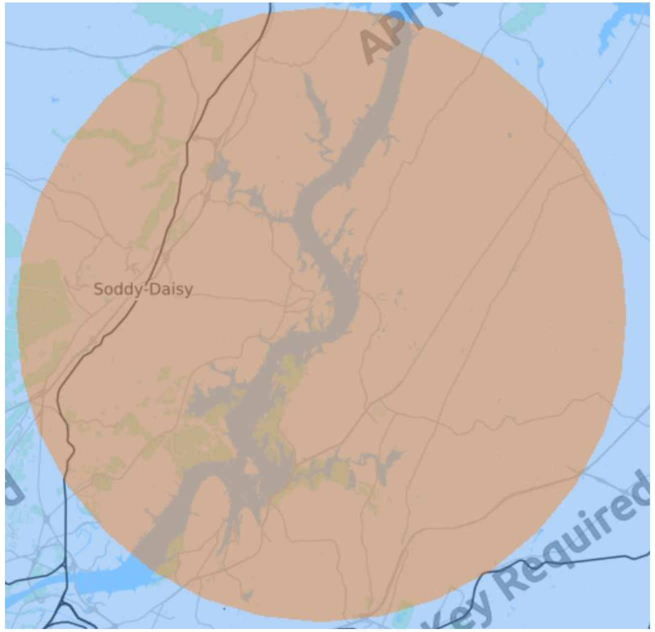


Fig. MATSim Evacuation road network in EPZ around Sequoyah NPP

f) Evacuation Area

- Set to a radius of **10 miles** (≒16 km) from the Sequoyah NPP

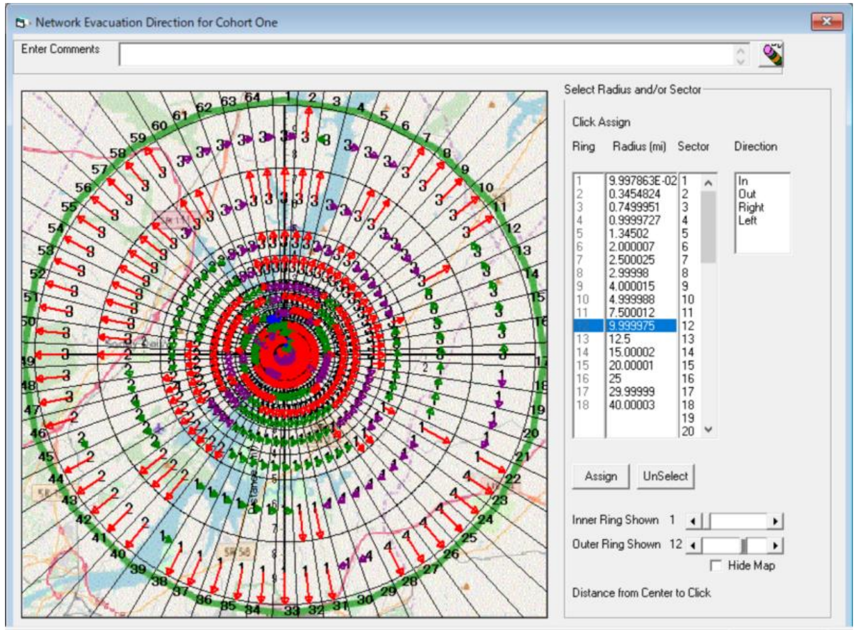


Fig. MACCS input window of Network Evacuation Direction

i) Weather Data

- Weather data around Sequoyah NPP were obtained from Tennessee Valley Authority (TVA)
- We calculated stability class and check this weather data is same as SOARCA[11]

