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Original Article

Traffic management for large-scale evacuation with public transportation and calculation of appropriate operating ratio

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ABSTRACT

In 2013, the International Atomic Energy Agency (IAEA) changed the recommended maximum range of the Emergency Planning Zone (EPZ) to 30 km, and the Kori Nuclear Power Plant in Republic of Korea has also expanded the EPZ to 30 km, following the recommendation. As a result, metropolitan cities with a high population density are contained within the EPZ, and evacuating millions of people should be considered if the 30 km range of evacuation is to take place. This study proposes an evacuation plan using buses (public transportation) to transport people outside of the EPZ, quickly and efficiently. To verify the appropriate mode share ratio of buses that can guarantee the right of vulnerable road users and reduce traffic congestion, a model was built simulating the Kori Nuclear Power Plant in Ulsan Metropolitan City. The scenarios were established by changing the mode share ratio of buses and passenger cars by 10%. Considering a large-scale network analysis at the city level, a cell transmission model was applied to calculate the evacuation time in each scenario. The result shows that the optimal mode share ratio of buses is 40%, with a total evacuation time of 132 min, considering feasible bus fleets in Ulsan Metropolitan City.

1. Introduction

Since the Fukushima Nuclear Power Plant accident, the International Atomic Energy Agency (IAEA) has recommended setting a precautionary action zone (PAZ) at a range of 3–5 km, and an urgent protective action planning zone (UPZ) at a range of 5–30 km for nuclear power plants exceeding 1000 MWth. However, to prepare for nuclear power plant accidents, it is recommended that the basic range of the emergency planning zone (EPZ) be set in a flexible manner, according to the circumstances of each country. The EPZ is to be set in advance with the necessary precautions. It is set to 7–10 km in China, 20 km in France, at least 25 km in Russia, and 16 km in the United States. In South Korea, it is set at the maximum range recommended by the IAEA: 30 km [1] (see Table 4).

Within the EPZ, the emergency action level (EAL) determines whether there will be an emergency evacuation or a planned evacuation. However, in the event of radiation, it can be expected that residents of nearby areas will self-evacuate because of anxiety and fear, even when an emergency evacuation is ordered only within the PAZ. Therefore, it is reasonable to include the entire EPZ when assessing resident evacuation during accidents.

In 2020, the population densities of the regions where Korea's nuclear power plants are located were as follows: 4354.94 persons/km^2 in Busan Metropolitan City; 1056.88 persons/km^2 in Ulsan Metropolitan City; 148.51 persons/km^2 in Jeollanam-do; and 138.04 persons/km^2 in Gyeongsangbuk-do [2]. Given the high population densities of cities near nuclear power plants, the evacuation of millions must be considered when evacuating within a 30 km range.

To date, evacuating a million people due to a single incident has not yet been experienced. Should such an emergency occur, it would generate massive traffic congestion. This study proposes a bus-based evacuation model—and aims to find the mode share ratio for the buses—to guarantee safe passage for the mobility disadvantaged group and mitigate road congestion in case of a large-scale evacuation due to a nuclear accident.

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2. Backgrounds

Since the 1980s, studies have been conducted on EPZs to gain insights on emergency evacuations during nuclear accidents [3]. The IAEA has recommended that plant operators regularly assess evacuation readiness in areas around nuclear power plants [4,5]. The Kori Nuclear Complex calculated the time to evacuate for 1036 people inside the PAZ, assuming that an accident occurred at the Kori Nuclear Power Plant [6]. The micro-simulation model VISSIM was used, assuming that a 20% shadow evacuation of the UPZ would occur as residents within the PAZ evacuated [7]. In the study, the mobility disadvantaged group consumed a maximum of 232.2 min, and the non-mobility disadvantaged group a maximum of 252.2 min. Similarly, the Nuclear Regulatory Commission has also proposed a method for calculating evacuation time when residents inside the PAZ are ordered to evacuate [7]. However, these studies assume the evacuation of a small number of people in the PAZ, and only a few people evacuating in the UPZ, thus the evacuation activity time is calculated for relatively smooth traffic scenarios.

The IAEA recommends a strategy where residents within a 2–5 km range of a nuclear power plant are evacuated. Regarding the PAZ evacuation, the wind direction is forecast, based on which the PAZ is divided into evacuation and non-evacuation zones [8]. However, considering the population around the Kori Nuclear Power Plant, there are more than one million people in the PAZ, and if Haeundae-gu is included, the expected number of evacuees would be nearly three million. IAEA Safety Standards define this kind of evacuation as a mass evacuation and predict various traffic related problems [9].

