Formulation of Tsunami Evacuation Strategy to Designate Routes for the Car Mode - Lessons from the Three Cities in Tohoku Area, Japan

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Abstract: This study analyzed the emergency escape mode and pattern of evacuation based on the questionnaire survey data collected by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan. The statistical results were derived from strategic designation of evacuation routes using the historical data. To illustrate the actual event during the disaster, we evaluated the situation using measures in terms of starting time of evacuation, evacuation distance and evacuation speed under the given geographical condition, population density and time. The results of such analysis were used as basis of appropriate recommendations for future decisions and political directions, such that the provision of a "buffer road" in hazardous prone area and assurance of "self-safety" are some of the noted significant basic priorities which form the fundamental criteria for the evacuation route strategy.

Keywords: Evacuation Starting Time, Evacuation Distance, Evacuation Speed, Evacuation Route, Buffer road, Self-Safety

1. INTRODUCTION

In the last tsunami disaster on March 11th, 2011, drowning was the main cause of death (92%) in Tohoku area, Japan, and more than fifteen thousand people lost their lives. This tragic incident is of a different story from that of the Kobe earthquake in 1995 wherein deaths were mainly due to the collapse of buildings and fires triggered by the collapse. Since the occurrence of these disasters, a great deal of attention has been directed for the evacuation management during the event of earthquakes, as well as Tsunami (Wegscheider et al., 2011, Charnkol et al., 2006, Li et al., 2012). Various approaches were applied and used for experimentations to understand different evacuation behavior.

Methods for numerical approaches such as agent-based and network-based models have been widely used. In the agent-based model, the evacuation movements are regarded as either crowd motion (Maury et al., 2011, Pan et al., 2007, Conca et al., 2012) or particle motion (Helbing et al., 1995, Muramatsu et al., 1999) which could further been categorized into force model (Helbing et al., 1995, 2000, Oven et al., 2009, Hoogendoorn et al., 2003) or cell-based model (Muramatsu et al., 1999, Doheny et al., 1996, Klupfel, 2003). Capacity (Zheng et al., 2010, Madireddy et al., 2011) and queuing (Lovas, 1994) theories are also being applied in the network-based model. Based on these approaches, researchers tried to calculate the evacuation time (Radwan et al., 1985, Lammel et al., 2008, Proulx, 1995), but evacuation behaviors under a serious disaster had shown different patterns of movement (Helbing et al., 2000, Sugimoto et al., 2003, Charnkol et al., 2006). Furthermore, these evacuation behaviors might be very difficult to observe in a real situation due to some data constraints. As a result, fewer researches are using real evacuation data (Apatu et al., 2012, Galea et al., 2011, Yun et al., 2012) in finding the optimal or reasonable solution for evacuation.

As mentioned, the researches focused on sophisticated modeling to relate the real scenario in finding the optimal solutions in a given network or site. However, there is a need to review the fundamental characteristics from the bulk of information about the real situations collected by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan. This study focused in a particular unique data containing detailed information on the evacuation behavior. The results using the basic statistical analysis were used to understand the data to define the criteria for evacuation. This study has tried to derive the solutions and proper recommendations related to evacuation routes management based from the observed problems. The researcher realized the basic reasons for the different level of damages on evacuees and thereby, suggested “buffer road” and “self-safety” for safety evacuation using the car mode.

2. DATA COLLECTION AND DISCRETION

2.1 Data Collected by MLIT

Since the occurrence of this disaster, MLIT worked to examine the situation from September to December in 2011. One of these reports is the “Survey Report of Reconstructing Method for the Damaged Cities by the Tsunami Disaster (2012),” which contains the awareness on Tsunami and evacuation behaviors for its utilization to various plans related to reconstruction, evacuation, positioning of shelters and driving evacuation strategies (MLIT, 2012). The survey items included all trip-chains containing destination choice, mode choice, route choice, travel time, travel distance and reasons for each choices (Archive of Reconstruction Supporting Investigation (ARSI), 2012). The awareness on disaster and acquisition of information on warning were also announced in this report. A total of 10,601 persons were probed and 20,429 trip-chains were sampled from citizens who were in the hazard area during the disaster. Using this information as values for data set, this study tackled a detailed analysis using three cities.

