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Original Article

Effects of child pick-up behavior on emergency evacuations

Sang Hoon Jang [a], Ha Hwang, Ph.D. [b], Ji-Bum Chung, Ph.D. [a, *]

[a] School of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology, Ulsan, 44919, Republic of Korea
[b] Division of Disaster & Safety Research, Korea Institute of Public Administration, Seoul, 03367, Republic of Korea

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A B S T R A C T

The child pick-up behavior of parents during an emergency can cause heavy traffic congestion and failing to evacuate an affected area successfully. In this study, we analyzed the effect of child pick-up behavior using, as an example, a nuclear power plant accident caused by an earthquake, which is a typical no-notice emergency. A quake was assumed to occur near the Shin-Kori nuclear power plant in Ulsan, Korea, resulting in a nuclear power plant accident. An agent-based dynamic simulation model using VISSIM was employed to conduct sensitivity analyses with different child pick-up rates. The results confirmed that parents are a major cause of congestion and a vulnerable class in an emergency evacuation. The child pick-up behavior caused significant traffic congestion, and parents who pick up their children showed a higher evacuation failure rate.

1. Introduction

The Great East Japan Earthquake in 2011 showed the seriousness of a nuclear power plant accident caused by an earthquake. Although there are fewer earthquakes in Korea than in neighboring countries, such as Japan and China, concerns about earthquakes and related nuclear plant accidents have been rising since the consecutive occurrence of the Gyeongju and the Pohang Earthquakes in 2016 and 2017. Currently, there are 24 nuclear power plants in the Republic of Korea (ROK), which is ranked one of the top countries in the world in terms of the number of nuclear power reactors per unit land area [1]. As a result, ROK has a very high sense of crisis about the possibility of nuclear power plant accidents caused by earthquakes.

With the development of science and technology, governments can predict the occurrence of disasters such as typhoons and hurricanes in advance and expect minimized disaster damage by notifying the evacuation paths and modes to the public. However, we have no way of knowing the occurrence of nuclear power plant accidents caused by earthquakes in advance. There are still some types of disasters where the location and time of the event are unpredictable. Such disasters are called no-notice disasters, such as earthquakes, chemical spills, and terrorist attacks. It is difficult to evacuate before such disasters occur, and in these cases, no-notice evacuation plans are necessary [2,3].

The evacuation of large numbers of people in an emergency can cause serious traffic congestion. In the case of Hurricane Irma in the United States in 2017, evacuation time was more than twice as long as expected because of the large amount of evacuation traffic, which was more than four times the average traffic [4]. In a no-notice emergency, such as an earthquake, the sudden heavy traffic during the evacuation may create a much more serious traffic jam because it is very difficult to prepare a step-by-step evacuation [5]. In ROK, there was severe traffic congestion on most of the main roads in Pohang City during the Pohang Earthquake in 2017 [6]. Minimizing the number of people who fail to evacuate due to congestion can significantly reduce the damage from a disaster [7]. Consequently, it is necessary to consider factors that affect congestion during evacuation in an emergency, particularly a no-notice emergency, such as an earthquake and a related nuclear power plant accident.

Analyzing the behavior of the evacuees during emergencies is necessary to develop an effective evacuation plan. Previous studies have demonstrated that people tend to visit homes instead of immediate evacuation. These are returning commuters, and they appear to move in the opposite direction to general evacuees [8,9]. They typically exhibit child pick-up behavior, which delays their efficient evacuation during an emergency. When parents go to their children's school, they wait near the school roads to find and pick

* Corresponding author.
E-mail addresses: jsh4319@unist.ac.kr (S.H. Jang), hahwang@kipa.re.kr (H. Hwang), leanring@unist.ac.kr (J.-B. Chung).

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up their children. If many parents go to the school, it causes severe congestion near the school and affects the traffic condition of the whole town. The congestion begins near the school and spreads to a wider area. Finally, it causes delays in the entire transportation network system. This phenomenon was observed in the 2017 Pohang earthquake during school hours in ROK [6].

This study aimed to analyze the effect of the child pick-up behavior of parents on the overall evacuation efficiency. The example used is an assumed nuclear power plant accident in Ulsan, ROK (Shin-Kori nuclear plants site). Various studies have already been conducted to select evacuation routes and analyze their efficiency using simulation techniques during emergencies [10–14]. However, few studies have examined the behavior of specific evacuees, such as parent child pick-up behavior, and their effects of evacuation delay from the perspective of the entire transportation network of the region using microscopic simulation tools. In this study, we used an agent-based model for the entire evacuation vehicle and parents' child pick-up behavior was reflected. A child pick-up behavior is an evacuation after a parent visits the school to pick up the children. Sensitivity analysis of the total evacuation time according to these child pick-up behavior ratios was performed.

2. Literature review

2.1. Evacuation simulation studies and nuclear power plants

Although it does not accurately reproduce the actual site, there is a reason why simulation research is inevitable. According to Harten et al. (2018), the cost is less than the actual evacuation exercise, and the evacuation simulation can be used to evaluate the total number of evacuees. In addition, various evacuation models can be verified through simulations to help make policy decisions [10,11,13].

These models can be classified according to the evacuation characteristics, such as mandatory evacuation, voluntary evacuation, recommended evacuation, declared or undeclared (self-initiative, shadow) evacuation, formal and informal evacuation, horizontal and vertical evacuation, general (mass) or partial evacuation, and selective and gradual evacuations [15]. Variables used in evacuation simulations include controllable variables, such as traffic routing, signalization, and population, and uncontrollable variables, such as weather and traffic accidents [9]. The time at which the disaster occurred or when the evacuation began is the most significant determining factor in describing the pattern of evacuation [16].