Numerous studies have been conducted on mass evacuations. A case study in Italy proposed evacuations utilizing public transportation, citing two benefits: the reduction of the number of vehicles because of the high transportation volume of public transportation, and evacuation opportunities for those without vehicles [10]. A mass evacuation studied an optimal school bus usage plan using a dynamic program solution algorithm on the Python platform. The results showed traffic volume reduction by 3.9–77% (at an overall evacuation demand of 5%, 10%, 15%, and 20%) and wait-time reduction by 9–22.7% when buses are provided compared to when only cars are used [11].

A case study in Auckland predicted the time taken to streamline transportation networks during an evacuation of residents within a 5 km area in response to a volcanic eruption in Auckland [12]. The results showed that an evacuation time of at least 7 h to more than 12 h would be required, but the analysis assumed that personal vehicles would be used as the majority transportation method, and buses were set to be less than 5% of overall traffic volume.

A large-scale evacuation analyzed methods of evacuating residents in the Toronto area using buses and subways in response to a hurricane. The results showed that 1.34 million people requiring public transportation could be evacuated within an average of 2 h. A total of 6.20 million people could be evacuated using a maximum of four subways lines, and 0.72 million people could be evacuated using 1320 shuttle buses [13].

However, these studies have focused on the number of buses and trips needed to transport all those requiring evacuation, which limits their scope. Moreover, the target disasters in these studies were hurricanes, volcanoes, etc., which are unlike radiation.

This study aims to analyze the effect of bus-based evacuation in response to radiation disasters. It quantitatively analyzes evacuation time reduction in case some PAZ residents use public transportation to evacuate and calculates the appropriate ratio of cars and buses to be used according to traffic network circumstances.

In addition to the benefits presented, it is necessary to create public transportation evacuation measures for the following reasons [10,14]. First, in the event of a radiation accident, evacuations have to be performed over 30 km at maximum, and on-foot evacuation may not be possible over such a long distance [4,15–18]. Second, the mobility disadvantaged group requires a means of transportation; therefore, it is necessary to establish a system to enable residents' evacuation—especially of children and the elderly—when private vehicles are unavailable. Third, it is necessary to mitigate congestion, which will surpass the morning and evening rush hours in case more personal transportation is used.

However, several limitations exist. For example, this study does not address some of the actual public transportation operation issues that will arise, such as who will drive the buses and whether buses are available for mobilization. The goal of this study is to verify the extent to which evacuation time can be reduced by using public transportation.

In order to establish a large-scale evacuation strategy, public transportation's target mode share ratio is determined first, then the number of buses needed and the order of precedence for car use can be determined accordingly (see Fig. 1).

3. Model construction

The model's target is Ulsan Metropolitan City's Kori Nuclear Power Plant, and the topography and road conditions are shown in Fig. 2. Looking at the main roads within 30 km, National Routes 31 and 14 run north–south, and Local Road 20 runs east–west. Highway 65 runs through the area in a north–south direction, accessible at four places within the analysis area: the Onyang IC, Cheongnyang IC, Munsu IC, and Beomsu IC.

3.1. Model assumptions

A macro-analysis was performed to compare the mode share ratios of cars and buses.

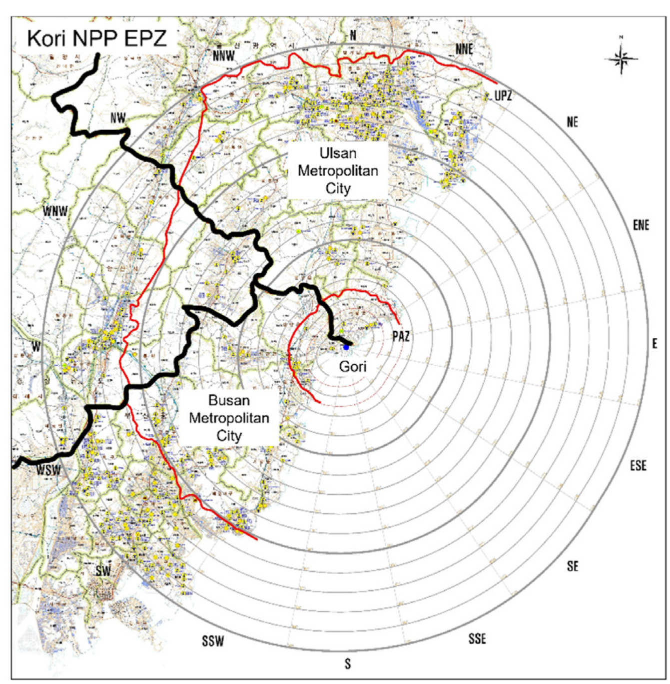

Fig. 1. Kori Nuclear Power Plant EPZ (source: Appropriateness of location of nuclear accident evacuation shelters based on population characteristics and accessibility [19]).

