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Original Article

# Cohort-based evacuation time estimation using TSIS-CORSIM

Sunghyun Park, Seokwoo Sohn, Moosung Jae*

*Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul, 04763, Republic of Korea*

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ABSTRACT

Evacuation Time Estimate (ETE) can provide decision-makers with a likelihood to implement evacuation of a population with radiation exposure risk by a nuclear power plant. Thus, the ETE is essential for developing an emergency response preparedness. However, studies on ETE have not been conducted adequately in Korea to date. In this study, different cohorts were selected based on assumptions. Existing local data were collected to construct a multi-model network by TSIS-CORSIM code. Furthermore, several links were aggregated to make simple calculations, and post-processing was conducted for dealing with the stochastic property of TSIS-CORSIM. The average speed of each cohort was calculated by the link aggregation and post-processing, and the evacuation time was estimated. As a result, the average cohort-based evacuation time was estimated as 2.4–6.8 h, and the average clearance time from ten simulations in 26 km was calculated as 27.3 h. Through this study, uncertainty factors to ETE results, such as classifying cohorts, degree of model complexity, traffic volume outside of the network, were identified. Various studies related to these factors will be needed to improve ETE's methodology and obtain the reliability of ETE results.



## 1. Introduction

In a radiation emergency, the most effective public protection measures are evacuation and sheltering-in-place. The evacuation before a plume reaches a residential area is the best way to reduce radiation dose. Therefore, a calculation of the time to evacuate people is required to respond to the emergency. The calculation results can be used as valuable information to decision-makers in the radiation emergency.

The nuclear power plant accident at Three Mile Island motivated us to develop procedures to perform the Evacuation Time Estimate (ETE). The first official guideline by the Nuclear Regulatory Commission (NRC) and the Federal Emergency Management Agency (FEMA) had some limitations on performing the ETE [1]. Since the first official guideline was published, various studies on the ETE have been conducted by the US. A recently published NUREG/CR-7002 presents the latest methodology and many considerations for the ETE [2].

In Korea, Jeon (2004) performed the ETE for the Ul-jin site based on the survey data and CORSIM code [3]. However, this study did not consider traffic control. The following year, Korea Electric Power Research Institute (KEPRI) conducted the ETE for Uljin site and Wolseong site to improve the domestic ETE methodology by CORSIM code [4]. KEPRI established a well-organized system for calculating evacuation time by deriving the factors necessary for the ETE and the field data. Korea Hydro & Nuclear Power (KHNP) also performed the ETE for all sites in Korea in 2014 [5]. KHNP collected local data, including traffic volume data, signal system data, road structure data, and presented the ETE results for each site by normal peak traffic and summer peak traffic. Lee (2016) also performed the ETE by VISSIM code, a microscopic traffic flow simulation software, to support off-site emergency action planning for the nuclear site [6]. However, the above studies do not cover all areas of the revised Emergency Planning Zone (EPZ) and present the ETE results based on the region.

The ETE involves calculating the time needed to evacuate the plume exposure pathway EPZ, an area with a radius of about 10 miles around a nuclear power plant [1]. ETE is a complex process because of considering the release of radioactive materials and response to that release [7]. Thus, ETE requires reasonable assumptions and has to deal with the uncertainties related to the ETE. A well-designed ETE methodology can provide 'best estimate' ETE based on reasonable assumptions and accurate data [8].

Through this study, we performed preliminary ETE for the reference site in Korea based on the latest methodology and site-

* Corresponding author. Department of Nuclear Engineering, Hanyang University, 418 HIT, 222 Wangsimni-ro, Seongdong-gu, Seoul, 04763, Republic of Korea.
*E-mail address:* jae@hanyang.ac.kr (M. Jae).



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specific data collected. In this paper, the methodology for ETE analysis is described in chapter 2, and the calculation results are presented in chapter 3. Chapter 2 includes literature reviews, scope, demand estimation, scenario development, data collection, and traffic model construction by Traffic Software Integrated System-CORridor SIMulation (TSIS-CORSIM). TSIS-CORSIM code is beneficial to construct a traffic simulation model that can allow the consideration and refinement of more scenarios [8]. Chapter 3 includes the ETE analysis results as clearance time and cohort-based evacuation time. These two result types are explained in chapter 3 in detail.

## 2. Methodology for ETE analysis

When planning a protective action and traffic management, the ETE result is commonly utilized [2]. The ETE result is affected by site-specific data, including population distribution, behavioral psychology in an emergency, road network, and traffic control system. Moreover, the ETE result is also affected by the features of the accident progression, weather conditions, and evacuation timing. For calculating the best estimation, the above factors should be comprehensively reviewed and applied to the process of ETE. Therefore, we developed the process of ETE and constructed the flowchart shown in Fig. 1.

### 2.1. Literature review

The first step of ETE is to understand an emergency preparedness plan and to review relevant documents for the plan. The EPZ of reference site includes three administrative districts, Busan, Ulsan, and Yangsan. The emergency preparedness plan is closely related to the administrative district. Several local governments should evacuate people who live in each district by an 'action manual for a radiation emergency' [9–11].

The 'action manual for a radiation emergency' focuses on evacuating people in the Precautionary Action Zone (PAZ, about 5 km) before or right after the release of radioactive material because it is essential to prevent or mitigate acute effects on people. Additionally, the manual recommends a staged evacuation for people who live in the Urgent Protective action planning Zone (UPZ, about 20–30 km), and the range of evacuation of UPZ can be varied by accident magnitude, wind direction, and wind speed.

This manual is fundamental to perform ETE because it contains massive information about emergency response, including guiding people, transportation, traffic control, evacuation paths. However, some information is insufficient for the ETE. Therefore, assumptions for insufficient information were inevitable. Available information from the manual and assumptions are described in the following sections.

### 2.2. Scoping study for ETE

This section covers the characteristics of EPZ. The EPZ is defined as the area in which protective actions might be required during a nuclear emergency to protect public health, safety, and the environment [12]. Before the Fukushima accident in 2011, the EPZ of Korea was a single area and 8–10 km from the nuclear power plant.

After the Fukushima accident, the EPZ of Korea was subdivided into two zones, PAZ and UPZ, to improve the emergency preparedness plan. The PAZ and UPZ are the areas for notifying people of evacuation or sheltering-in-place in the early stage. People in the PAZ are highly recommended for taking response actions before releasing radioactive materials, whereas people in the UPZ take response actions before or shortly after the start of the release [13]. The sizes of PAZ and UPZ are determined in consideration of preventing deterministic effects and minimizing stochastic effects by radiation exposure. Notably, the shape of PAZ and UPZ is determined in consideration of road networks, population distribution, and administrative districts. Consequently, the PAZ and UPZ considered in this study are shown in Fig. 2.