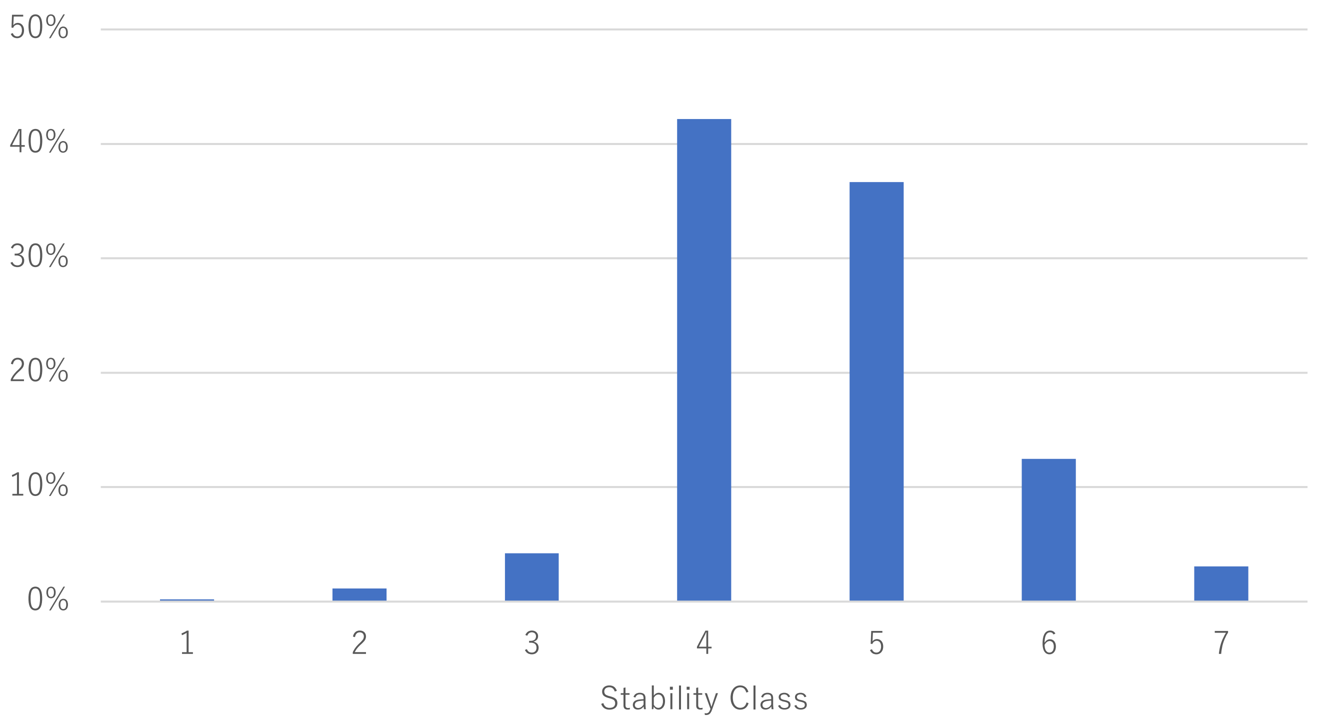


Fig. Stability Class Probability, weather data around Sequoyah in 2012

j) Source Term

- Select Realization 554 in SOARCA that is **the highest risk source term** and **most early release**[11].
- The timing of an increase of Rlz554 is **3.6 hours** from an occurrence of the IE