The nuclear power plant evacuation study was conducted in the 1980s due to the Chernobyl nuclear power plant accident; the related research received attention again due to the 2011 Great East Japan earthquake [9,15,17–20]. For the Korean cases, Lee et al. (2016) conducted a simulation study to estimate the evacuation time for an emergency planning zone (EPZ) in the Shin-Kori nuclear site of ROK. The researchers assumed that a severe accident occurred at Shin-Kori Nuclear Unit 3. They evaluated the dispersion speed of radiological material and the evacuation time of the residents in the Precautionary Actions Zone (PAZ), approximately a 5-km radius from the nuclear power plant site, using the VISSIM simulation software [19]. They concluded that it would take about 80–252.2 min for permanent residents to move out of the PAZ boundary, which is adequate for safe evacuation. However, there was a lack of consideration for human behavior in this model. Given that severe congestion in the evacuation route can occur for various reasons, it is necessary to consider simulation models that include human behaviors that cause congestion.

Previous studies have identified various methods of preventing congestion through simulations. These methods can be divided into permanent and temporary ways. The permanent one is to expand road capacity or create new roads. However, existing roads are built to reflect the current traffic volume, and a permanent increase in road capacity through the construction of additional lanes or roads has low investment efficiency. Temporary solutions utilize fluid transportation policies. These include contraflow, regulation of the use-of-own-vehicle rate, phased evacuation by distance, and traffic signals reflecting traffic volume using intelligent transport systems (ITSs) [11–14,21].

2.2. Human behaviors in emergency evacuations

People show various behaviors even in the same disaster evacuation situation. Examples include following the instruction or choosing evacuation modes [17]. In addition, the evacuation behavior may vary depending on the method of disaster warning (sirens, radio, route notification, and more), the extent to which people participated in evacuation drills, and the degree of evacuation education [17,22–24]. Moreover, people try to move faster than usual in a disaster situation, increasing accidents, and as a result, the evacuees themselves become obstacles to evacuation [25]. They sometimes drive over speed limits, make unreasonable decisions based on visual information alone, or violate traffic signals [5]. These factors are affected by people's disaster preparedness, disaster situation information, and education levels [15].

These human behaviors result from choice in various evacuation processes, including: evacuate/stay, accommodation type choice, evacuation destination choice, mode choice, vehicle usage choice, and departure time choice [14,26]. These evacuation decisions are also affected by the surrounding environment. In particular, people show different behavior depending on early warnings [5]. In emergency evacuation without early notice, more congestion is expected as the uncertainty in the evacuation behavior increases. Individual and government-level preparedness for disasters affects vulnerability across society [15]. Therefore, to establish an effective evacuation plan, it is necessary to understand various evacuation behaviors.

Furthermore, when creating an evacuation simulation model considering human behaviors, spontaneous and shadow evacuation should be considered [3,9,20]. The former is the voluntary evacuation without an evacuation order in the declared evacuation zone, and the latter is the voluntary evacuation from areas outside the zone. These two behavioral phenomena and permanent traffic volume should be properly reflected to infer the bottleneck in the actual evacuation situation. The permanent traffic volume refers to the traffic volume that travels on the road under normal conditions [19].

2.3. Child pick-up behaviors

The considerable history of survey research shows that human behaviors can influence traffic congestions and evacuation outcomes [15,16,18]. However, research on the effect of evacuation behaviors of specific classes on the entire evacuation population through micro-simulation is ongoing [12,27,28]. Examples of these classes are parents with children who are students. In the event of a disaster, the presence of children is an important variable in determining evacuation routes because parents try to evacuate with their children [18]. The behavior of parents who are stopping by the school to pick up their children can hinder the evacuation of others. During the Pohang earthquake in Korea in 2017, the extreme congestion near the schools affected all evacuation traffic [6].

Child pick-up behavior has often been the subject of research in the transportation sector [29,30]. These studies have identified that child pick-up behavior is an important factor in evacuation decision-making and delays the overall evacuation [18,31]. In a recent study, behavior analysis through MATSim simulation proved that child pick-up behavior is important in determining the departure time and evacuation route [8]. This study confirmed that child pick-up behavior causes more severe congestion in some sections while alleviating congestion in others [8]. However, the effect of the child pick-up behavior rate on the evacuation outcomes for all evacuees and the parents who picked up their children was little known. This study tried to investigate this effect through the sensitivity analysis on the ratio of parents' child pick-up behavior.

3. Background

3.1. Study area

Ulsan and its vicinity are the heart of Korean nuclear power generation. Based on PRIS data provided by the IAEA (International Atomic Energy Agency), Ulju County, an administrative county in Ulsan, is the most concentrated area of nuclear power plants globally [32]. The Kori and Shin-Kori nuclear power plant complexes, which have seven commercial reactors currently under operation, are located. In addition, the 1400-MW Shin-Kori Units 5 and 6 are under construction.

Given the case of the Fukushima nuclear power plant accidents, the Kori and Shin-Kori nuclear power plant complexes may also be vulnerable to large earthquakes, and they can cause enormous damage to nearby cities, such as Ulsan and Busan. They are located on the southeastern coast, and they are near Gyeongju and Pohang, where 5.8 and 5.4 magnitude earthquakes hit in 2016 and 2017, respectively. The distances from the Shin-Kori nuclear power plant and the epicenters of the Gyeongju and Pohang earthquakes are approximately 51 and 89 km, respectively. In addition, Ulsan is the largest petrochemical industry center in South Korea. Therefore, the occurrence of a nuclear plant accident resulting from a combined disaster, such as the Fukushima accident, could result in massive and serious secondary damage.

Furthermore, the Kori and Shin-Kori nuclear power plant complexes are located near densely populated areas. They are located close to the downtown of Ulsan and next to Busan, the second-most-populous city in Korea. The number of people living within a 30-km radius of the nuclear power plants is 3.8 million, the largest such concentration in the world [33]. In addition, various key facilities of the Korean economy, including Busan Port (32 km), the Ulsan Hyundai Heavy Industries shipyard (26 km), the Hyundai Motor Ulsan plant (25 km), and the Ulsan petrochemical complex (18 km) are within the boundary. Thus, Ulsan is the most suitable site for the simulation of nuclear accidents for these reasons.