2.2 Geographical Conditions

For better comparison on the geographical conditions, the tsunami damaged areas were divided into two parts: Rias areas and plain areas. The Rias areas contain IWATE and MIYAGI prefectures, which have mountains near the residential areas and small fishery sectors in the lower lands. These areas are characterized by low population density and sites of fishing industry, which were historically recognized as areas that are vulnerable to tsunami (such as Minamisanriku, Onagawa, and Otsuchi). On the other hand, the plain areas are of relatively wider areas allotted for agricultural farm, characterized by cities with comparatively higher population density (such as Sendai, Iwanuma, and Yamamoto) than others.

Here, three cities from Tohoku, Japan, were chosen as samples for the comparison of evacuation behavior: Iwanuma, Yamamoto and Otsuchi. Iwanuma (61km^2) and Yamamoto (64km^2) were planned area in terms of urban planning, and the regions are located in plain areas, whereas Otsuchi (201km^2) is located in a Rias area, which was reported as one of the serious damaged areas. Other cities are a mixture of high and low density areas, or plain and Rias areas together. These three cities were chosen using the observed comparable characteristics such as similarity in size and road length but of different population densities. The basic information of Iwanuma, Yamamoto, and Otsuchi is shown in Table 1.

Table 1. General Information for the Three Cities

	Otsuchi	Iwanuma	Yamamoto
Geography[1]	Rias	Plain	Plain
Population (person)[2]	15,276	44,187	16,704
Area (km^2)[3]	201	61	64
Planned Area (km^2)[4]	30	61	64
Population/Planned Area (person/ km^2)	509	724	261
Type[5]	City	City	Rural
Number of Shelter[6]	37	14	11
Road Length (m)[7]	254.8	329.8	315.5
Height of tsunami (m)[8]	12.6	8.8	N/A

[1] Ministry of Land, Infrastructure, Transport and Tourism, [2] Statistics Bureau, Director-General for Policy, Planning & Statically Research and Training Institute, [3] Geospatial Information Authority of Japan, [4] Digital Japan Portal Web Site, [5] Archive of Reconstruction Supporting Investigation, [6] Disaster Prevention Information, [7] Ministry of Land Infrastructure, Transport and Tourism, [8] Japan Weather Association

3. COMPARISON OF THE THREE CITIES

3.1 Evacuation Starting Time

The citizens living in the Rias area (Otsuchi) were found to have evacuated earlier than those in the plain areas (Figure 1). Around 50% of the evacuees in Otsuchi who evacuated on foot started within 25 minutes after the earthquake, while those in plain areas of Yamamoto started to evacuate within 40 minutes. In Yamamoto, for the rest 50% people who evacuated on foot, it might have slower to use car mode. The median EST (Evacuation Starting Time) value of car mode in the Rias area is 22 minutes faster than that of the plain areas (paired t-test, t=-14.650, p=0.000). The EST between walking and car mode showed that car mode is faster than walking mode in Otsuchi and Yamamoto but there was no significant difference (paired t-test, t=-1.852, p=0.072) in Iwanuma. Moreover, it is also safe to say that the EST in the plain areas is later than that of the Rias area (paired t-test, t=18.462, p=0.000).