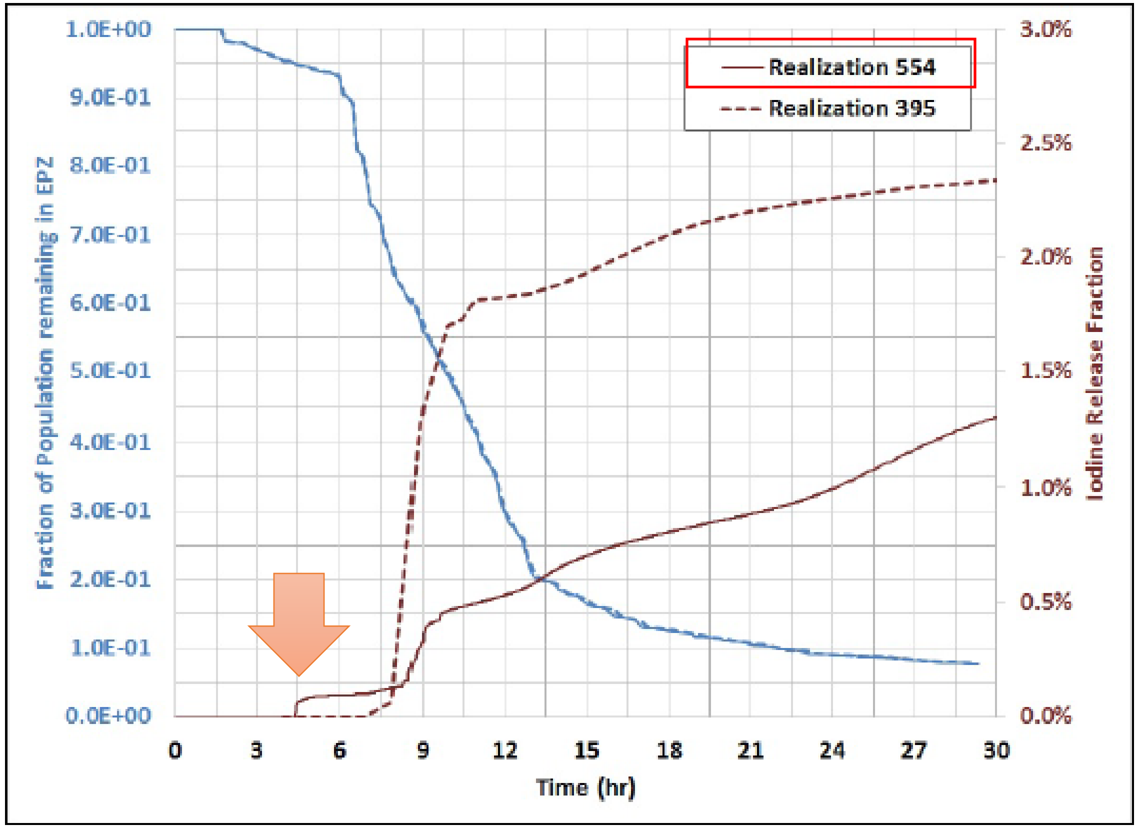


Figure 6-16 Fraction of population remaining in EPZ and iodine release fraction from early containment failure cases Realization 554 (solid line) and Realization 395 (dashed line) as a function of time

Table 6-10 Source term releases for Sequoyah accident scenarios.

MELCOR Realization	Scenario	Time in Cycle	Environmental Release Fraction by MELCOR Chemical Class									Time (hr)	
			Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La	Start*	Increase**
266	STSBO Reference	MOC	0.997	0.001	0.000	0.004	0.000	0.000	0.226	0.000	0.000	3.4	57.6
554	STSBO Early Release	EOC	0.999	0.018	0.009	0.051	0.024	0.001	0.092	0.005	0.000	2.7	3.6
395	STSBO Highest Cs Release Mass	EOC	0.999	0.027	0.009	0.079	0.041	0.000	0.051	0.001	0.000	2.9	6.9
36	STSBO Highest Cs Release Fraction	MOC	0.998	0.036	0.009	0.107	0.054	0.000	0.077	0.001	0.000	3.0	7.0

* The "start" time indicates the timing of the first environmental release, no matter how small (e.g., release fraction on the order of 1.0E-9).

** The "increase" time indicates the timing of the first significant increase in the rate of release.

[11]U.S.NRC, State-of-the-Art Reactor Consequence Analyses (SOARCA) Project; Sequoyah Integrated Deterministic and Uncertainty Analyses. 2017

k) Dose Coefficient
l) Sheltering and Filter Coefficient

- The radiation exposure paths, and dose conversion factors are set to the **same conditions as** those in SOARCA[11].
- The average value of SOARCA is used for the shielding coefficient and the filter coefficient.
- Administration of stable iodine is **not** considered (the same assumption as SOARCA [11]).

[11]U.S.NRC, State-of-the-Art Reactor Consequence Analyses (SOARCA) Project; Sequoyah Integrated Deterministic and Uncertainty Analyses. 2017

Summary of inputs data in our base case

Inputs	MATSim	MACCS
Population		97,731
Vehicle occupancy rate	2.11	
Number of vehicles	46,316	
Departure time distribution	Telephone survey data[19]	Telephone survey data[19]
Road network	Open Street Map [20]	Four directions are set for each concentric mesh, SOARCA[11]
Evacuation area	10 miles from NPP	10 miles from NPP
Notification time (min)		165
Evacuation speed (mph)		Outputs from MATSim
Weather data		In 2012 from TVA
Source Term		Realization 554 in SOARCA[11]
Dose coefficient		SOARCA [11]
Sheltering, filtering coefficient		SOARCA [11]

m) Selection of MACCS outputs (Risk metric)

- Risk metric should be able to capture the following aspects:
  1. **Effective Dose**: To compare with the **Protection Action Guide** (**PAG**) **of EPA** [21]
  2. **Number of people**: To reflect demographic data
  3. Distance from site: To consider evacuation area
- We selected the fraction of **population exceeding a threshold dose** in MACCS outputs as the risk metric
  - Percentage of people who exposed more than PAG**: Pr(d>PAG)**
  - PAG for evacuation**: 10** to 50 [**mSv/4 days**]

$$\boxed{Pr(d > PAG) = \frac{Pop(d > PAG)}{Pop(total)}}$$

EPA: Environment Protection Agency, U.S

[21] EPA, PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents, in EPA-400/R-17/001. 2017.