3.2. Radiation evacuation system of Shin-Kori nuclear power plants

Ulju County provides a *Working Manual for Radiological Emergency Response*, which is based on the national-level nuclear emergency manuals and laws related to radiological emergencies and disasters to enable the public to cope with radioactive disasters. It provides detailed measures to respond to the emergencies of nuclear power plant accidents. According to this manual, radiation emergency alerts consist of three stages: White, Blue, and Red. The difference depends on the extent of the effects of the radioactive material. A White, Blue, or Red alert is issued when radioactive material is expected to affect the inside of the power plant building, the inside of the plant site, or the area outside the plant site, respectively. Table 1 compares the emergency alert stages used in Korea and the United States.

An evacuation order is issued to the residents within evacuation zones in the case of a Red alert. Evacuation zones are divided into two categories: one is the PAZ, and the other is the urgent protective action planning zone (UPZ). The PAZ is an area within a radius of 3–5 km from the nuclear power plants that are expected to have serious health risks from radioactive leaks [20]. The UPZ is an area within a radius of 30 km from the nuclear power plants. When an evacuation order is issued, residents within the PAZ are to evacuate first, followed by those within UPZ [20]. However, it is questionable whether such control is possible in actual situations.

In Korea, an evacuation drill has been conducted at least once a year since 2014. It is rooted in Article 37 of the *Act on Physical Protection and Radiological Emergency*. The accident scenario of the Shin-Kori Unit 3 evacuation drill conducted in 2018 can be summarized as follows.

- 0h 0min: Occurrence of magnitude 8.6 earthquake in the East Sea, 48 km away from the Ulsan seashore (**Issued White alert)**
- 1h 0min: Loss of the plant outside electrical power
- 1h 15min: Issued tsunami alerts (**Issued Blue alert)**
- 3h 20min: Loss of all alternating-current power
- 5h 40min: Loss of coolant in steam generator
- 6h 50min: Damage in POSRV, possible core meltdown (**Issued Red alert**, evacuation preparation for the residents in PAZ)
- 7h 10min: **Evacuation started**
- 8h 40min: Core meltdown 5.5%
- 9h 50min: Hydrogen explosion, the release of the radioactive materials to the outside air

In this study, all students were assumed to be in schools when the red alert was issued for a conservative approach, i.e., 10 a.m. on a weekday. According to the *Ulju County Working Manual for Radiological Emergency Response,* the specific evacuation target time is set to a total of 2 h and 35 min after the Red alert is issued. First, residents have up to 20 min to prepare for evacuation and travel to Namchang Station (Fig. 1) within 40 min by individual or group transportation. Second, after arriving at the station, people take a train for 35 min and then transfer to buses prepared for them. They arrive in the designated relief shelters within 60 min. After arriving at Namchang Station, people travel by train and buses at the same time under strict control, so this study simulates an hour of traveling to Namchang Station, where individual behavior is more likely to be reflected in an evacuation.

The evacuation plan was verified by reflecting the rate of radioactivity leakage in a previous study that established Shin-Kori Nuclear Power Plant as the target site for analysis. As a result, the target time for evacuation and the actual time taken was similar [19]. However, if not only shadow evacuation but also various behaviors are reflected, the real evacuation will take more time [28]. In a recent paper dealing with Sin-Gori Nuclear Power Plant as a target site, each cohort's evacuation time and characteristics were identified by dividing the number of evacuation personnel into several cohorts [20]. In this study, we will more specifically verify how much the entire network is affected by the evacuation behavior of a certain group, that is, the parents who want to pick-up their children.

4. Method

4.1. Research design

Previous studies have mainly examined ways to solve traffic congestion problems caused by emergency evacuation. Traffic flow was controlled in congested areas through various technical methods, such as contraflow, regulating the rate of use of cars, step-by-step evacuation according to the distance, and ITS traffic signals

Table 1
Emergency alert stages.

Phase	Korea	United States (International Atomic Energy Agency, 2007)
Stage 1	White alert - Events that may result in damage to the sealing conditions of radioactive materials or damage to the power supply function for maintaining the safety of nuclear facilities, etc. - Any releases are expected to be confined within the building of the nuclear facility.	Alert - Events are in progress or have occurred which involve an actual or potential substantial degradation of the level of safety of the plant or a security event that involves probable life-threatening risk to site personnel or damage to site equipment because of hostile action. - Any releases are expected to be limited to small fractions of the Environmental Protection Agency (EPA) protective action guides (PAGs).
Stage 2	**Blue alert** - Events that may cause damage to the main safety functions of nuclear facilities due to the reduction of the ability to restore to a safe state. - Any releases that are expected to be confined within the site boundary.	Site Area Emergency (SAE) - Events are in progress or have occurred that involve actual or likely major failures of plant functions needed for the protection of the public or hostile action that result in intentional damage or malicious acts 1) toward site personnel or equipment that could lead to the likely failure or 2) that prevent effective access to the equipment needed for the protection of the public. - Any releases are not expected to result in exposure levels that exceed EPA PAG exposure levels beyond the site boundary.
Stage 3	**Red alert** - Events that may result in damage to the last barrier of a nuclear facility due to damage or melting of the core. - Releases are expected to occur outside the site area.	General Emergency Events are in progress or have occurred that involve actual or imminent substantial core degradation or melting with the potential for loss of containment integrity or hostile action that results in a real loss of physical control of the facility. Releases can be reasonably expected to exceed EPA PAG exposure levels offsite for more than the immediate site area.