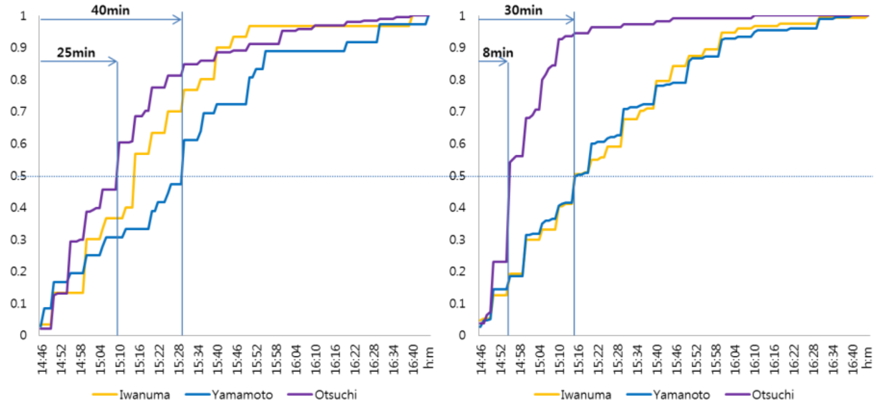


Figure 1 Cumulative Relative Frequency of Evacuation Starting Time for Walking (Left) and

Car Mode (Right): Iwanuma (N=134trips), Yamamoto (N=238trips), Otsuchi (N=397trips)

3.2 Evacuation Distance

Figure 2 shows the distribution of ED (Evacuation distance) in the three cities. The average ED of walking and car are 321m and 2.3km, respectively. In the ED of walking mode, 95% of people walked to shelters in less than 1.5km, while 50% of them reached their evacuation destination in less than 300m. It may show the maximum and the median value of ED when they evacuate on foot.

Using the car mode, the plain area (Iwanuma and Yamamoto) movements were measured to be three times longer (3km) than the Rias area (Otsuchi) when comparing the median. The differences among lines show that the variations of walking mode are smaller than the car mode. This is accounted to the difference in the limitations of human level of physical capacity. The case of car mode does not have limitations on distance, so evacuees can easily direct to their preferred destinations. In the case of car mode, ED of plain area is longer than ED of Rias area as observed from the distance.

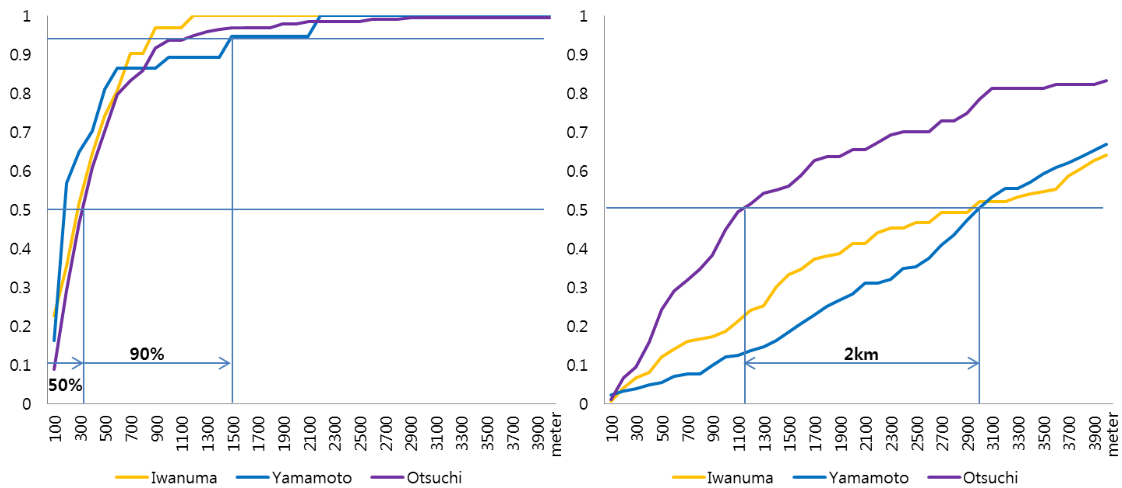


Figure 2 Cumulative Relative Frequency of Evacuation Distance for Walking (Left) and Car Mode (Right): Iwanuma (N=134trips), Yamamoto (N=238trips), Otsuchi (N=397trips)