Results of the base case

- The calculation conditions of the base:
  - (i) The **shortest distance route** scenario
  - (ii) VOR = 2.11 based on the telephone survey data [19]
  - (iii) DTD based on the telephone survey data [19]
  - (iv) No road closures

Table. Results of the base case

Effective Dose (mSv)	0	0-1	1-10	>10
Probability of residents	**97.5%**	1.17%	0.66%	**0.65%**

- Results: 97.5% of the residents can evacuate outside the EPZ without radiation exposure.
- **Pr(d>PAG)** of the base case is 0.65% (95% CI [0.64%, 0.68%]).

[19]ARCADIS, Evacuation Time Estimates for Sequoyah Nuclear Power Plant Plume Exposure Pathway Emergency Planning Zone., 2012

Sensitivity Analyses

- One of the key advantages of integrating the transportation simulation with the Level 3 PRA code is that sensitivity analyses can be conducted to **rank the input parameters** of the transportation simulation that can impact the evacuees' performance.
- In our research, we conducted two types of analyses:

  (i) sensitivity analyses to study how the **route selection** can impact

  (ii) **global Importance Measure** analysis that generates **a ranking of the key input parameters** based on their impact on the risk metric

  - At this stage of research, the **2k factorial design**, which is a **simplified way** to perform a global sensitivity analysis for k factors is used.

Global sensitivity analysis for five factors

Table. Five factors of global sensitivity analysis

	Name	Lower	Upper
X1	Route selection	Shortest **distance**	Shortest **time**
X2	DTD	Telephone survey	Doubled
X3	VOR	2.11	3.00
X4	Road Closure	No	Yes
X5	Notification Time	135 min	195 min

- X1; **Route selection**:
  - Lower bound: vehicles select **shortest distance**, upper bounds: vehicles select **shortest time**,
- X2; **Departure Time Distribution**: For the upper bound, the time interval is **doubled** with the NRC's expert judgment provided in SOARCA[11] to evaluate the delay of the evacuation start time **due to an earthquake**,
- X3; **Vehicle Occupancy Rate**: For the upper bound, VOR is increased to **3.00**,
  - which is the value suggested in the ETE report of Ehime prefecture in Japan to evaluate the effect of **ride sharing** [24].
- X4;**Road Closure** : The lower bound is set to the baseline road network **without any road closure**.
  - For the upper bound, the road with the **highest traffic volume** listed in the ETE **is blocked [19]**.
- X5; **Notification Time ;**In the SOARCA 2012 study[12], a sensitivity analysis was conducted to evaluate the impact of a delay in the notification time by ±**30 minutes.**

[12]NRC, WinMACCS, a MACCS2 Interface for Calculating Health and Economic Consequences from Accidental Release of Radioactive Materials into the Atmosphere. 2007
[24] Ehime-prefecture. Ehime Prefectural Nuclear Emergency Preparedness Zone Evacuation Measures (Evacuation Time Estimate). 2013

Results of global Importance Measure

Table. The results of Global IM analysis using the 2^5 factorial design

Main Effects		Interaction Effects			
e1	-1.24E-02	e12	1.84E-04	e24	7.74E-06
e2	**-2.54E-02**	e13	2.77E-04	e25	-1.98E-04
e3	**-2.50E-02**	e14	**5.04E-04**	e34	2.36E-04
e4	-6.76E-03	e15	-7.36E-05	e35	-1.94E-04
e5	1.02E-02	e23	1.84E-04	e45	-4.07E-05

- **The main effects :** the effect of each input parameter on the risk metric averaged between the upper and lower bounds of the other input parameters,
  - Rank 1: X2 (**DTD**) , Rank 2: X3 (**VOR**).
  - Rank 5: X4 (Road Closure)
- **The interaction effects** : the impact of the second input parameter on the effect of each input parameter.
  - The combination of two input parameters with the largest interaction effects is **Route Selection** (X1) and **Road Closure** (X4).
    - This suggests that the combination of **traffic guidance** and **traffic restriction** can have synergy effects on the risk reduction.