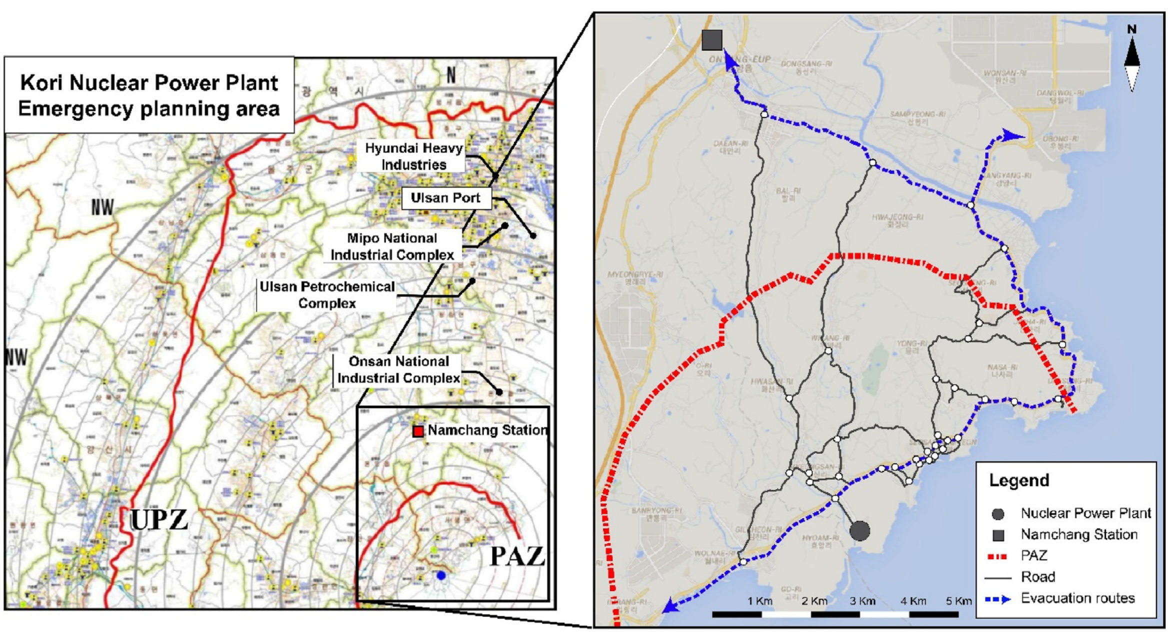

Fig. 1. Major facilities around the site (source: Field of Action on the Safety of Nuclear Power Plants (Radioactive Leakage) (with author edits).

in case of a disaster [11,13,21,34]. The purpose of this study was to analyze the effect of family evacuation behavior, especially the evacuation behavior of parents going to schools to pick up their children. Such behavior of parents is expected to affect the entire transportation network in the evacuation area, but research on this is lacking. The hypothesis is that, as more parents move in different directions to pick up their children, traffic congestion worsens and delays evacuation. To demonstrate this, a sensitivity analysis was conducted that changed the proportion of parents who picked up their children. It is also aimed at determining the level of behavioral regulation of parents to ensure that all evacuees are most effectively evacuated. Fig. 2 shows the research design of this study.

Φ is to minimize the total evacuation time. This function calculates the value by adding the link travel time of each vehicle i on link j as it travels along the evacuation route J_i. The traffic volume was divided into two categories: general evacuation vehicles and vehicles for child pick-up behavior. A sensitivity analysis was conducted to see the change in the total evacuation time by controlling the ratio of child pick-up behavior vehicles (V^p).

$$\Phi = min\sum_i\sum_j\left[T^j{}_o\left\{1+\alpha_j\left(\left(V_j^e+V_j^p\right)/C_j\right)^{\beta_j}\right\}\cdot J_i\right]$$

Φ = total evacuation time; i = vehicle index; j = link index; $J_i = 1$ if vehicle i used link j for evacuation, else 0; $T^j{}_o$ = free-flow travel time of link j; V_j^e = general evacuation traffic volume on link j; V_j^p = child pick-up traffic volume on link j; C_j = road capacity of link j; α_j, β_j = link coefficients.

The objective function is the network-wide extension of the volume delay function developed by the Bureau of Public Roads.

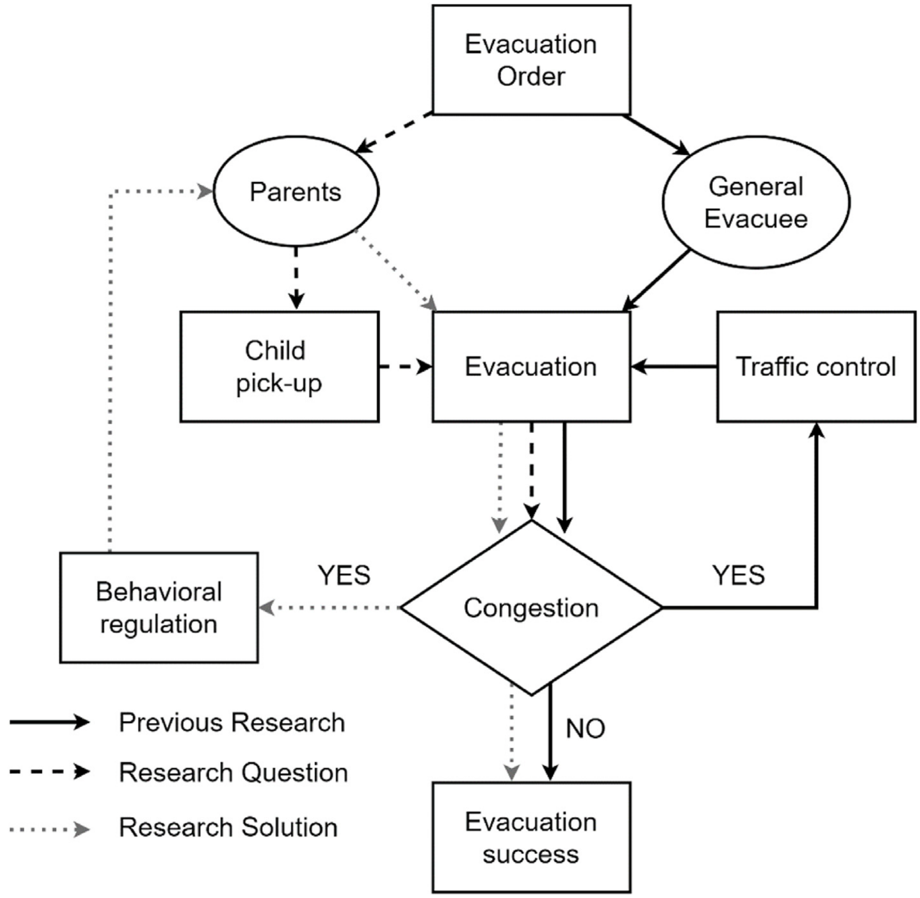

Fig. 2. Research design.