1) The evacuation time is assumed to be non-peak time during the day, and it was assumed that everybody moves in the evacuation direction at the beginning of the evacuation activity.
2) Weather and seasonal circumstances are not considered. These can have a significant impact on the mode share ratio, but extreme heat and cold are not considered, and it is assumed that there are no restrictions on the mode selection between buses and cars. It is also assumed that other events, such as traffic accidents on the road network, do not occur.
3) There are many evacuation routes, but it is assumed that the buses will use Local Road 20, Highway 65, and National Routes 14 and 31, which allow inter-region connectivity. It is assumed that the buses are driven up to 30 km and then driven back to the source station.
4) It is assumed that there are no bus stops or staging areas for boarding buses, and the buses can be driven on bus routes.
5) In the case of car usage, it is assumed that the time to prepare and depart from home is 10 min.
6) In the case of bus usage, it is assumed that it takes 30 min to reach the bus route. It is assumed that there is a bus stop within a 2 km-radius, and the person's walking speed is 4 km/h.
7) It is assumed that 10% of people belong to the mobility disadvantaged group and cannot perform evacuation activities that utilize public transport. This percentage was chosen arbitrarily, and it is assumed that the mobility disadvantaged group evacuates using cars because they cannot access bus routes.
8) The bus movement speed is assumed to be 90% of cars' maximum speed, considering bus size and boarding time.
9) It is assumed that 2.5 people board each car and a maximum of 45 people can board each bus.
10) Evacuation routes depart from residence registration locations. The populations at residence registration locations are used (see Table 1).
11) The condition of the main arterial roads are indicated in Table 2
12) Condition of other roads

It is assumed that there are one or two lanes each way, and the maximum speed of all vehicles is 50 km/h. The speed was set according to a relational formula between traffic volume and density [14]. The roads were configured in a simplified manner with a total of 124 links (Fig. 3).

13) Regarding access from residences to transportation links, the time spent moving in order to ride the bus was set at 30 min on foot and 5 min by car. The constructed network is shown in Fig. 3. In the case of bus travel, up to 45 people can ride

Table 1
EPZ ranges in each country.

	EPZ Range	
	PAZ	UPZ
IAEA	3–5 km	5–30 km
Canada	Not pre-determined	
China	7–10 km	
France	20 km	
Korea	3–5 km	20–30 km
Russian Federation	<25 km	
USA	16 km (10 miles)	

Source: Reconfigured by the author from the SMR Regulators' Forum Pilot Project Report

Table 2
Condition of the main evacuation road.

Route	Length	Max speed	Lane	Capacity
65	60 km	100 km/h	6	2,000veh/h
14	80 km	80 km/h	3	1,500veh/h
31	48 km	80 km/h	3	1,500veh/h
20	25 km	60 km/h	2	1,000veh/h

Table 3
Mode (car & Bus) share ratio conditions by scenario.

Scenario number	Car share Ratio (%)	Bus share ratio (%)
1	90	10
2	80	20
3	70	30
4	60	40
5	50	50
6	40	60
7	30	70
8	20	80
9	10	90
10	0	100

Table 4
Evacuation time and number of buses required and cars by bus share ratio.

Bus ratio (%)	Evacuation time (min)	No. of buses	No. of cars
0	435	–	400,000
10	283	6498	283,036
20	218	10,070	218,740
30	167	12,278	178,996
40	132	13,780	151,960
50	123	14,868	132,376
60	101	15,585	124,552
70	87	15,692	117,544
80	90	16,339	105,898
90	102	16,858	96,556
100	119	22,222	–