Conclusion

- This presentation reports the recent progress in the authors' line of research to **improve Level 3 PRA** through an **"explicit"** incorporation of underlying risk-contributing factors.
- This presentation focuses on development of an **integration of a transportation simulation** using the MATSim with MACCS.
  - The MATSim-MACCS integration is applied to a test case, adopting the **Sequoyah NPP** and evacuation scenario from the U.S. NRC's **SOARCA study**.
- For the case study, a **global importance measure** analysis is conducted.
  - Based on the main effects, **Departure Time Distribution** is identified as the most influential parameter, followed by **Vehicle Occupancy Rate**.
  - It is also indicated that the combination of the evacuation **Route Selection** and **Road Closure** has the largest two-way interaction effects.

Geographical distribution of the evacuation start area

- The geographical distribution of the evacuation start area is set in MATSim based on the Emergency Response Planning Area (ERPA) described in the ETE report around the Sequoyah NPP

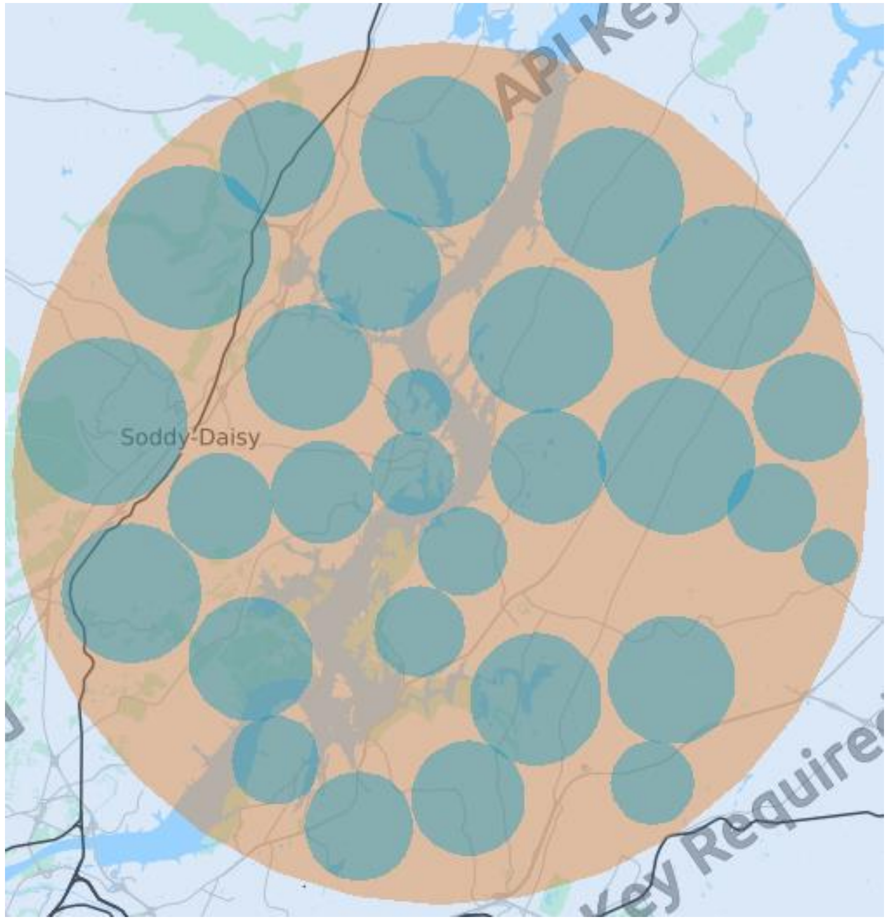


Fig. geographical distribution of the evacuation start area in MATSim

Target of Cohorts

- **MACCS set Cohorts** that represents the movements of residents
- **Cohort** is defined as a segment of the population with specific response characteristics
- In SOARCA 2017, 9 **cohorts** were set in Early phase.
    - **General Population within 10 miles EPZ** that **evacuate** after General Emergency (**GE**) **siren**.
        - Cohort 6,7,8 (70% in EPZ)
        - Each cohort set single for parameters value (evacuation timing) .
- In our calculation, **one cohort** was set using **Departure Time Distribution (DTD)**.