While alpha and beta are the core coefficients that determine the dynamic of road congestion, VISSIM does not allow to enter such values directly to each link. Instead, the dynamic can be applied indirectly by entering road conditions such as the number of lanes, speed limits, lane width, type of pavement, and so on.

4.2. Microsimulation using VISSIM

Previous studies have used various simulation programs to verify the effects of traffic policies. There are several well-known simulation software: VISSIM, CORSIM, and MITSIMLab for microscopic analysis; DYNEV and ETIS for macroscopic analysis; and OREMS and DYNASMART-P for mesoscopic analysis [14]. Microsimulations can be used to analyze various traffic policy scenarios to increase vehicle flow or avoid expected bottlenecks [13]. VISSIM was used in this study. It is among the most commonly used microsimulation programs for transportation analyses. VISSIM simulates traffic conditions by assigning vehicle agents on a network of nodes and links. It provides various output values, such as vehicle throughput, average traffic density, and average speed [35].

The cost of dynamic assignment of VISSIM is determined by the sum of travel time, travel distance, financial cost, and user-defined surcharge [36]. In the current study, the ‘smoothing factor’, a setting affecting cost calculation, was set to 0.2. The lower the value of the smoothing factor, the more the previous simulation results are used to calculate the cost. Each vehicle repeatedly recalculated the cost every 10 min so that the route could be set.

We used an Open Street Map to construct the road network for simulations. Link information such as the number of lanes and speed limit was manually entered through an on-site investigation. A total of three OD matrices were used to represent the traffic volume: permanent traffic, general evacuation traffic, and child pick-up behavior traffic. Permanent traffic occurred an hour before issuing the red alert, and we assumed that no more permanent traffic volume was generated after the red alert. The general evacuation vehicles originate from their respective TAZs and are destined to the Namchang Station. While the vehicles for child pick-up behavior also share the same origins and the destination with the general evacuation ones, child pick-up behavior vehicles were set passing through either of the schools. Since VISSIM dynamic assignment does not have the function to set waypoints, we set them indirectly by using the ‘dynamic vehicle routes’ function. The original purpose of this function is to allow vehicles to change destinations according to the vehicle type (car, heavy goods vehicle, bus, tram, etc.). We set the vehicles for child pick-up behavior as a new vehicle type, and the characteristics were set the same as the permanent evacuation vehicle. Using this function, the vehicles for child pick-up behavior were set to stay near either of the schools for 10–15 min and then head to Namchang Station. The default values were used for the dynamic assignment variables. For the VISSIM simulation result, the average value of 6–15 simulations except for the first five was used.

This study aimed to investigate the impact of the behavior of parents who visit schools to pick up their children, unlike the rest of the population. There are two main reasons for using VISSIM in this study. First, because VISSIM is an agent-based model, more realistic evacuation modeling is possible. Second, it is possible to assign multiple vehicle groups separately. In other words, the general evacuees move along the shortest path calculated by the dynamic assignment algorithm based on the general evacuees' OD matrix, starting from their location and ending at Namchang Station. This process is similar to human decision-making in the event of a disaster [14]. However, parents go to the school from their respective origins and then travel to Namchang Station based on child pick-up behavior.

4.3. Model calibration and validation

Using VISSIM, a model of the Ulsan transportation network covering the Kori and Shin-Kori nuclear power plants and Namchang station was created. It consisted of 185 links and 62 nodes, covering an area of 55 km^2. The road hierarchy, number of lanes, speed limits, and pavement types were considered.

To model the network condition before issuing the evacuation order, permanent traffic volume should be assigned to the network. Permanent traffic OD data were generated using the National Traffic Survey data of two links and on-site traffic count data on 32 links, which were measured from 10:00 a.m. for an hour. Fig. 3 shows the model calibration by comparing the link volumes between the on-site traffic volume and the estimated traffic volume generated by the permanent traffic OD data. As a result, R^2 of 0.89 between the on-site traffic volume and the estimated traffic volume of 32 links was obtained (Fig. 3). After assigning the permanent traffic volume, we also validate the network. Origin and destination points were randomly selected 33 times to compare travel times within the site. Fig. 4 shows the validation outcome, comparing the estimated travel time calculated by the route-finding function of KAKAO MAP with the simulated travel time using the calibrated VISSIM model. As a result, R^2 of 0.965 between the observed travel time and simulated travel time was obtained (Fig. 4).