Performing the ETE also requires to review demography features and weather characteristics for the EPZ. The EPZ of the reference site is one of the most densely populated areas in the world because it contains three big cities, Busan, Ulsan, and Yangsan. Therefore, approximately three million people are residing in the UPZ. The population is concentrated in some industrial areas or big cities,

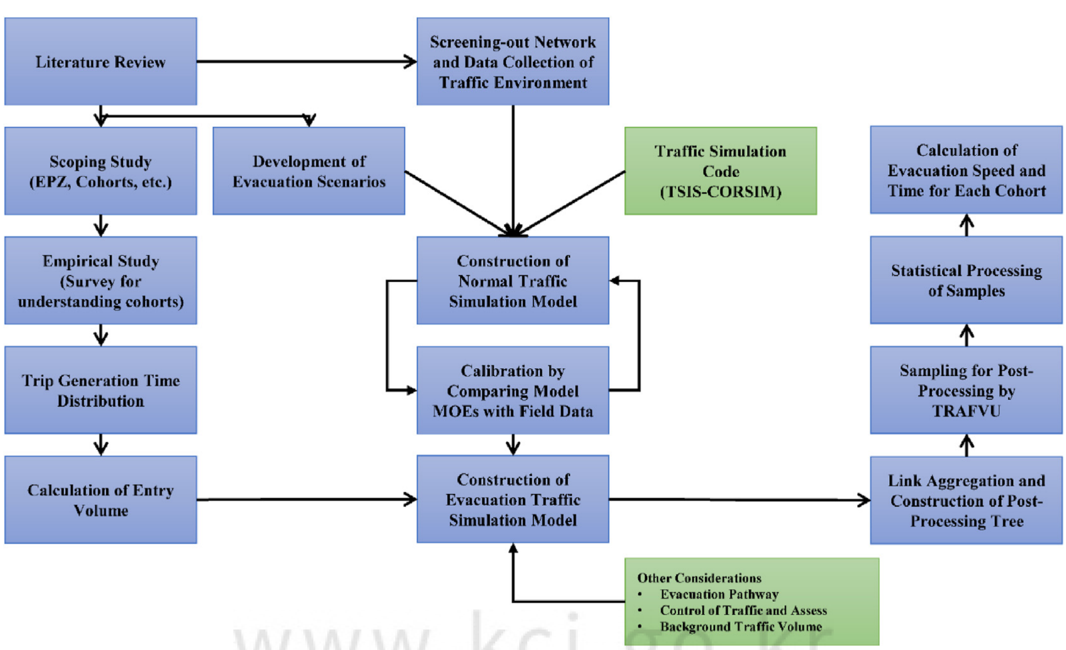



**Fig. 1.** Flowchart of ETE analysis.

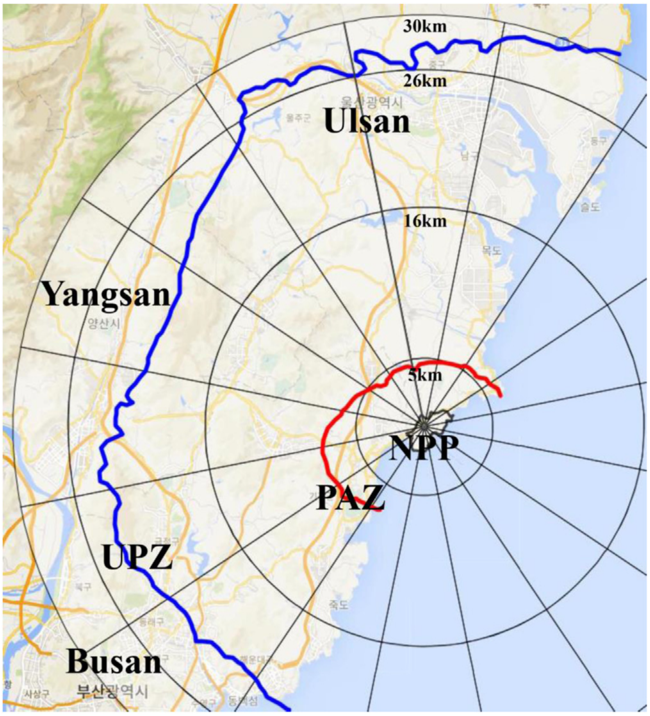


**Fig. 2.** PAZ and UPZ of the reference site (red: PAZ, blue: UPZ). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

which are located near the UPZ boundary. Because the reference site is surrounded by sea, it is heavily influenced by the ocean climate caused by wind patterns. The annual average temperature is about 14.5 °C, the annual average rainfall is 1983 mm, and 60% of the rainfall is concentrated from May to August [9].

### *2.3. Demand estimation of evacuating population*

The next step of the ETE is to estimate the size of the evacuating population [8]. It is important to consider all populations in the UPZ, including permanent residents, transient people, people in special facilities who feel uncomfortable to move by themselves, students, and others. The permanent residents and transient people are permanently and temporarily residing in the UPZ, respectively. The special facilities include nursing homes, hospitals, and prisons.

NUREG/CR-7002 report, which includes the latest methodology for the ETE, demonstrates how to classify the population [2]. The population classification can be varied depending on a site because some data for the population might be hard to obtain, or a preparedness plan for the site might not cover a specific population. Therefore, we identified accessible information and make assumptions. The population groups considered in this study are presented in Table 1, including descriptions and ratio to permanent residents.

The population groups are classified by distances of 5 km, 16 km, and 26 km from the nuclear power plant to consider the PAZ boundary, previous EPZ boundary, and UPZ boundary, respectively. The reason why we consider 26 km is as follows. A distance from the reference site to the UPZ boundary is about 20 km–30 km. We calculated an equivalent radius of 26 km. A circle area with a 26 km radius is roughly equivalent to the original UPZ.

The ETE analysis by KHNP considers an evacuation only inside 16 km, not the UPZ boundary [5]. They also consider a shadow evacuation between 5 km and 16 km, whereas this study considers a shadow evacuation between 16 km and 26 km. In other words, this study classified population groups based on a situation in which a radioactive plume affects up to 16 km, and a shadow evacuation occurs outside 16 km.

#### *2.3.1. Cohort 1, 2, and 3*

Cohort 1, 2, and 3 are permanent residents in the PAZ. These cohorts are divided into evacuating and non-evacuating group. The non-evacuating group refuses to comply with the evacuation order though they have been ordered to evacuate. A questionnaire survey can identify the ratio of this group. 0.5% value used in the previous study was applied to the non-evacuating group because the survey is beyond our scope [14]. The evacuating group is divided into a general evacuation group and a delayed evacuation group. The delayed evacuation group includes population returning home from work to evacuate with their family, population to pick up their children, and population to evacuate after closing stores or dealing with other things that have happened at work [2]. The general evacuation group is divided into two groups. The first group is evacuated by private cars, and the second group is evacuated by buses provided by local governments [9–11].

When estimating the number of evacuating vehicles, the analyst should consider a person per vehicle. Therefore, it is assumed that three people take a private car, and 45 people take a bus [4]. The people to evacuate by bus will gather at the pre-designated assembly places and begin to evacuate [5].

It is challenging to consider all assembly places because of the limitation of the number of source nodes in the TSIS-CORSIM. Therefore, representative assembly places per several towns were chosen by population density. It means that the larger the population, the higher the number of assembly places were considered. The representative evacuation paths were considered the same as the evacuation paths presented in the 'action manual for a radiation emergency' [9–11]. Moreover, the local government considers buses, temporary trains, ships, and helicopters [9–11]. However, simultaneously considering these transportations is hard to model in the traffic simulation model, so only buses are considered.

#### *2.3.2. Cohort 4 and 5*

Cohort 4 and 5 are also permanent residents from 5 km to 16 km. It is assumed that 90% of them, which is cohort 4, is the general evacuation group, and 10% of them, which is cohort 5, is the non-evacuating group. The classification method and assumptions are the same as the previous one.

#### *2.3.3. Cohort 6 and 7*

Cohort 6 and 7 are permanent residents from 16 to 26 km. Cohort 6 is a shadow evacuation group, and cohort 7 is a non-evacuating group. The shadow evacuation is defined as an evacuation of people who do not take notification of evacuation [2]. The shadow evacuation provides realism because these are observed in large-scale evacuations and can slow down the evacuation from the affected area [15]. Although the ratio of shadow evacuation should be decided through a questionnaire survey, the questionnaire survey has not been in the study scope. Therefore, the value of 20% utilized in the previous study was utilized in this study [16]. Additionally, it is assumed that cohort 6 evacuate themselves by private vehicles, and they also are divided into general and delayed evacuation group.