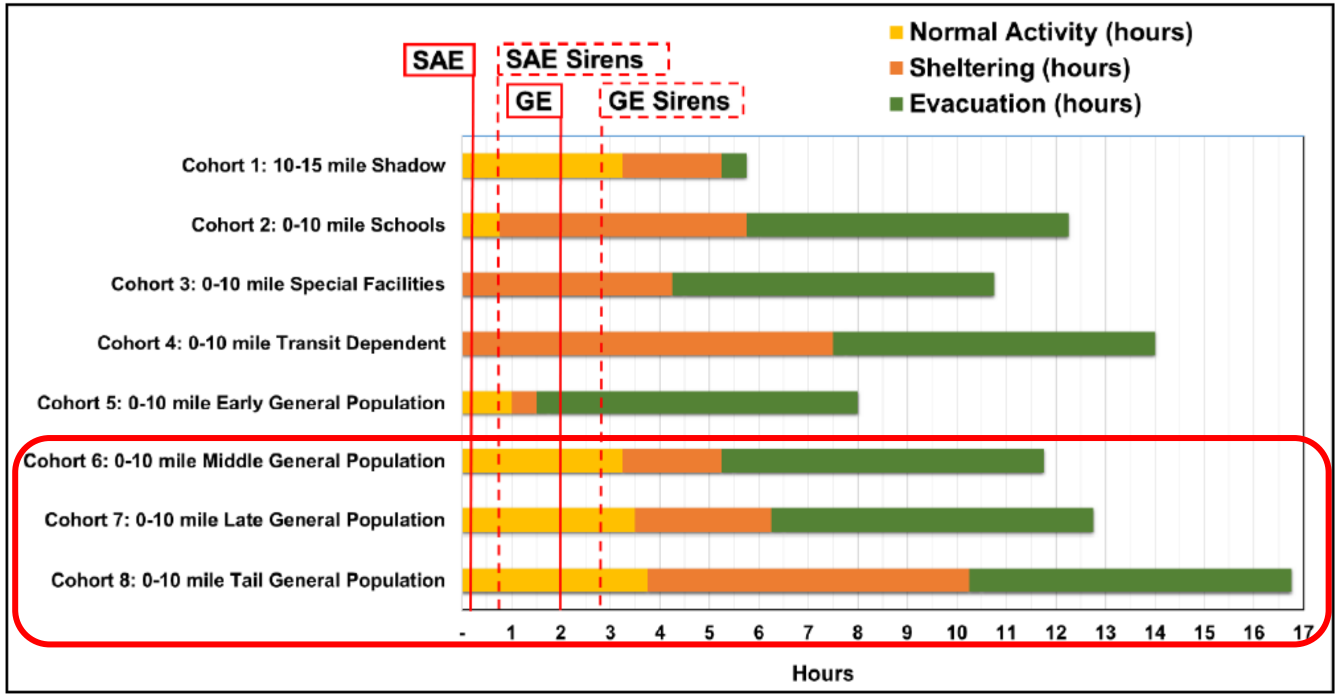


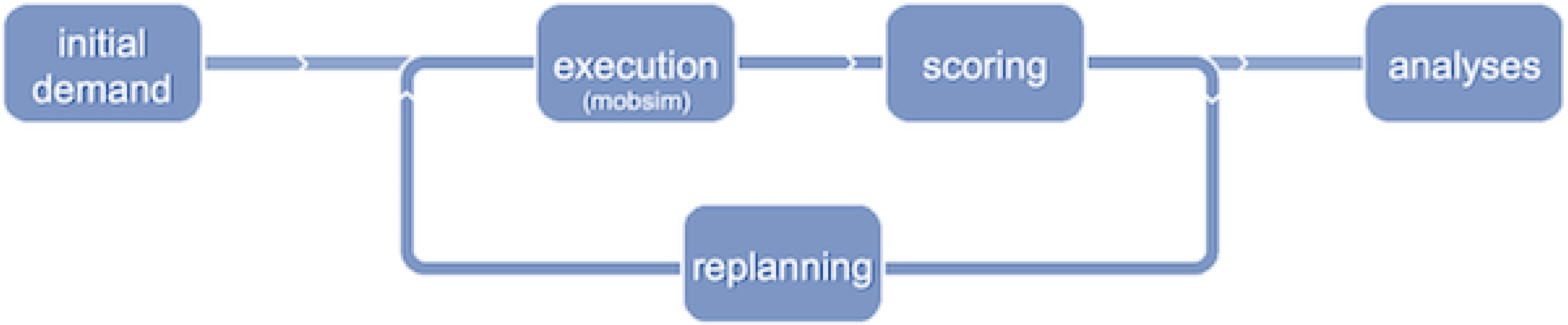
Figure 5-9 Sequoyah emergency response timeline and travel speeds