4.4. Model simulation

This study employed the scenario used for the Shin-Kori Unit 3

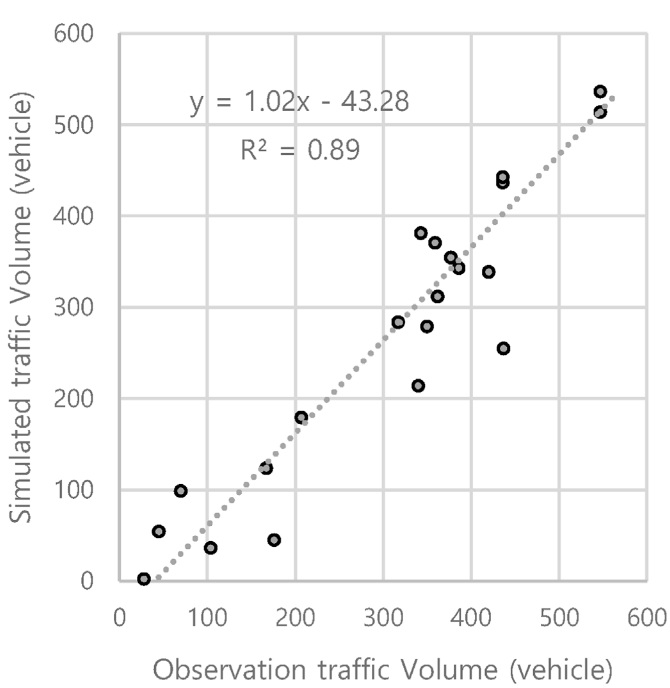

Fig. 3. Model calibration outcome.

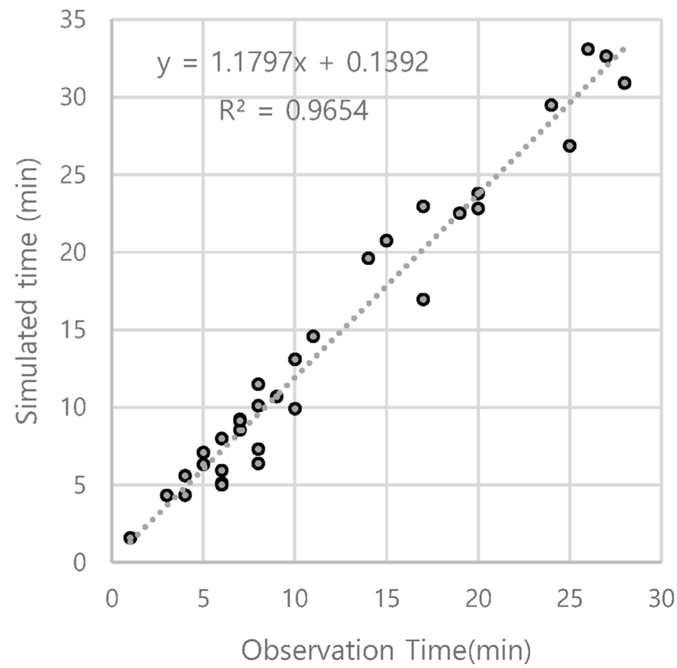

Fig. 4. Model validation outcome.

event drill conducted in 2017 and 2018 and the Nuclear Safety Field Action Manual Shin-Kori Nuclear Power Plant. All evacuees, including parents, depart for 20 min after the Red alert. However, parents wait for their children in the vicinity of the school for at least 5–10 min. Simulations were conducted at every 10% from 0% to 100% of the child pick-up behavior rate to analyze how parents' behavior affects the overall evacuation. Before examining, the permanent traffic before the Red alert was considered. Traffic collected on-site was reflected in the network before the actual evacuation. The simulation results are based on 110 simulations by adopting the average value of 10 times for each model [23]. The analysis was conducted more than 10 times for each model because the analysis focused on the time required for the entire evacuation [37].

In previous studies, evacuation route selection, and traffic lights were considered as controllable variables [9]. In this study, traffic routes were selected by vehicles themselves using dynamic assignment [37]. Based on the accident scenario of the Shin-Kori Unit 3 evacuation drill, the traffic signals were assumed to be off because of blackout due to the earthquake, and the first-in-first-out method was used. The time when a disaster occurs or evacuation begins is the most significant determinant of evacuation patterns [16]. The evacuation start time was set at 10 a.m. on weekdays when students were at school.

The modeling area is comprised of five administrative areas. They are Sinam-ri (a), Sinam-ri (b), Sin-ri, Nasa-ri, and Daesong-ri. These are divided into Traffic Analysis Zones (TAZs), where about a hundred fifty households are residing (see Fig. 5 and Table 2). Evacuation vehicles were generated by TAZs according to the number of households.

Seosaeng Elementary School and Seosaeng Middle School were set as child pick-up destinations for parents. According to the Ulsan Metropolitan Office of Education (2018), there were 152 students enrolled in Seosaeng Elementary School and 322 students enrolled in Seosaeng Middle School [38,39]. The Monte Carlo method was used to determine whether each vehicle will visit a school and which of the two schools will be visited. All vehicles were set to

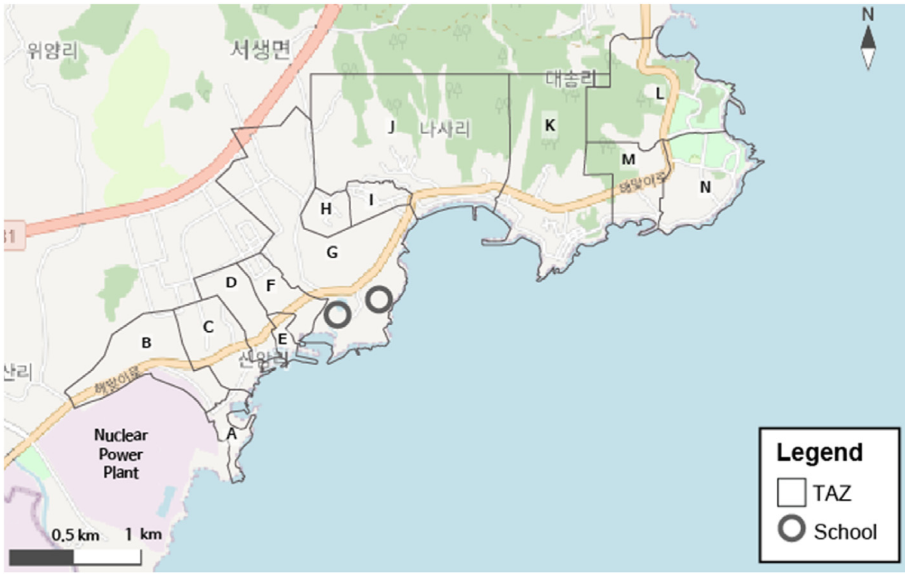

Fig. 5. Traffic analysis zone of the study area.