3.3 Evacuation Speed

The average ES (Evacuation Speed) of walking and car mode are 2.5km/h and 14km/h, respectively, in these areas as is shown in Figure 3. By analyzing the 5-minutes interval data, it was found that the average ES of walking mode did not exceed 8km/h. The ES of car mode is found to be in the upper range of 8km/h boundary. These show that evacuees who used car mode with a speed not less than 8km/h had successfully escaped. As a matter of course, the average ES of car is higher than the average ES of walking. Moreover, the plain area (Yamamoto) is faster than Rias area (Otsuchi) and urban area (Iwanuma). It means that Yamamoto (plain and rural area) faced fewer congestion problems in the walking mode due to the fewer numbers of people in the area and that they were able to keep their own speed in flat lands. The ES of car mode was found to be the fastest among the cities for the same reasons. However, the maximum average ES of car mode did not exceed the 20km/h and the average ES of walking mode shows constant average speed, while the average ES of car mode was decreasing over time. While the numbers of evacuees have increased in time, the ES of walking is not greatly affected by the number of other evacuees. But in the case of car mode is affected by other factors such as the road conditions. Finally, we can observe a relatively lower speed and shorter distance in Otsuchi (Rias and urban area).

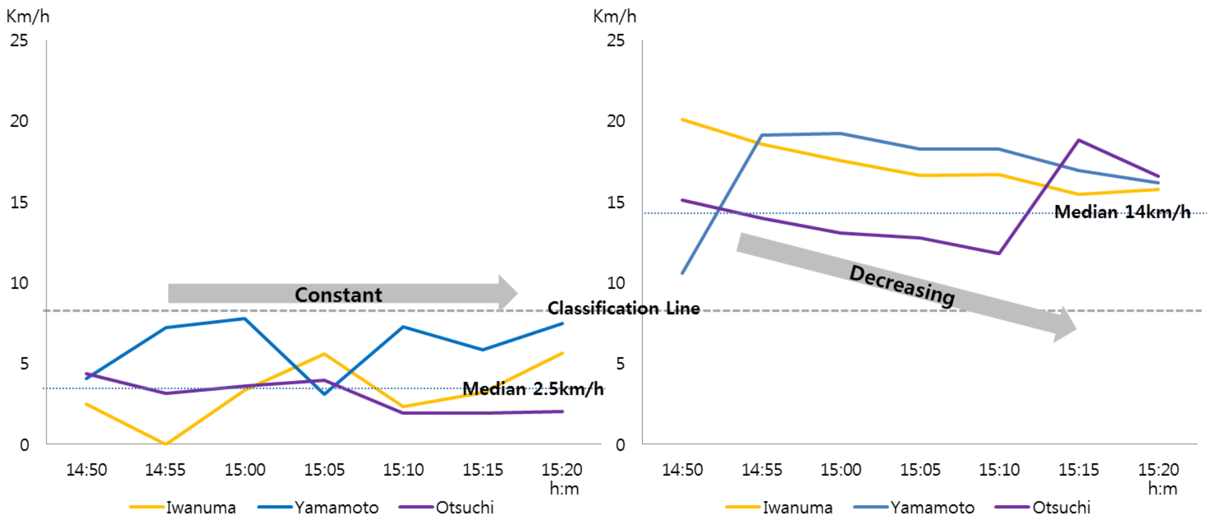


Figure 3 Evacuation Average Speed: Walking (Left) and Car Mode (Right): Every 5minutes

3.4 Results of the Questionnaires

The several results of the questionnaires were summarized to capture the actual scenario during the evacuation. It contains the written statement of emotions and thoughts of evacuees in deciding their actions during the tsunami disaster. One of the interesting questions was, "What made you (the evacuees) decide to use the car mode for evacuation?" as one important source of information to understand the evacuees' tendency to prefer the car mode. Another question is, "What were the problems you encountered before you reached your shelters?" as we could find the main problems as the evacuees approached their shelters. Lastly, "What are the reasons for preferring shelters other than that of the nearest from your places of residence?" explains the main reasons why some evacuees changed their destinations and the possibility of finding the temporal shelters before the inundation of the tsunami.