Table 5-7 Sequoyah evacuation cohorts

Cohort	Distance	Cohort Description	Percentage of Radial Distance Population
1	10 to 15 miles	Shadow	(20% 10-15 mile population)
2	0 to 10 miles	Schools	19.3 %
3	0 to 10 miles	Special facilities (e.g. hospitals)	0.8 %
4	0 to 10 miles	Transit dependent evacuees	1.5 %
5	0 to 10 miles	Early general public evacuees	7.8 %
6	0 to 10 miles	Middle general public evacuees	31.2 %
7	0 to 10 miles	Late general public evacuees	31.2 %
8	0 to 10 miles	Tail general public evacuees	7.8 %
9	0 to 10 miles	Non-evacuating public	0.5 %

Sensitivity Analysis for the Selection of Evacuation Routes (Replanning)

- MATSim has a function of selecting the route with the **shortest time** by the Replanning function in addition to selecting the route with the **shortest distance**.



https://matsim.org/about-matsim

Replanning

- In the Replanning function, **first**, each agent selects the route with the **shortest distance** from the starting point to the destination.
- Then, a simulation in which all agents move on the road network is started, and MATSim calculates the cumulative value of the moving time (referred to as “**score**”) of the evacuees.
- If **congestion** occurs on the evacuation route, the route with the **shortest distance** may **not** be the route with the **shortest time**.
- To minimize the total evacuation time of all agents, MATSim **changes the route** of some agents and **repeats the evacuation simulation**.
- In MATSim, this recalculation is called replanning.

Iteration

- The number of recalculations is called "**Iteration**" in MATSim, represented by n.
- MATSim calculates the **total score** of agents for each iteration, and **automatically select their routes** that improve their scores.
- Then, when the **equilibrium of the total score** (i.e., the Nash equilibrium) is reached, it is considered that these agents have selected the route with the **minimum evacuation time**.
- In this study, the Replanning function of MATSim is used to compare the case of routes that optimize the evacuation time of residents and the case of routes that minimize the evacuation distance of residents.

Number of Iterations (n)

- To evaluate an impact of evacuation route selection on the radiation exposure risk to evacuees, the results of the MATSim's Replanning function with two different settings of the number of **Iterations (n)** are compared**:** **n = 0** and **n = 100.**
    - The relative value of the MATSim score when the calculation is continued from n = 0 to n = 100 is shown in Fig.
- From the change in the MATSim score as a function of n, the MATSim Replanning iteration has reached the **Nash equilibrium before n = 100** and, thus, the total evacuation time has been optimized.
- By comparing the results between n = 0 and n = 100, it is possible to analyze the impact of the evacuation route, **the one with the shortest distance vs. the one with the optimized (shortest) evacuation time**.