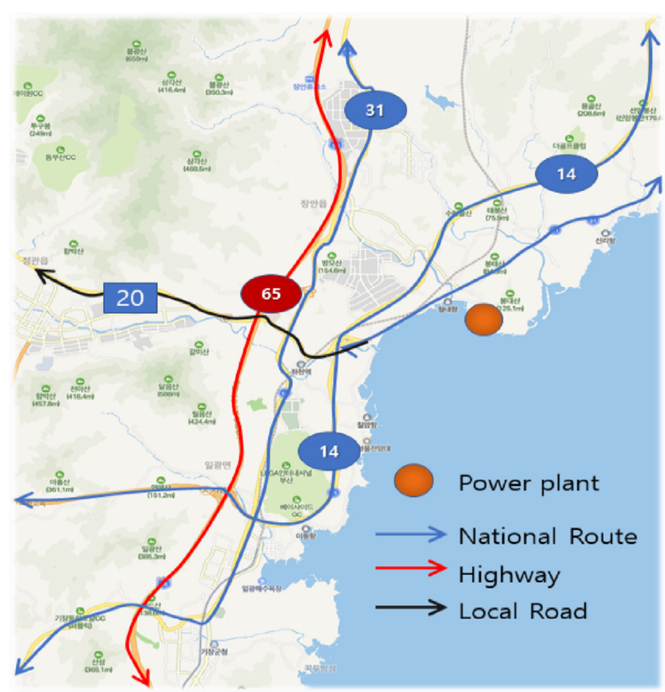

Fig. 2. Main evacuation roads from the Kori Nuclear Power Plant.

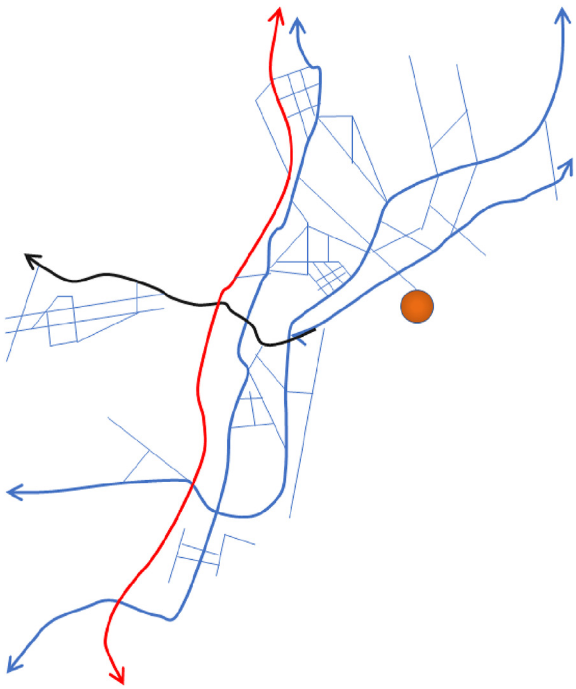

Fig. 3. Main evacuation routes and applied background roads from Fig. 2.

together while picking-up evacuees at random times at all links.

14) Ulsan City's population is 1.166 million (as of 2019), and it is assumed that 1.0494 million people, excluding the 10% in the mobility disadvantaged group, will evacuate to nearby locales outside 30 km.
15) A 30-s time penalty is applied for delays caused by traffic signals and turns.

The KTDB origin destination traffic volume data issued by the Korea Transport Institute includes basic road information, such as traffic signal cycles and road capacity, based on actual data. The number of EPZ evacuees is calculated using this data [20].

3.2. Scenario set-up

This study compared 10 scenarios, which were created by changing the bus and car mode share ratios by 10% increments (Table 3). Evacuation travel can take place using only buses or cars, and the evacuation mode is selected based on the scenario's mode share ratio.

3.3. Analysis model

Since a large-scale, city-level network analysis is required, this study used a cell transmission model that can be used as a mesoscopic model. This model determines the traffic volume passing through a cell by density and speed, as shown in Fig. 4, and the formula for this is as follows [20–23]:

$$q = \min\left[vk, q_{max},\ w(k_j - k)\right],\ for\ 0 \le k\ \le k_j \tag{1}$$

q = traffic volume;
q_{max} = maximum traffic volume(capacity);
v = free speed;

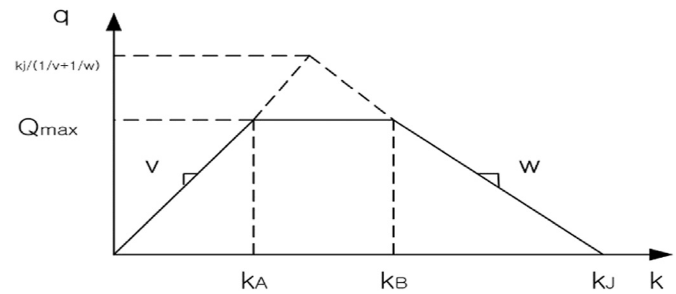

Fig. 4. Density relation in cell transmission model.