1) **Why did you use the car mode for evacuation? :** In Figure 4, the answer of "Time/distance" links to the reasons related to the lack of evacuation time, long distance, and difficulty in reaching the areas on foot, while the answer of "together" explains that the evacuees wanted to meet their families or tried to save their assets before they decided to start their evacuations. ED of the plain areas is longer than that of the Rias area in Figure 2, and it may affect the mode share ratio of car. The "Time/distance" has a bigger portion in the plain areas (Iwanuma and Yamamoto) than in the Rias area (Otsuchi). Evacuees responded that the shelter is very far and that they have no options but to use the car mode. In the Rias area, on the other hand, evacuees tried to reach for their families.

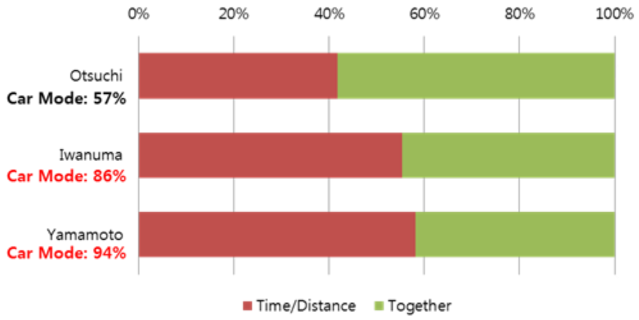


Figure 4 Answer for "Why did you use the car mode for evacuation?"

2) **What were the problems when you access the shelters?** : In Figure 5, the problem on "Accessibility" means evacuees had troubles from the ground geography, route search, dangerous roads and collapsed shelters in approaching the shelters, while "Capacity" contains information on traffic congestions and number of persons to stay. The problems on capacity occurred in almost all three areas and modes in approaching the shelters. In particular, the modes in Iwanuma (urban and plain area) have problems of over capacity because a high number of evacuees in urban area used car mode (86%) in addition to the serious congestion due to high population density in waking. In Otsuchi (urban and Rias area) the main problem was on the accessibility for walking because this area is the mountainous Rias area with complex and narrow roads. Otsuchi has accessibility problems for walking due to its natural geographical condition. The main problems in Yamamoto (rural and plain area) on the contrary are the accessibility on car mode, because 94% of the evacuees chose the car mode for evacuation, while the physical distance to shelter is comparatively longer.

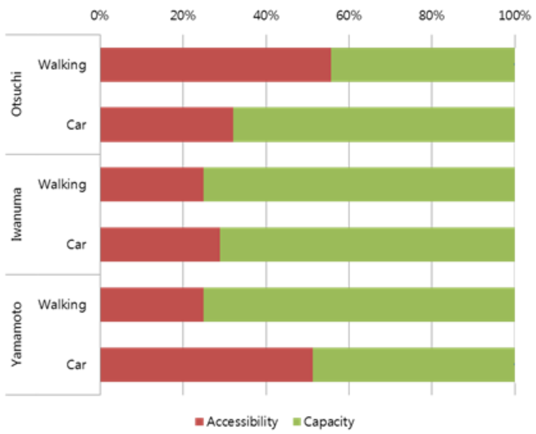


Figure 5 Answer for "What were the problems when you access the shelters?"

3) **Why didn't you go to the nearest shelter? :** Some evacuees were found to be preferring shelters other than that of nearer from them. In this disaster, Otsuchi (urban and Rias area) is one of the most seriously damaged cities; 8.22% of citizen died or are still missing. One of the main reasons in changing route instead of insisting for nearest path was "to contact family (walking 22%; car 38%) in this area. While in Iwanuma (urban and plain area) they changed their destinations because of the congestions (walking 18%; car 13%), more active escaping behavior

was observed in finding the shelter than in the case of Otsuchi. Even though the evacuees in Iwanuma had to change their destination or route, the death ratio is lower than that of the other cases. In Figure 6, "Congestion" means that the access road has exceeded its capacity resulting to delays along the road. "Easy place" refers to the location of evacuees who were able to found safe area, and "family" shows effort in trying to reach for their family members and to evacuate together.