#### *2.3.4. Cohort 8*

Cohort 8 is a population in special facilities. The special facilities include schools, hospitals, nursing homes, welfare centers,

**Table 1**
Classification of cohort.

| Cohort | | Distance (km) | Descriptions | Ratio to Permanent Resident |
|---|---|---|---|---|
| 1 | 1–1 | 0–5 | Permanent, private vehicle | 0.8955 |
| | 1–2 | | Permanent, bus | |
| 2 | | | Permanent, private vehicle, delayed evacuation | 0.0995 |
| 3 | | | Permanent, no evacuation | 0.005 |
| 4 | 4–1 | 5–16 | Permanent, private vehicle | 0.81 |
| | 4–2 | | Permanent, bus | |
| | 4–3 | | Permanent, private vehicle, delayed evacuation | 0.09 |
| 5 | | | Permanent, no evacuation | 0.1 |
| 6 | 6–1 | 16–26 | Permanent, private vehicle, shadow evacuation | 0.2 |
| | 6–2 | | Permanent, private vehicle, delayed evacuation, shadow evacuation | |
| 7 | | 16–26 | Permanent, no evacuation | 0.8 |
| 8 | 8–1 | 0–5 | Special facility | N/A |
| | 8–2 | 5–16 | Special facility | N/A |
| 9 | 9–1 | 0–5 | Transient | N/A |
| | 9–2 | 5–16 | Transient | N/A |
| | 9–3 | 16–26 | Transient | N/A |

and prisons. A detailed list of special facilities should be developed to assess each facility on an individual basis or reports [17]. This group needs special transportations, such as vans and ambulances. The special facilities considered in this study are welfare centers, nursing homes, hospitals, which are presented in the 'action manuals for a radiation emergency.' This manual also includes only the population for each facility and their destinations but does not provide specific information such as evacuation paths and transportations [9–11]. Therefore, it was assumed that cohort 8 follows the district's evacuation path in which each facility is included.

Because the manual does not contain the composition of these people, an assumption is inevitable. Therefore, it was assumed that half of the cohort 8 could not move by themselves, people who can walk use a vehicle per three people, and people who cannot walk by themselves use a vehicle per person.

#### 2.3.5. Cohort 9

Cohort 9 is a population temporarily staying in the UPZ. This group includes tourists, shoppers, and workers who do not live in the UPZ. When estimating the number of this group, the average value is generally acceptable [2]. However, the average value depends on the scenario. For example, the average value is different, whether the scenario is for a night or not.

Only tourists were considered as cohort 9 because of the lack of information. Among various tourism facilities, some representative facilities, and beaches are selected by considering the relatively large number of visitors. The number of visitors to the selected place also depends on the scenario. The scenario considered in this study is summer (in August), weekday (on Friday), daytime (at noon), and normal weather condition. In other words, the population of cohort 9 refers to the number of visitors at noon, on Friday, and in August.

To estimate the number of cohort 9, official statistical data of Korea were used [18]. The data consists of monthly, quarterly, and yearly visitors that are not enough to calculate the number of cohort 9 for the scenario. Therefore, the 'Fermi Estimate' method was used to overcome this limitation. The 'Fermi Estimate' method estimates approximate value in a short time with basic knowledge and logical reasoning for a problem. The number of cohort 9 can be calculated by Equation (1).

$$N = F \cdot P_1 \cdot P_2 \quad (1)$$

Where N is the number of visitors at noon on Friday in August, F is the fraction of visitors in August during a year, $P_1$ is the probability of visiting on Friday ($P_1$ was assumed 0.25), and $P_2$ is the probability of visiting at noon ($P_2$ was assumed 0.5).

### 2.4. Scenario development

Evacuation scenarios can be developed differently depending on seasons, day of the week, time of the day, and weather conditions. Essential data for performing the ETE, such as the location of taking notification, Trip Generation Time (TGT), evacuation path, traffic volume, and traffic signals, is different by scenarios. The ETE result for various scenarios is informative for a decision-maker when implementing protective actions. However, a field survey for each scenario is required to obtain essential data for performing the ETE. Because a field survey for one scenario was performed through this study, we consider one scenario mentioned in section 2.5.

The methodology in this study is applicable to other scenarios that may occur in a nuclear power plant. Although release behavior, including release timing, amount of release, and release direction, will be varied by accident, this study does not consider these factors in detail. The evacuation start time may vary depending on the release timing. The evacuation start time was fixed 1 h after the beginning of the traffic simulation in this study. Additionally, the size and location of evacuating people who live from the PAZ to UPZ can be different by the amount of release and release direction. The people in the PAZ must be evacuated, and the people outside of the PAZ who are living downwind from the projected path of plume travel are also evacuated, which is also known as keyhole evacuation. In this study, the keyhole evacuation was not considered because we classified cohorts and their appearance in Fig. 3. As future works, keyhole evacuation for each wind direction will be evaluated based on this study's methodology. As described earlier, a scenario considered in this study is summer, weekday, daytime, and normal weather conditions. Plus, under normal weather conditions, all road segments' maximum free flow rate is assumed to the maximum legal speed.

### 2.5. Trip Generation Time Distribution

TGT is the time interval between the evacuation order and entering the road network [8]. The TGT distributions can be calculated using an empirically known distribution, an observed probability distribution, technical judgment of experts, or survey results. Among these various methods, the survey result performed by KHNP in Table 2 was used to calculate the TGT distribution in this

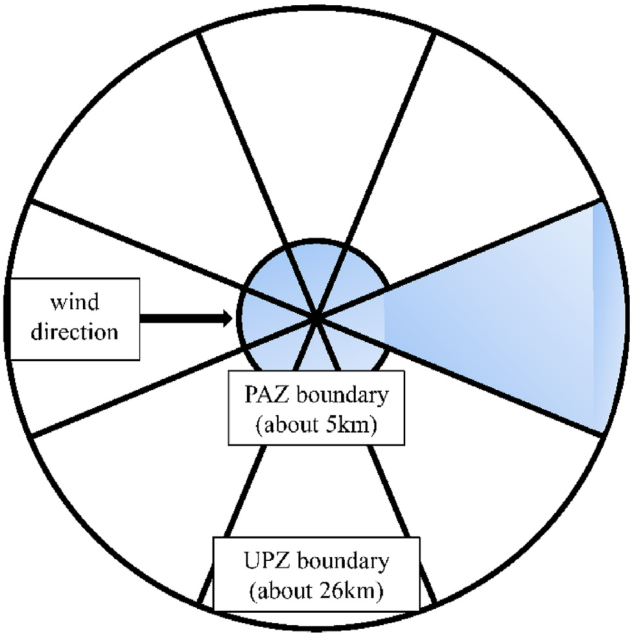


**Fig. 3.** Keyhole evacuation.

study [5].

The TGT distribution was calculated by probabilistic summation. The probabilistic summation is a simple way to obtain distributions over time for a cohort that has completed each action type (warning receipt, preparation for evacuation at a workplace or outside, return from work to home, preparation to leave home) [8]. It is essential to develop all TGT distributions to reflect the feature of cohorts adequately. However, only two TGT distributions were developed because of limited available data from survey results. The A TGT distribution in Table 3 consists of 'warning receipt' and 'preparation for evacuation at the workplace or outside.' The B TGT distribution in Tables 4 and 5 consists of 'warning receipt,' 'return from work to home,' and 'preparation to leave home.'

First, it was assumed that cohorts evacuating by private vehicles take the A TGT distribution, and a delay of 30 min is applied to cohort 4–1 and cohort 6-1 because of the relatively long distance from the nuclear power plant. Second, it was assumed that cohorts evacuating with delay take the B TGT distribution, and a delay of 30 min is applied to cohort 4–3. Third, it was assumed that shadow evacuation cohorts take the same TGT distribution as cohort 4. Fourth, it was assumed that cohorts evacuating by buses take the uniform distribution. The loading curves for each cohort can be obtained by multiplying the population and the TGT distribution in Table 6 and presented in Figs. 4 and 5.