k = density;
k_j = maximum density;
w = rear shockwave speed during congestion

Additionally, as shown in (Fig. 5), cell transmission occurs according to the following rules:

$$Y_i(t) = min[n_{i-1}(t),\ Q_i(t)\delta\ \times (N_i - n_i(t)) \tag{2}$$

$Y_i(t)$ = transition amount of cell i;
$n_i(t)$ = density of cell i (traffic volume) at time t;
$Q_i(t)$ = unit time traffic capacity of cell i;
N_i = congestion density of cell i;
δ = shockwave coefficient ($\delta = 1,\ if n_{i-1}(t) \le Q_i(t),\ \delta = \frac{W}{V},\ if n_{i-1}(t) > Q_i(t)$);
$\delta \times (N_{i\_}n_i(t))$ = remaining density of cell i at time t;
i = cell's location;
t = current time interval

This study was configured to analyze the flow of node and link traffic based on a cell transmission model. Python 3.0 was used in a Windows environment.

4. Simulation results

The results of the simulation for each scenario are shown in Fig. 6. The x-axis is time, and the y-axis is the number of people remaining in the PAZ, which gradually decreases from an initial 100% as time passes. Measurements were taken until 1400 min (10 h) after the evacuation began. It was assumed that 10% of the people were mobility disadvantaged and had difficulty self-evacuating, and the number of remaining people did not decrease to less than 10% (see Fig. 7).

Scenario 1 (90% cars, 10% buses) shows that 600 min of evacuation time was consumed, and the number of remaining people at certain times was the highest because of severe congestion. However, it was observed that the evacuation time decreased from Scenario 1 (90% cars, 10% buses, 600 min) to Scenario 7 (30% cars, 70% buses, 165 min) and then increased again from Scenario 8 (20% cars, 80% buses, 175 min). This is due to the contradiction that

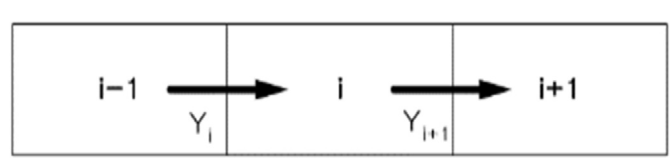

Fig. 5. Cell transmission concept.

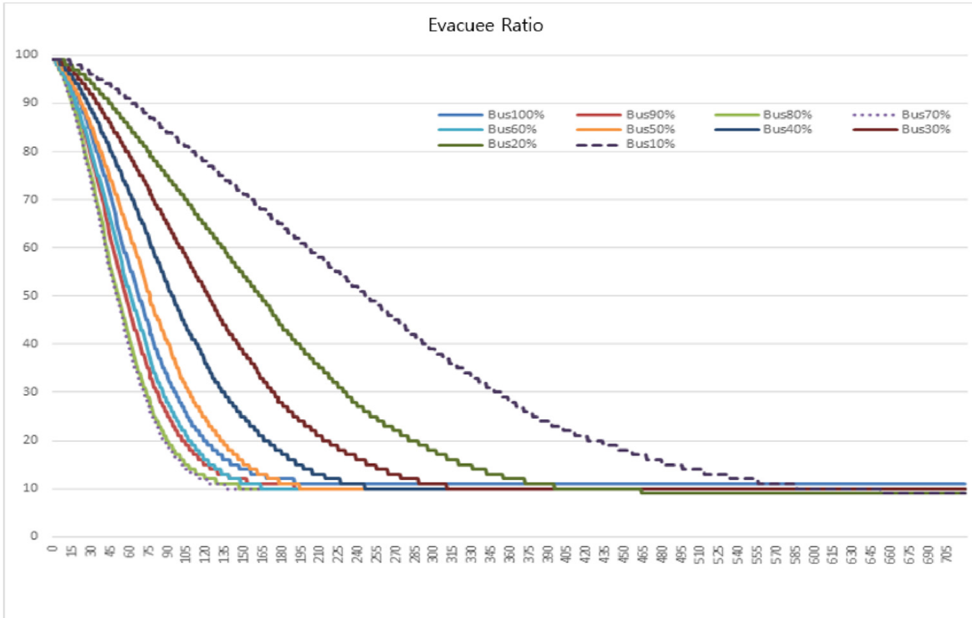

Fig. 6. Simulation analysis result (x-axis is minutes, and y-axis is share of population remaining within the PAZ).