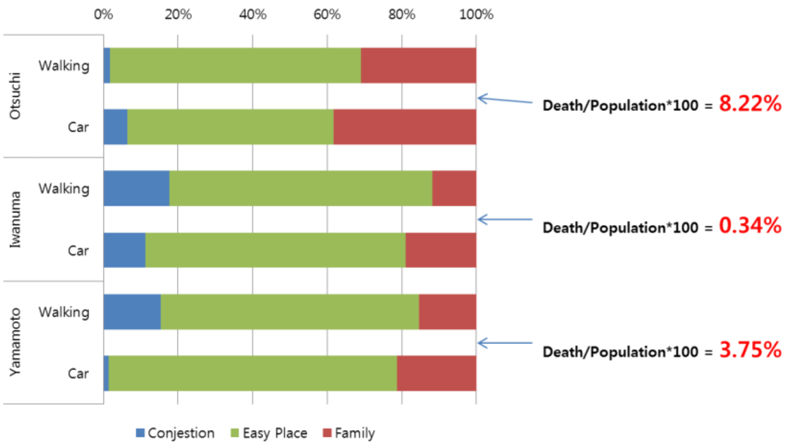


Figure 6 Answer for "Why you did not go to the nearest shelter?" The number of death: National Police Agency (NPA), Metropolitan Police Department (MPD)

3.5 Summary

Geographically, the Rias area is higher than the plain areas. The EST of Rias was faster than in the plain areas. Yamamoto has lower population density and EST was found to be the fastest in Otsuchi. However this area shows the highest death ratio among the three cities. Although 94% of evacuees used the car mode for evacuation in Yamamoto, its ES is faster than Otsuchi. Serious damage occurred in Otsuchi (Death Ratio: 8.22%) and only 57% of the evacuees used car mode in this area. The summary for these comparisons are shown in Table 2.

Table 2 Characteristics Summary of Three Cities

Contents	Otsuchi (Rias)		Iwanuma (Plain)		Yamamoto (Plain)	
	Walking	Car	Walking	Car	Walking	Car
Geography	High		Low		Low	
Density	High		High		Low	
Evacuation Starting Time (50%)	Fast	Fast	Middle	Slow	Low	Slow
Evacuation Distance (50%)	Same	Short	Same	Long	Same	Long
Speed Variation	Constant	Decreasing	Constant	Decreasing	Constant	Decreasing
Median Speed	Slow	Slow	Fast	Fast	Fast	Fast
Median Distance	Same	Long	Same	Long	Same	Short
Reason Using Car Mode is Traffic Problems	Low		High		High	
Reason changing shelter is to evacuate with family	High		Low		Low	
Death Ratio	High(8.22%)		Low (0.34%)		Middle (3.75%)	
Mode Ratio of Car Mode	Low (57%)		High (86%)		High (94%)	

4. DISCUSSION

4.1 EST and Geographical Conditions

Citizens in Otuschi started evacuation earlier than the other two areas and the difference of EST is almost 22 minutes in the car mode for 50% of the evacuees as shown in Figure 1. In this case, Otuschi was already historically known to be a tsunami-prone area as shown from the records (1960, 1933, and 1896) even before the Tohoku earthquake incident which leaded to serious damages in 2011. The MLIT report (2012) shows that the 64.7% of citizens in Rias areas predicted that "Tsunami will come", while 60.6% of citizens in plain areas otherwise predicted, "Tsunami will NOT come". For the same height of tsunami which had reached the Tohoku area, there was fewer evacuation roads in Rias area than in the plain areas (Otsuchi: Area 201km^2, R~~L~~oad Length 254.8km; Iwanuma: Area 61km^2, ~~L~~Road Length 329.8km; Yamamoto: Area 64km^2, R~~L~~oad Length 435.5km, in Table 1). This inadequacy of evacuation roads can lead to more serious traffic congestions and citizen already might have understood this situation. It might force the citizens in Otsuchi to start evacuation earlier.