Table 2
Number of simulated vehicles of each area.

	TAZ	number of households	population	male	Female	number of simulated vehicles
Sin-ri	A, B, C	474	1080	573	507	474
Sinam-ri (a)	D, E, F, G	443	944	485	459	443
Sinam-ri (b)	H, I	351	749	408	341	351
Nasa-ri	J, K	335	672	347	325	335
Daesong-ri	L, M, N	320	664	354	310	320

Source: Seosaeng Town Office.

depart within 20 min after the Red alert was issued in accordance with the evacuation manual. All parent vehicles were set to stop near the school for a random time between 10 and 15 min to pick up their children and then depart for Namchang Station.

Evacuation simulation studies considered spontaneous, shadow evacuation, and permanent traffic [3,9,19,20]. We did not consider spontaneous and shadow evacuation because we assumed that evacuees have no information about the accident before the Red alert. The permanent traffic volume was placed on the network of VISSIM for 1 h before the evacuation began.

5. Results

5.1. Preliminary result: 100% child pick-up behavior

The goal of the radioactive evacuation simulation is for all people in the evacuation area to arrive at Namchang Station within 60 min after the Red alert was issued. Preliminary results show the evacuation results assuming all parents are escaping by first going to a school to pick up their children, as in Fig. 6. The evacuation rate curve of the total population has a gentle sigmoid curve, and the parental evacuation curve has an irregular increasing pattern. After 60 min, only 54% of the total population and 33% of the parent population were able to evacuate. Even after 80 min, only 81% of the people and 50% of the parent population succeeded in evacuating. The simulation result shows that it is impossible to evacuate all the people successfully within an hour in the present situation, especially in the case of parents.

The reason for evacuation failure could be inferred from the congestion caused by parents who flock to the school to pick up their children. In the early stages of evacuation, severe congestion was observed in major evacuation routes, which was expected. However, after 1 h, congestion was still observed on some links. This simulation result suggests that the child pick-up behaviors of parents may have caused traffic congestion around the schools, which may have reduced the evacuation success rate.

5.2. Sensitivity analysis: pick-up behavior rate of parents

Reducing pick-up behavior can alleviate congestion around schools, resulting in increased evacuation success rates. Sensitivity analyses were conducted to test this hypothesis. We changed the proportion of parents passing through schools to pick up their children. The sensitivity analysis result confirmed that evacuation success rates increased as the school visit rate decreased (Fig. 7). Sixty minutes after the red alert was issued, the escape success rate increased from 54% to 65% and 78%, with the rate of child pick-up behavior reduced from 100% to 50% and 10%, respectively. Similar patterns were shown 70 and 80 min after the alert (see Fig. 8).

In addition, the evacuation rate decreased when the evacuation was completed by approximately 80%, and all subsequent evacuees were parents visiting the school. This finding indicates that those who have to go to school to pick up their children in an emergency evacuation are at risk and vulnerable in a disaster situation.

The unique point is that evacuation success rates were higher when 10% of parents went to a school than when no one did. This can be seen more clearly in Fig. 8. At 50, 60, and 70 min of evacuation time, the inflection point is generated when 10% of parents pick up their children. This is evidence supporting previous claims that early departures or parental departures to school alleviate

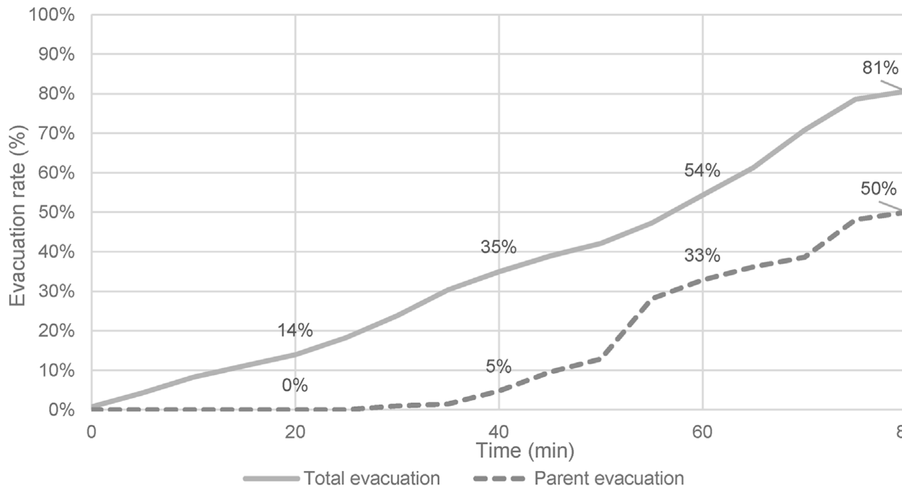

Fig. 6. Preliminary evacuation outcome: 100% of parents visit schools to pick up their children.

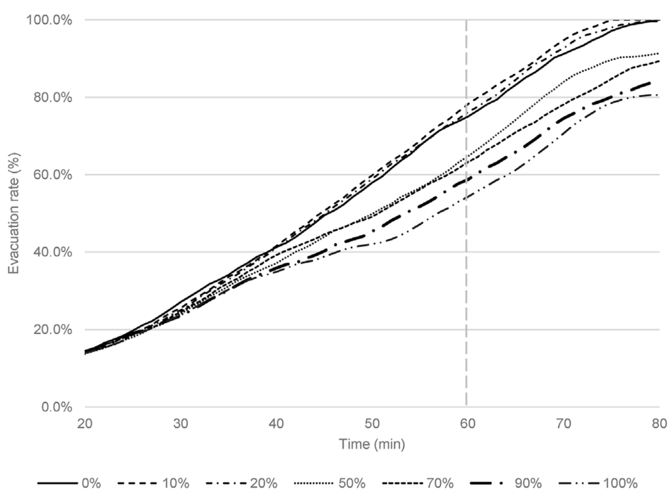

Fig. 7. Result of sensitivity analysis for child pick-up behavior ratio.

certain congestion intervals [8]. Some parents alleviate the traffic on the main evacuation route as they travel in the opposite direction.