### 2.6. Roadway data collection

The next step is to collect data about the road network in UPZ, including traffic volume, turn movements, traffic regulations, signal timing, roadway geometry, and street type. These data are used to construct a traffic simulation model. The traffic geometry includes the location of links and nodes, the number of lanes, turning pockets, and auxiliary lanes [19]. The whole road network can be divided into many segments. Each segment has various information. It is not easy to model all segments because all data must be obtained. Therefore, we selected relatively essential points based on the selection criteria in Table 7. The selection criteria were developed by considering cross points of major roads and evacuation paths.

For health effects by early exposure, the road network in the PAZ, which is relatively near nuclear power plants, is more

**Table 2**
Survey result for TGT.

| Type | Time (min.) | Population | P(t) | Type | Time (min.) | Population | P(t) |
|---|---|---|---|---|---|---|---|
| Warning receipt | <10 | 333 | 0.33 | Preparation for evacuation at workplace or outside | <10 | 384 | 0.38 |
| | 10–20 | 426 | 0.43 | | 10–20 | 417 | 0.42 |
| | 20–30 | 126 | 0.13 | | 20–30 | 98 | 0.10 |
| | 30–60 | 101 | 0.10 | | 30–60 | 87 | 0.09 |
| | >60 | 14 | 0.01 | | >60 | 14 | 0.01 |
| | Total | 1000 | 1 | | Total | 1000 | 1 |
| Return from work to home | <10 | 176 | 0.18 | Preparation to leave home | <10 | 220 | 0.22 |
| | 10–20 | 446 | 0.45 | | 10–20 | 481 | 0.48 |
| | 20–30 | 198 | 0.20 | | 20–30 | 139 | 0.14 |
| | 30–60 | 158 | 0.16 | | 30–60 | 135 | 0.14 |
| | >60 | 22 | 0.02 | | >60 | 25 | 0.03 |
| | Total | 1000 | 1 | | Total | 1000 | 1 |

**Table 3**
Summation of probabilities for A TGT.

| | | Preparation for evacuation at workplace or outside | | | | |
|---|---|---|---|---|---|---|
| Warning receipt | Time | 10 | 15 | 25 | 45 | 60 |
| | P(t) | 0.384 | 0.417 | 0.098 | 0.087 | 0.014 |
| | 10 | 20 | 25 | 35 | 55 | 70 |
| | 0.333 | 0.1254 | 0.1386 | 0.033 | 0.0297 | 0.0033 |
| | 15 | 25 | 30 | 40 | 60 | 75 |
| | 0.426 | 0.1634 | 0.1806 | 0.043 | 0.0387 | 0.0043 |
| | 25 | 35 | 40 | 50 | 70 | 85 |
| | 0.126 | 0.0494 | 0.0546 | 0.013 | 0.0117 | 0.0013 |
| | 45 | 55 | 60 | 70 | 90 | 105 |
| | 0.101 | 0.038 | 0.042 | 0.01 | 0.009 | 0.001 |
| | 60 | 70 | 75 | 85 | 105 | 120 |
| | 0.014 | 0.0038 | 0.0042 | 0.001 | 0.0009 | 0.0001 |

**Table 4**
Summation of probabilities for B TGT (1).

| | Return from work to home | | | | | |
|---|---|---|---|---|---|---|
| Warning receipt | Time | 10 | 15 | 25 | 45 | 60 |
| | P(t) | 0.176 | 0.446 | 0.198 | 0.158 | 0.022 |
| | 10 | 20 | 25 | 35 | 55 | 70 |
| | 0.333 | 0.0586 | 0.1485 | 0.0659 | 0.0526 | 0.0073 |
| | 15 | 25 | 30 | 40 | 60 | 75 |
| | 0.426 | 0.075 | 0.19 | 0.0843 | 0.0673 | 0.0094 |
| | 25 | 35 | 40 | 50 | 70 | 85 |
| | 0.126 | 0.0222 | 0.0562 | 0.0249 | 0.0199 | 0.0028 |
| | 45 | 55 | 60 | 70 | 90 | 105 |
| | 0.101 | 0.0178 | 0.045 | 0.02 | 0.016 | 0.0022 |
| | 60 | 70 | 75 | 85 | 105 | 120 |
| | 0.014 | 0.0025 | 0.0062 | 0.0028 | 0.0022 | 0.0003 |

**Table 5**
Summation of probabilities for B TGT (2).

| | Preparation to leave home | | | | | |
|---|---|---|---|---|---|---|
| Warning receipt and Return from work to home | Time | 10 | 15 | 25 | 45 | 60 |
| | P(t) | 0.22 | 0.481 | 0.139 | 0.135 | 0.025 |
| | 20 | 30 | 35 | 45 | 65 | 80 |
| | 0.0586 | 0.0129 | 0.0282 | 0.0081 | 0.0079 | 0.0015 |
| | 25 | 35 | 40 | 50 | 70 | 85 |
| | 0.2235 | 0.0492 | 0.1075 | 0.0311 | 0.0302 | 0.0056 |
| | 30 | 40 | 45 | 55 | 75 | 90 |
| | 0.19 | 0.0418 | 0.0914 | 0.0264 | 0.0257 | 0.0048 |
| | 35 | 45 | 50 | 60 | 80 | 95 |
| | 0.0881 | 0.0194 | 0.0424 | 0.0122 | 0.0119 | 0.0022 |
| | 40 | 50 | 55 | 65 | 85 | 100 |
| | 0.1405 | 0.0309 | 0.0676 | 0.0195 | 0.019 | 0.0035 |
| | 50 | 60 | 65 | 75 | 95 | 110 |
| | 0.0249 | 0.0055 | 0.012 | 0.0035 | 0.0034 | 0.0006 |
| | 55 | 65 | 70 | 80 | 100 | 115 |
| | 0.0704 | 0.0155 | 0.0339 | 0.0098 | 0.0095 | 0.0018 |
| | 60 | 70 | 75 | 85 | 105 | 120 |
| | 0.1123 | 0.0247 | 0.054 | 0.0156 | 0.0152 | 0.0028 |
| | 70 | 80 | 85 | 95 | 115 | 130 |
| | 0.0497 | 0.0109 | 0.0239 | 0.0069 | 0.0067 | 0.0012 |
| | 75 | 85 | 90 | 100 | 120 | 135 |
| | 0.0156 | 0.0034 | 0.0075 | 0.0022 | 0.0021 | 0.0004 |
| | 85 | 95 | 100 | 110 | 130 | 145 |
| | 0.0056 | 0.0012 | 0.0027 | 0.0008 | 0.0008 | 0.0001 |
| | 90 | 100 | 105 | 115 | 135 | 150 |
| | 0.0160 | 0.0035 | 0.0077 | 0.0022 | 0.0022 | 0.0004 |
| | 105 | 115 | 120 | 130 | 150 | 165 |
| | 0.0044 | 0.001 | 0.0021 | 0.0006 | 0.0006 | 0.0001 |
| | 120 | 130 | 135 | 145 | 165 | 180 |
| | 0.0003 | 0.0001 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |

**Table 6**
Number of population and TGT distribution type.

| Cohort | Number of population | Distribution type |
|---|---|---|
| 1–1 | 4772 | A |
| 1–2 | 1685 | Uniform |
| 2 | 712 | B |
| 4–1 | 144,015 | A+30 |
| 4–2 | 51,387 | Uniform |
| 4–3 | 21,711 | B+30 |
| 6–1 | 354,216 | A+30 |
| 6–2 | 39,357 | B+30 |
| 8–1 | 174 | Uniform |
| 8–2 | 2747 | Uniform |
| 9–1 | 4846 | Uniform |
| 9–2 | 5008 | Uniform |
| 9–3 | 35,264 | Uniform |

important than outside of the PAZ. Therefore, most of the segments in the PAZ were considered in the traffic simulation model. Segments can be a highway, national road, street, and intersection. Most of the evacuation paths include highway interchanges and national roads, and intersections in Table 8. Next, a field survey was carried out to obtain the data of segments in Table 8. Closed Circuit Television (CCTV) and 'road view' function provided by the internet was used to obtain some data.