4.2 Shelter Choices and Evacuation with Family

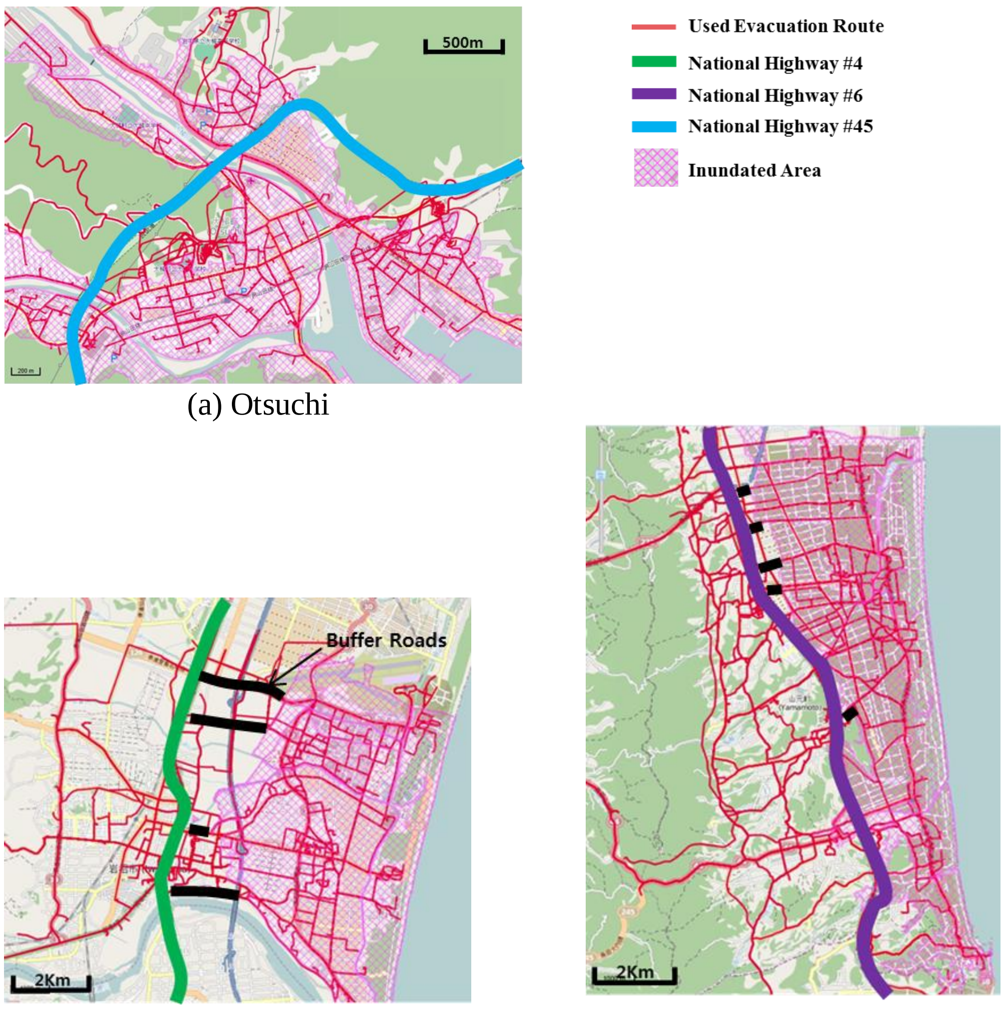
The maximum distance of walking mode is less than 1.5km as shown in Figure 2 and this seems to be a physical ability for human. Although walking had some accessibility problem (39%, Figure 5), still 51% of the evacuees decided to derive in order to reach their families shown in Figure 4. Moreover, 57% of the evacuees in Otsuchi used the car mode to escape with families as shown in Figure 4, wherein 31% of them did not go to the nearest shelters as shown in Figure 6. As a result, these behaviors generated higher death ratio (8.22%, Table 2). Even though citizens in Otsuchi started evacuation in earlier time, they had slower ES (Table 2) due to the lack of evacuation roads and negligence to seek their nearest shelters to escape together. As a result, if an evacuee is alone, it seems better to evacuate alone.