6. Conclusions

The behavior of parents stopping at schools to pick up their children during an evacuation was analyzed through VISSIM simulations. The results confirmed that parents are not only one of the major causes of congestion but also a vulnerable class in an emergency evacuation. Parental pick-up behavior caused traffic congestion on the site, and because of this congestion, parents evacuated later than others and had a higher evacuation failure rate. If more than 40% of parents visited the schools, there was severe congestion on the roads near the schools. This congestion was confirmed to persist after 60 min.

It hypothesized that as the parent pickup behavior increases, the traffic delay also increases. The current study verified that the relationship is not linear, but the congestion was most alleviated when the child pick-up ratio was 10%. The peak point could be vary depending on site condition, such as major evacuation routes and the location of schools. In this study, since the schools are located

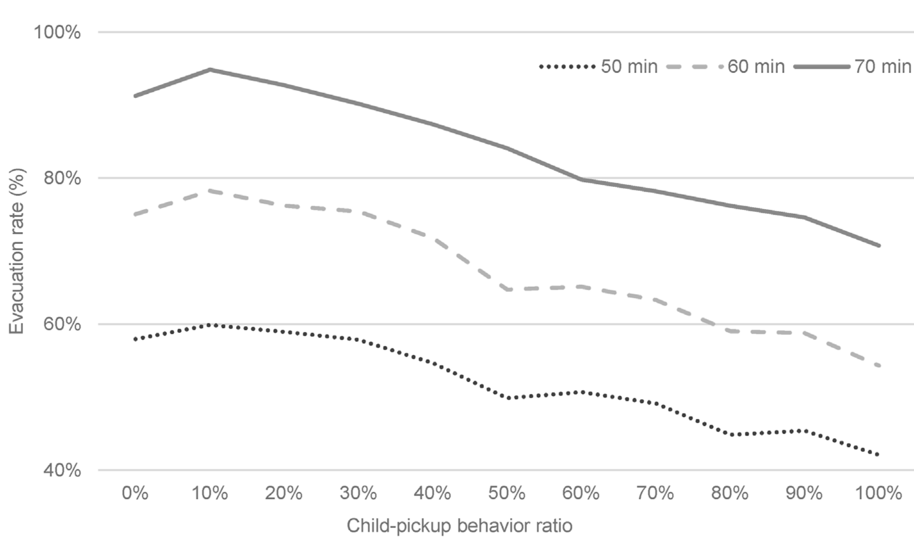

Fig. 8. Evacuation success rate by child-pickup behavior ratio at 50, 60, and 70 min.

on the main evacuation route, congestion nearby the schools affected the overall evacuation vehicles quickly. If the school is away from the main evacuation route, the peak point of the child pick-up ratio would be greater than 10%. From a policy point of view, it is necessary to consider parental behavior and major evacuation routes when selecting locations for schools near the nuclear power plant area.

According to the Korea Hydro & Nuclear Power (the sole operator of all nuclear power plants in ROK) Shin-Kori Units 3 and 4 radiation emergency plan, the evacuation of the school students will be done by buses. They do not consider the congestion caused by the child pick-up behavior of parents. However, in the case of an emergency, many parents may come to school to pick up their children, resulting in heavy congestion near school roads. Furthermore, roads near the schools in the study area are mostly narrow and shoulderless two-lane roads. Therefore, if many cars come to school simultaneously, it results in a heavy traffic jam. The Shin Kori Units 3 and 4 radiation emergency plan is based on the United States Nuclear Regulatory Commission (NRC) [40]; the early protective actions for evacuation of schools before the general public, if time allows, should be considered. However, the NRC criteria also did not consider congestion caused by the pick-up behavior of parents.

The results of this study imply that child pick-up behavior should be reflected in the evacuation plan, indicating the need for a student evacuation system and education for parents to minimize such behavior. The child pick-up behavior of parents should be regulated during an emergency, and it should be reflected in the development of an emergency evacuation policy. Currently, the *Ulju County Working Manual for Radiological Emergency Response* requires schools to evacuate students on their own. The establishment of specific evacuation plans and methods is left to the schools' discretion. Therefore, when creating a new evacuation manual, the schools must establish a system such that, in the event of an emergency, parents can immediately and continually know the location and safety of the students. Furthermore, schools need to develop effective drop-off zones to mitigate severe congestion during an emergency.

If the traffic vulnerable classes are evacuated preemptively at the Blue alert stage, congestion in the evacuation situation after the Red alert can be alleviated. One of the traffic vulnerable groups could be the lower grade students who need the care and help of their parents during evacuation. Parents with lower grade students could be contacted by the school at the Blue alert stage so that they could make "early child pick-up travel".

This research is meaningful academically and for policy for the following reasons. First, there is an academic significance in analyzing the effect of a group's behavior on the entire network using a combination of agent-based models, unlike previous evacuation studies. Second, the simulations proved that the major cause of traffic congestion in large-scale emergencies could be the child-pickup behavior of parents and suggested that this should be reflected in evacuation drills and manuals.

This study has limitations because of the simple road network of the study site. If the road network is simple, the ability of the driver to select various bypass routes when traffic is congested is limited. However, other evacuation patterns may occur in cases of accidents at chemical complexes, for example, near urban centers or residential areas where the road network is complicated. Evacuees can choose from a variety of bypass routes if the road network is complex. Subsequent studies should identify how evacuation behaviors, such as the pick-up behavior of parents, vary depending on the complexity of the road network.

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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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