### 2.7. Construction of ETE model

The scenario was simulated by the traffic simulation code, CORSIM. The CORSIM can be used to prepare a comprehensive evacuation plan, including the ETE, traffic management and control strategies, and other elements of an evacuation plan [20]. TSIS-CORSIM version 6.3, developed by McTrans, was used to construct the traffic simulation model. The traffic simulation model consists of a normal traffic phase and an emergency traffic phase. The first normal traffic phase is by 1 h from the simulation start and requires field survey data, including traffic volume, signal timing, and signal patterns. The second emergency traffic phase is a period

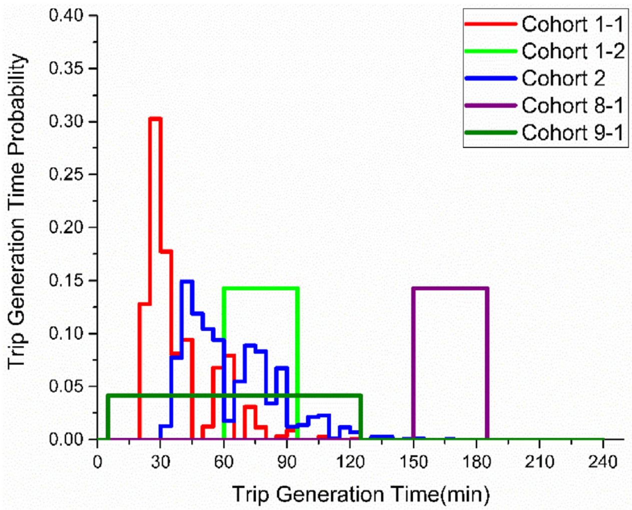


**Fig. 4.** Trip Generation Time (TGT) distribution in 5 km.

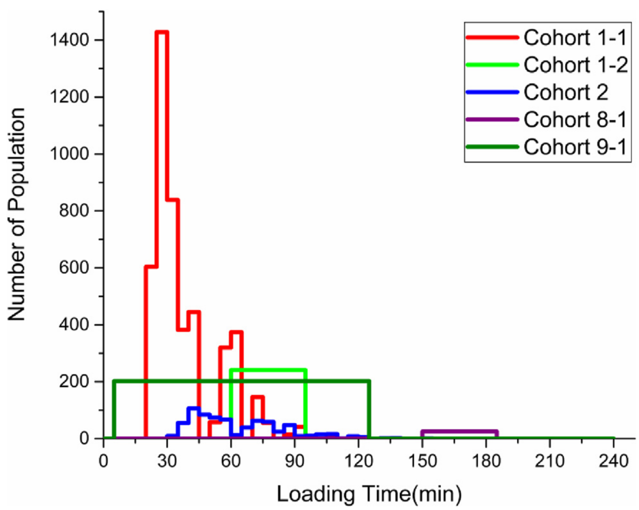


**Fig. 5.** Loading curve in 5 km.

after the first phase and requires the loading curve for each cohort, traffic control plan, and evacuation paths.

#### 2.7.1. TSIS-CORSIM

CORSIM consists of an integrated set of two microscopic simulation models, NETwork SIMulation (NETSIM) and FREeway SIMulation (FRESIM). The NETSIM and FRESIM are designed to simulate urban streets and highways, respectively. An integrated network constructed by NETSIM and FRESIM is called a multi-model network. Two sub-networks of the NETSIM and FRESIM are simulated independently in the multi-model network, and each calculation is integrated over time. The multi-model network consists of nodes and links. The nodes generally represent urban intersections or points at which geometric property changes, and the links represent urban streets or freeways [19].

The CORSIM applies a time step simulation to describe traffic operation. Each vehicle is a distinct object that is moved every second. Each variable control device, such as traffic signals, is updated every second. The CORSIM is a stochastic model, which means that random numbers are assigned to a driver and a vehicle in the decision-making process.

The Measure Of Effectiveness (MOE) obtained from simulation is the results of a specific set of random number seeds. Each time step, a vehicle moves its position on the link, and its speed, acceleration, status, and relationship to other cars nearby are recalculated. Vehicles are driven by car-following logic in response to traffic control devices and other demands. Congestion can result in queues that a specific link where demand exceeds available capacity is blocked. Therefore, congestion can impede traffic flow. CORSIM accumulates data every time step. At the end of each time period, the accumulated data is used to produce MOEs [19].

#### 2.7.2. Construction of normal traffic model

To construct a simulation model of the normal traffic phase, the collected data, such as street length, intersection geometry, relative turning volume, signal timing and pattern, and background traffic volume, were inputted into the model. Additionally, to simplify the model, underpass and overpass streets were converted into surface streets. To prevent an unintended increase in traffic flow by the conversion, traffic signal timing for that surface streets was rearranged. Also, pavement type was assumed to be dry asphalt, and speed reduction was applied instead of modeling toll gates. Consequently, the multi-model network, as Fig. 6, consists of 1227 nodes, 59 dummy nodes, and 469 source-sink nodes.

As shown in Fig. 7, the normal and emergency phases are divided by a time interval of 1 h [19]. Next, the multi-model network was calibrated by TRAF-Visualization Utility (TRAFVU), post-processor. To fix abnormal traffic flow on some segments, free-flow speed, headway, auxiliary lane length, and lane drop were adjusted, which results in the equilibrium state within the time period 1. Next, to compare the multi-model network with reality, the calculated speed for some links was compared with the observed speed [21]. The comparison result is presented in Table 9.

The speed difference in Table 9 can affect the evacuation pattern. Still, it is not sure whether it may increase the evacuation time or not because the number of vehicles in the emergency phase is highly larger than in the normal traffic condition. To reduce the speed difference, additional considerations will be needed for future works. It is necessary to model as many segments as possible in the UPZ. Therefore, network capacity will be closely matched to reality. Also, consideration of factors, such as driver characteristics,

**Table 7**
Selection criteria for intersection.

| Type | Selection criteria |
|---|---|
| Inside of PAZ | A point at which a national road intersects with another national road |
| | A point at which a national road intersects with a highway |
| | A point at which a street intersects with a national road, where bottlenecks are likely to occur |
| | A point at which a street intersects with a national road, where is essential for evacuation path |
| | A point at which a street intersects with another street, where bottlenecks are likely to occur |
| | A point at which a street intersects with another street, where is essential for evacuation path |
| From PAZ to UPZ | A point at which a national road intersects with another national road |
| | A point at which a national road intersects with a highway |