4.3 Congestion and Death Ratio

In Iwanuma, citizens faced the congestion (capacity) problems when they accessed their shelters (walking: 76%, car: 63%, Figure 5). Around 17% (walking: 18%, car: 16%, Figure 6) of them changed their destinations from the nearest shelters to others which are relatively farther due to these congestion problems. In the case of Yamamoto, citizens had capacity problems on their personal human levels to access their shelters (walking: 76%, car: 50%, Figure 5) and congestion problems (walking: 16%, car: 2%, Figure 6) for car mode. These congestions were observed in national routes near the hazard area (KSP, 2013, Chunichi, 2011). However these two cities show a ten times difference in their death ratios (Iwanuma: 0.34%, Yamamoto: 3.76%, Figure 6). This difference can be viewed in the map below. The congestion lines in Figure 7(b) of Iwanuma (National Route 4), are observed outside the tsunami inundation area, while Yamamoto in Figure 7(c), shows congestion mainly inside the hazard area. Both in Iwanuma and Yamamoto long congested lines were observed in the National Route 6, but these queues were in the hazard areas only in the case of Yamamoto. It yields more victims in the same plain area and the similar size of land.

4.4 Congested Lines and Inundation Areas

When citizen evacuated from the tsunami, they had to move along a direction perpendicular to ~~costal~~coastal lines to avoid immediate risks from the tsunami wave shown in Figure 7. The evacuees tried to access the main roads or national routes that connect to safer places. The congested lines observed in the parallel roads from ~~costal~~coastal line in Figure 7 (b), (c): National Route 4 and National Route 6. This is because; the evacuating cars were coming from every corner of the city area, which resulted to over congestion. However the locations of these two national routes are different, in Iwanuma this road is longer distance from the inundation area than Yamamoto's. Even though evacuees are locked in a congested line, if particular roads are located in a safe area away from tsunami, there is a high possibility to save lives. However, the ES cannot guarantee safety. The roads between the national routes and hazard area could be served as "buffer roads" which could absorb the evacuating trips to safe area. So it could effectively save the evacuees.



(a) Otsuchi

(b) Iwanuma

(c) Yamamoto

Figure 7 Evacuation Route (MLIT 2013) and Congested National Highways

5. CONCLUSION

We discussed evacuation behaviors based on the MLIT data. These three cities showed the significance of the provisions for an evacuation route and evacuation distance. In deciding for the evacuation route, two issues are necessary to be considered. First, “evacuees who derived might be faced to serious dangers, when the congestion occurred in the hazard area”, “evacuation time can be increase when evacuees want to meet the family”, and “the evacuees who walked have to consider their physical strength during evacuation and reduce the evacuation distance and time”, so evacuees have to consider “self-safety” while they are escaping. The second point is, “the evacuation route should have enough buffer roads to move additional cars from the hazard area to safe area” and “these buffer roads are located in a direction perpendicular to ~~costal~~coastal lines to prevent the expected dangers.”

Furthermore, the following conclusions were realized. It is safer to use the safe roads than take risks in using the uncongested roads for the purpose of evacuation using the car mode, a buffer road could absorb the evacuation traffics, and evacuees who aim to escape with their families usually do not use the nearest shelter. Additionally, the relationships between national highway and buffer road should be clarified in the future work. To know the capacity drops or absorbing volume of traffics in the buffer road, more detail cases, changes of traffic parameters (speed, density and flow), should be collected and discussed in the microscopic point of view to lead the optimal car evacuation strategies. The other hand, self-safety could be research issues not only education and practice drill for prevention and evacuation but also evacuation crowd and self-organized evacuation models.

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