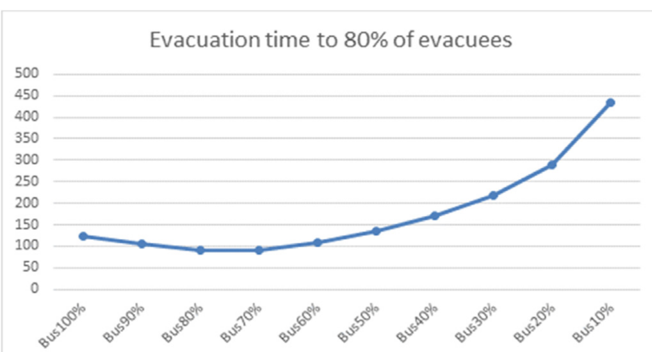

Fig. 7. Evacuation time to 80% of evacuees by bus.

occurs when the buses' mode share ratio exceeds 70%, in which people are unable to use cars and must wait for the relatively slower buses even though traffic density decreases and travel speed improves. Therefore, it was found that there is a suitable mode share ratio for buses.

Fig. 6 shows the time taken until the evacuations were 80% complete in each scenario. In the fastest scenario, it took 87 min at a bus mode share ratio of 70%, and in the slowest scenario, it took around 435 min at a bus mode share ratio of 0%. However, when the bus mode share ratio was 70%, the required number of buses was calculated to be 15,692. If approximately three round trips are possible during evacuation, 5230 buses are needed; however, only 1000 express buses and 1000 regular buses can be currently mobilized in Ulsan Metropolitan City—around 3000 buses too few. According to the simulation results, the evacuation took 132 min at a mode share ratio of 40% buses and 60% cars. In this scenario, the buses were operated six times during the evacuation, requiring around 2297 (13,780/6) buses—a realistic plan of operation considering the number of buses in Ulsan.

5. Discussion and conclusions

This study presents an evacuation strategy using public transportation during large-scale, city-level evacuations. A traffic flow model was used to analyze the extent to which evacuation time varied at different evacuee mode share ratios, and it was found that a mode share ratio of 70% buses and 30% cars was the most appropriate when considering the road conditions and population size. However, considering the number of buses in Ulsan Metropolitan City (around 2000), it was determined that a scenario that takes 132 min is possible when operating at a share ratio of 40% buses and 60% cars. The results were derived from fairly strong assumptions, but currently if the share ratio of cars exceeds 90% with no measures taken, the evacuation time is expected to take 435 min (over 7 h). Even if the bus mode share ratio is only 20%, the evacuation time can be reduced by more than 50% to 218 min (3.5 h). If the bus mode share ratio is 70%, it was found that the evacuation will take around 87 min (1.5 h), which is a 70% improvement compared to the maximum. In short, if the residents of Ulsan Metropolitan City are to be evacuated within 2 h, 5000 buses are needed. If around 2000 buses are used, the bus mode share ratio will be 40%, and the evacuation time will be around 3.5 h. Therefore, in the event of a radiation disaster, realistic countermeasures should be prepared by considering the available time and resources.

To date, previous studies have only established plans by using the maximum number of buses that can be mobilized without calculating the target mode share ratio, and they have not been able to calculate a realistic required number of buses. This study's findings can be used to determine whether preparations have been made that can mobilize appropriate resources by predicting the demand for traffic infrastructure and cars for resident evacuations during disasters. In particular, if it is advantageous to use 20–30% cars during an evacuation, a strategy can be devised in advance regarding who uses cars, when, and how. Moreover, this study can help create new radiation accident response evacuation plans using public transportation.

However, as this analysis was based on extremely strong assumptions, follow-up studies using micro-simulations and other means must be performed in the future. It will be necessary to consider elements that this study did not consider, such as differences in resident population during daytime and night-time, assigning evacuation priorities according to wind direction, and the mobility disadvantaged. Strategically, it will be necessary to review the use of strategic measures other than public transportation modes, such as car control strategies and one-way travel on roads.

The evacuation plan currently being prepared by local governments includes selecting and managing major evacuation routes and moving vulnerable road users and institutions (group unit) to the relief center by bus during evacuation. However, calculating the number of buses for actual evacuation plans and the efficient transportation sharing rate have not been determined. The results of this study are expected to enable the establishment of an evacuation plan reflecting the effective use of buses.

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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