**Table 8**
Major intersections selected by criteria.

| IC or national road segments near major IC of highway | | |
|---|---|---|
| Name | Collected data | Straight-line distance (km) |
| Jangan IC | Relative Turn Volume | 5.3 |
| Gijang IC | Relative Turn Volume, Signal | 8.3 |
| Onyang IC | Relative Turn Volume | 10.0 |
| Gijang-cheolma IC | Relative Turn Volume, Signal, Traffic Volume | 14.3 |
| Haeundae IC | Relative Turn Volume, Signal, Traffic Volume | 15.2 |
| Cheongnyang IC | Relative Turn Volume, Signal, Traffic Volume | 16.8 |
| Geumjeong IC | Relative Turn Volume, Signal, Traffic Volume | 17.4 |
| Nopo IC | Relative Turn Volume, Signal, Traffic Volume | 18.3 |
| Hoidong Intersection | Relative Turn Volume | 19.2 |
| Gooseo IC | Relative Turn Volume, Traffic Volume | 19.9 |
| Daecheonramp Three-way Intersection | Relative Turn Volume, Signal, Traffic Volume | 20.2 |
| Munsu IC | Relative Turn Volume, Signal, Traffic Volume | 21.4 |
| Yangsan Highway Rest Area | Traffic Volume | 21.5 |
| Wondong IC | Relative Turn Volume, Signal, Traffic Volume | 22.0 |
| Janggum IC | Relative Turn Volume, Signal, Traffic Volume | 25.5 |
| : | | |

**Fig. 6.** Multi-model network (black: NETSIM, gray: FRESIM).

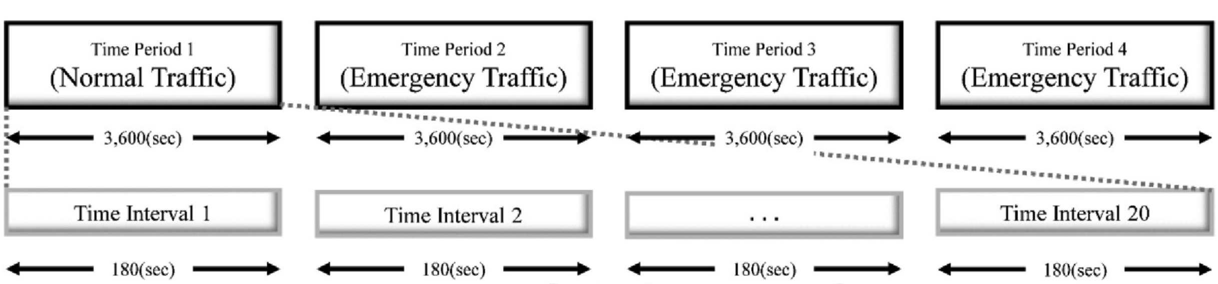


**Fig. 7.** Time interval per time period [18].

**Table 9**
Comparison of calculated and observed vehicle average speed.

| | Type | Name of street | Distance (km) | Number of nodes | Calculated Average Speed (km/h) | Observed Average Speed (km/h) |
|---|---|---|---|---|---|---|
| 1 | Downtown | Central | 22.8 | 6 | 42.6 | 25.6 |
| 2 | Suburb | Gijang | 6.3 | 10 | 45.9 | 28.1 |
| 3 | Urban Express | Shin-jeonggwan | 5.7 | 8 | 40.8 | 56.9 |
| 4 | Urban Express | Jeonggwan industry | 11.4 | 10 | 45.6 | 64.9 |

bus modeling, pedestrian, detector modeling, accident modeling, etc., will reduce the speed difference.

*2.7.3. Construction of emergency traffic model*

The next step is to construct the multi-model network in the emergency phase. In this step, the essential points are to input entry volumes for evacuation vehicles, to change turning volumes for considering evacuation paths, to reflect the traffic and access control plan, and to adjust the background traffic volume. First, it is required to input the entry volume generated by the loading curve. The CORSIM provides two methods to input it, vehicle count, or vehicles per hour. The vehicles per hour were used to generate a flow rate over the specified time interval because it is more convenient to reflect the loading curve. Second, turning volumes on all intersections of surface streets and ramp roads were changed to consider evacuation paths. Another method to consider paths is Orientation-Destination (O-D) function that is to assign paths between two source nodes. Still, it can be applied to a model constructed only by the NETSIM. To change the turning volumes, it was assumed that people in the same administrative area follow the same evacuation path planned by the local government. Besides, the turning volumes for each lane were rearranged based on the number of vehicles entering intersections. Third, the traffic and access control plan in Table 10 was considered in the model. Two important principles are to induce people to the outside of EPZ and to prevent unpermitted entering people. Therefore, these two principles were reflected in the control points in the emergency phase. Finally, the background traffic volume in the time period 1 was adjusted by reducing linearly over 3 h.

## 3. Results

Evacuation time can be defined in two ways. First, the evacuation time is defined as the time needed to complete evacuation in a specific region or within a certain radius from a nuclear power plant. It is also known as 'clearance time.' For an example of ETE results for the Indian Point Energy Center in the US [22], the report presents the ETE results in the way of clearance time. The time to clear 100% of the entire EPZ is 5 h and 40 min in winter, weekend, midday, and west point football as a special event, and 7 h and 40 min in case of summer, midweek, midday, and road impact. Second, the evacuation time is defined as the time needed to move for a specific group in a cohort. It is defined as a cohort-based ETE in this study. It is advantageous to obtain data of a specific group in a cohort in a large-scale evacuation.

**Table 10**
Traffic and access control plan by local governments [5–7].

| Administrative area | Type | Number of control points |
|---|---|---|
| Busan | Traffic | 22 |
| | Access | 18 |
| Ulsan | Traffic | 38 |
| | Access | 9 |
| Yangsan | Traffic | 9 |
| | Access | 5 |

### 3.1. Clearance time

To calculate the clearance time, the multi-model network was simulated ten times by different sets of random number seed in Table 11. Several times of simulations provide a better understanding of network performance. The results are presented in Table 12, and the average clearance time is 27.3 h resulting from traffic jams near Busan and Ulsan. The number of vehicles over time is shown in Fig. 8. At the beginning of the emergency traffic condition, evacuating vehicles enter the network resulting in the mean value peak after 4.4 h.

The move time per travel time ratio is presented in Fig. 9. The travel time consists of move time and delay time in CORSIM. The move time is the total theoretical time for discharged vehicles to travel the network if moving unimpeded at the free-flow speed. In contrast, the delay time is the difference between the travel time and the move time, which represents the time that vehicles are delayed if they cannot travel at the free-flow speed [19]. In Fig. 9, a decrease in the move time ratio rapidly is caused by traffic jams. Therefore, the move time ratio remains around 0.1 by the end of traffic jams. After this period, the total number of vehicles in the network are decreased gradually, and it increases in the move time ratio. Also, the move time ratio has fluctuated during the increase because of instantaneous traffic shock waves.

### 3.2. Cohort-based evacuation time

*3.2.1. Post-processing for ETE*

The evacuation time for a specific group in a cohort was obtained by aggregating links and constructing post-processing trees. The multi-model network includes numerous links and nodes, so it is tough to deal with the outputs of a particular link or node. Therefore, link aggregation was performed, and the multiple links, which are the evacuation paths, were grouped into a single link. Consequently, 43 links in NETSIM and 8 links in FRESIM were obtained by the link aggregation.