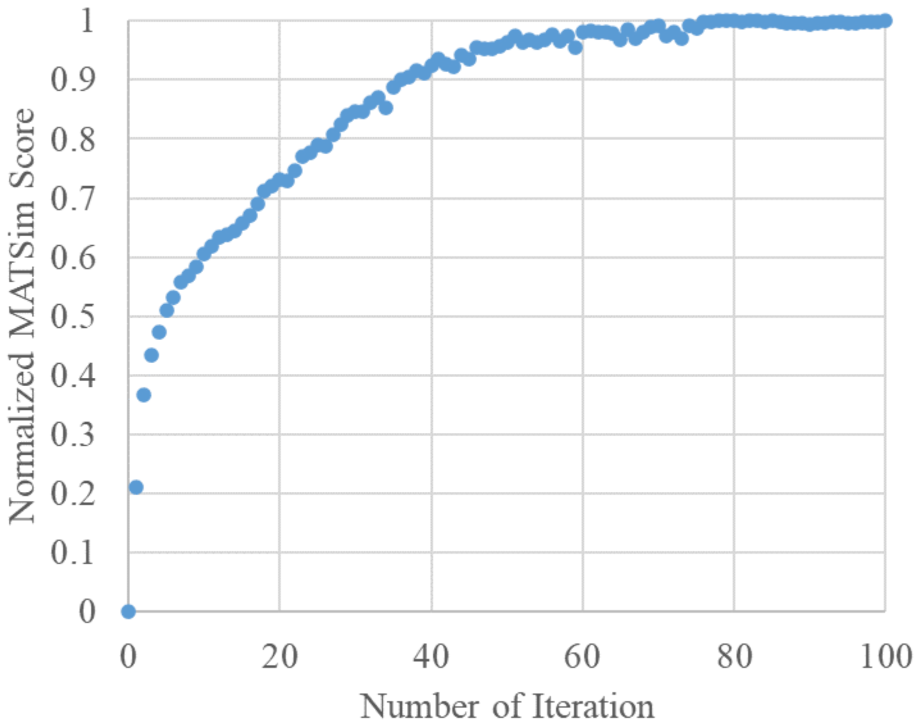


Fig. The relative value of scores in MATSim

Results of Sensitivity Analysis for the Selection of Evacuation Routes

- Using the average evacuation speed distribution as an input to MACCS, the key risk metric of interest, Pr(d>PAG), is computed.
- For n = 0 (minimized evacuation **distance**), Pr(d>PAG) = 0.65% (95%CI: [0.64%, 0.68%]);
- For n = 100 (minimized evacuation **time**), Pr(d>PAG) = 0.47% (95% CI: [0.44%, 0.49%]).
- The radiation exposure risk with n = 100 is about **30% lower** than that with n = 0.

Effects of DTD for risk

- Fig shows the correlation between risk outputs and the average **speed** of evacuees.
- From Fig, the results with DTD2 generally have a faster average evacuation speed and lower risk than the DTD1 results.

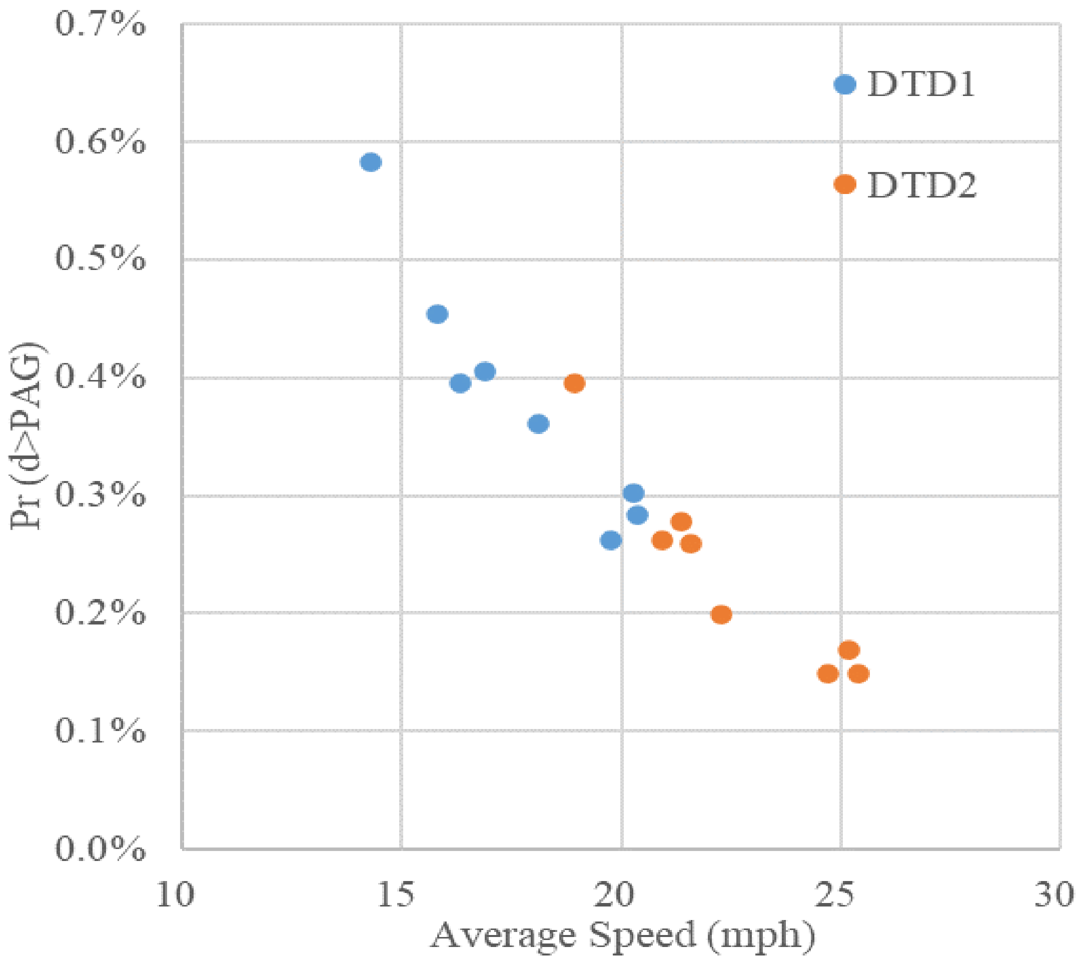


Figure 6. The correlation between risk outputs and average speed of evacuees