Although a turning volume was calculated by evacuation path information, a particular vehicle can move in various directions at

**Table 11**
Random number seeds.

| Run | Headway | Vehicle | Traffic |
|---|---|---|---|
| 1 | 9927 | 8219 | 24,007 |
| 2 | 8321 | 15,119 | 357 |
| 3 | 29,133 | 1549 | 18,901 |
| 4 | 10,769 | 16,147 | 30,109 |
| 5 | 27,971 | 177 | 12,979 |
| 6 | 1393 | 2531 | 8629 |
| 7 | 22,837 | 10,889 | 12,551 |
| 8 | 18,491 | 29,707 | 2073 |
| 9 | 619 | 14,629 | 2139 |
| 10 | 21,303 | 20,753 | 25,709 |

**Table 12**
Clearance time.

| Run | Clearance Time (hr) |
|---|---|
| 1 | 27.2 |
| 2 | 27.4 |
| 3 | 27.4 |
| 4 | 27.5 |
| 5 | 27.3 |
| 6 | 27.1 |
| 7 | 27.2 |
| 8 | 27.2 |
| 9 | 27.4 |
| 10 | 27.6 |
| Mean | 27.3 |

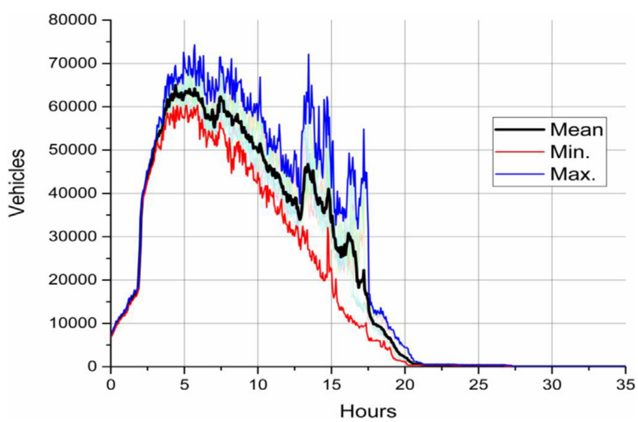


**Fig. 8.** Network content average.

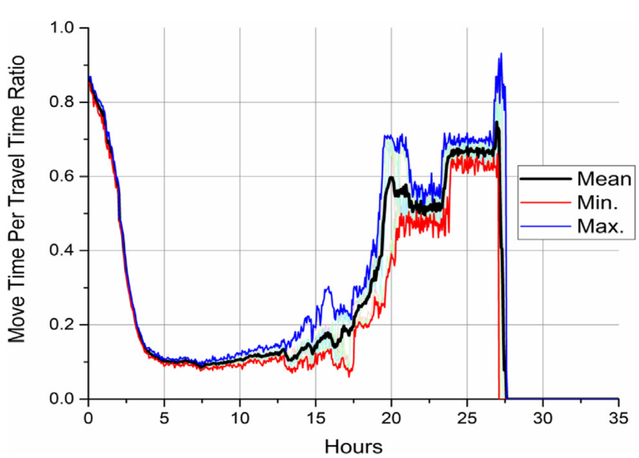


**Fig. 9.** Move time per travel time ratio.

an intersection, as Fig. 10. In Fig. 10, a vehicle from town A should move to shelter A by the pre-designed evacuation path. However, the vehicle can move in different directions because the CORSIM is a stochastic model. To deal with this problem, post-processing trees were developed in this study as Fig. 11. In Fig. 11, the branch name is the name of the aggregated links, and branch probabilities are likely to move to the link. For example, a vehicle from cohort 1, 2, and 8−1 can move along the FRESIM 1 and FRESIM 2 with the probability of 0.35. The average speed is shown in Fig. 12.

### 3.2.2. *Results of cohort-based ETE*

The average speed is highly decreased at the beginning of time period 2 and has a minimum value after 4.4 h at which the number of vehicles is the highest. To check the duration of moving vehicles, the animation of the multi-model network was check by using TRAFVU. Each cohort includes many source nodes, so a source node for each cohort, which is close to the nuclear power plant and traffic jams, was selected as a representative source node. Also, five vehicles were chosen as representative vehicles, as Fig. 13, and the intervals between the representative vehicles are the same. In Fig. 13, the black and orange arrow sign means the time of the beginning and end of the evacuation, respectively.

The beginning of evacuation is sequential, but the end of evacuation is not. Each vehicle from the same source node suffers from different traffic jams. The tracking results for each cohort are presented in Table 13.

Cohort 2 takes relatively less time to evacuate than cohort 1. This result means that slowly entering the network may reduce the total evacuation time by avoiding traffic jams. Moreover, the proper use of these results will help develop an efficient emergency preparedness plan for the PAZ. Next, cohort 4 takes a relatively long time to evacuate because they suffer traffic jams caused by traffic volumes from both the PAZ and outside of 16 km. Therefore, it is required to develop a special plan for these people. Next, cohort 6 resides near the densely populated area, but the distance needed to move is shorter than the other cohorts. Consequently, cohort 6 takes a very relatively short time to evacuate. However, cohort 6 suffered the most massive traffic congestion, resulting in the lowest evacuation speed.

## 4. Conclusions

To prevent or mitigate health effects by exposure, the most effective protection measures are evacuation and sheltering-in-place. To develop a systematic emergency preparedness plan, including the evacuation and sheltering-in-place, various studies should be performed, and the ETE is one of them. The ETE is to calculate the time needed to evacuate people to the outside of EPZ. The ETE result is helpful to improve the emergency preparedness plan and to be valuable information to decision-makers. In this study, the ETE for the reference site in Korea was performed. First of all, the emergency preparedness plan and relevant documents were comprehensively review. The action manual for a radiation emergency, which is the most practical manual, was comprehensively reviewed. The primary information, such as target population, evacuation paths, and means of evacuation, were reflected in the analysis. People in the UPZ were classified into nine groups by considering the distance from the reference site, means of evacuation, and shadow evacuation. Also, we considered one scenario that is summer, weekday, daytime, and normal weather condition. Each group takes trip generation time that is the time interval between the evacuation order and entering the road network. To calculate the loading curve for each group, the probabilistic summation was performed using population and trip generation time. Besides, through this study, a field survey was carried out to collect local roadway data, including traffic volume, turning volume, traffic signal, and roadway geometry. The scenario was simulated by the traffic simulation code, TSIS-CORSIM. The traffic simulation model consists of a normal traffic phase and emergency traffic phases. Field survey data, loading curves, evacuation paths, and traffic and access control plan were reflected in the model.

As a simulation result, clearance time and cohort-based time are presented in this paper. To calculate the clearance time, the multi-model network was simulated ten-time by different sets of random number seed. The average clearance time was calculated as 27.3 h resulting from traffic jams near Busan and Ulsan. To calculate the cohort-based time, link aggregation was performed, and post-

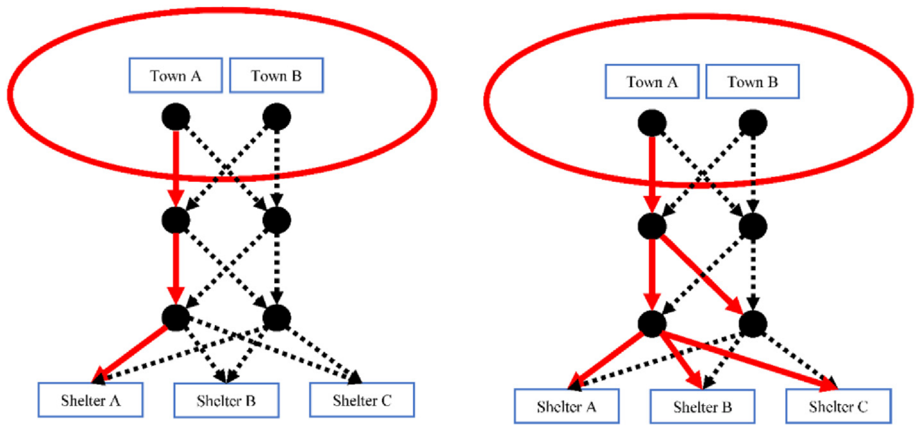


**Fig. 10.** Example of various direction to evacuate at intersections.

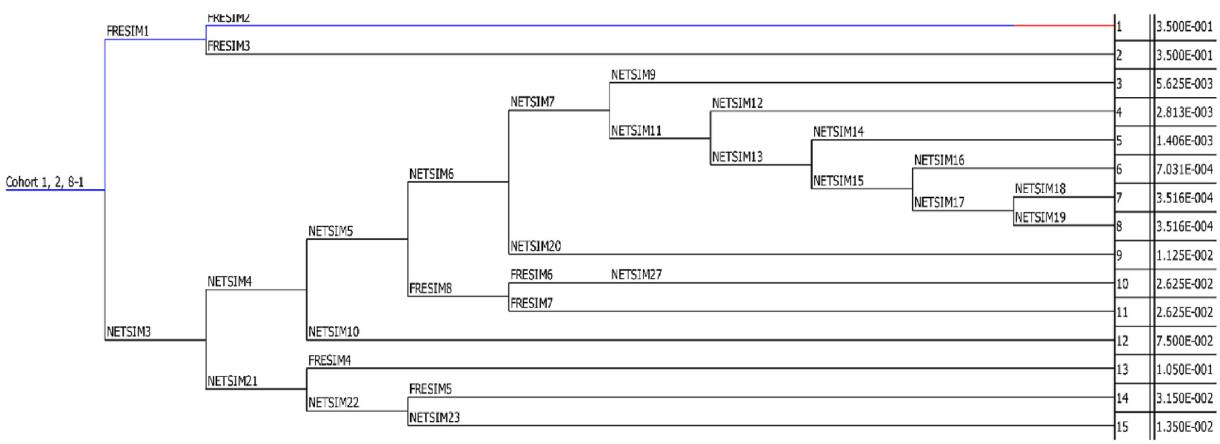


**Fig. 11.** Post-processing tree for cohort 1, 2, and 8-1.

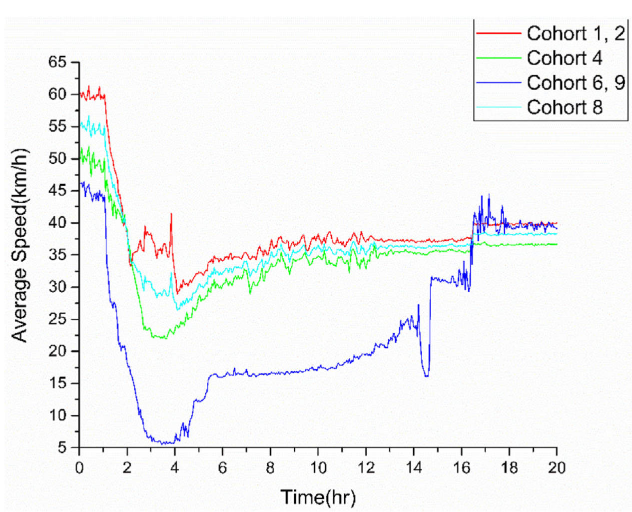


**Fig. 12.** Calculated average speeds by link aggregation and post-processing tree.

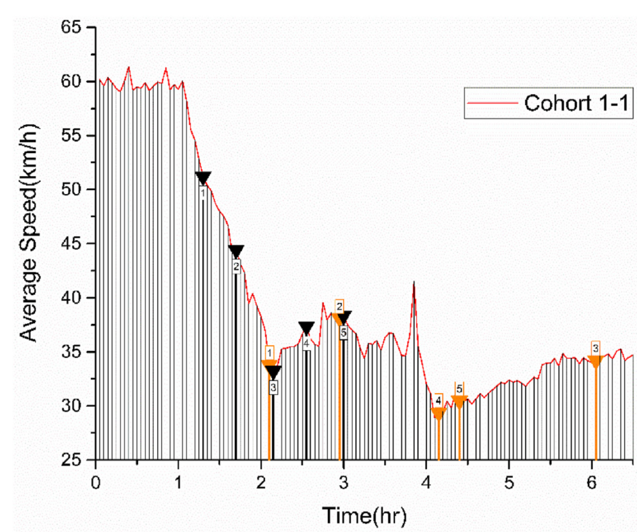


**Fig. 13.** Tracking vehicles for cohort 1-1.

processing trees were developed. The cohort-based results are summarized as follows. Cohort 2 takes relatively less time to evacuate than cohort 1, which means slowly entering the network may reduce the total evacuation time by avoiding traffic jams. Cohort 4 takes a relatively long time to evacuate because of traffic jams that occurred both inside of the PAZ and outside of 16 km. Cohort 6 resides near the densely populated area, but the required distance to evacuate is short. Therefore, they suffer the most massive traffic jam resulting in the lowest evacuation speed.

**Table 13**
Cohort-based results by tracking vehicles.

| Cohort | TGT (hr) | | | Evacuation time (hr) | | | Total time (hr) | | | Evacuation speed (km/hr) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Avg. | Min. | Max. | Avg. | Min. | Max. | Avg. | Min. | Max. | Avg. | Min. | Max. |
| 1–1 | 1.3 | 0.5 | 2.2 | 1.8 | 0.9 | 3.9 | 3.1 | 1.4 | 5.2 | 36.9 | 34.1 | 42.7 |
| 1–2 | 1.3 | 1.0 | 1.5 | 1.9 | 1.3 | 4.3 | 3.2 | 2.4 | 5.3 | 36.0 | 34.2 | 36.6 |
| 2 | 1.5 | 0.3 | 2.8 | 0.9 | 0.6 | 1.2 | 2.4 | 1.1 | 3.8 | 37.4 | 31.8 | 44.9 |
| 4–1 | 1.6 | 0.8 | 2.3 | 2.3 | 0.7 | 4.1 | 3.9 | 1.9 | 6.1 | 25.9 | 23.2 | 27.8 |
| 4–2 | 1.6 | 1.5 | 1.8 | 5.2 | 4.0 | 6.3 | 4.9 | 2.4 | 9.6 | 27.5 | 26.6 | 28.5 |
| 4–3 | 1.7 | 1.1 | 2.3 | 3.2 | 0.8 | 7.3 | 6.8 | 5.8 | 7.8 | 25.9 | 22.7 | 30.3 |
| 6–1 | 1.8 | 0.8 | 2.8 | 1.6 | 1.1 | 2.2 | 3.4 | 2.4 | 4.4 | 8.6 | 6.2 | 10.8 |
| 6–2 | 1.9 | 1.0 | 2.8 | 1.6 | 1.2 | 1.9 | 3.5 | 2.7 | 4.3 | 7.9 | 6.4 | 8.9 |
| 8–1 | 2.3 | 2.0 | 2.5 | 1.2 | 0.6 | 1.4 | 3.4 | 2.9 | 3.7 | 28.6 | 28.3 | 29.3 |
| 8–2 | 2.6 | 2.3 | 2.9 | 2.1 | 0.9 | 5.1 | 4.8 | 3.5 | 7.9 | 29.2 | 27.8 | 32.0 |
| 9 | 1.0 | 0.0 | 2 | 1.6 | 0.5 | 2.2 | 2.4 | 0.2 | 4.2 | 17.2 | 6.8 | 40.7 |

To reduce the uncertainties of the ETE in Korea in the future, uncertainty factors identified through this study are demonstrated as follows. The first factor is the way of classifying cohorts. The loading curve calculated by cohort data may profoundly affect the evacuation pattern, including evacuation speed and location of traffic jams. The detailed classification of cohorts can reduce uncertainty, but it requires lots of data. Therefore, the number of cohorts should be increased within the range that data can be obtained. The second factor is the degree of model complexity. It is the best way to model all road segments in the UPZ, but it is not possible. However, a car can exist on any road segment, and it may result in the difference of demand on the road segments between reality and simulation. Therefore, it is necessary to develop a methodology for this problem. The third factor is the traffic volume outside of the UPZ. In this study, the allowable free-flow speed on links near the UPZ was rearranged to deal with this problem, but it must be verified in the future. Other factors are driver behaviors, underpass and overpass roads, incidents during the evacuation, modeling toll gates, the feasibility of traffic access control, and background traffic volume.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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