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Comparison of emergency transport times affected by road closures under normal conditions and during an earthquake disaster

Running title: Emergency transport times in road closures

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ABBREVIATIONS

GIS: Geographic information systems

START: Simple Triage and Rapid Treatment

ABSTRACT

Objective: This study aimed to examine emergency transport times considering closed roads to propose more efficient transport routes to improve the life-saving rate for seriously injured people in Sapporo during an earthquake disaster. Sapporo is the capital of Hokkaido and has a population of approximately 1.97 million as of 2020.

Methods: Transport routes were created using publicly available data and a geographic information system (GIS), and the emergency transport times in Sapporo were subsequently calculated. Closed roads were defined as roads in “areas with high liquefaction potential” and “areas with a total house destruction rate $\geq 20\%$ ”.

Results: Closed roads were concentrated in the northeastern part of the city, as were extended emergency transport times, with delays of up to 101 min. Other areas did not experience significant delays.

Conclusions: The emergency transport time was prolonged in areas with closed roads. Triage posts and semi-closed roads were also suggested to affect emergency transport times. To minimize emergency transport times, it is necessary to consider having nurses and doctors ride in ambulances to triage patients, and to coordinate with disaster base hospitals outside of the city to transport seriously injured people.

NARRATIVE ABSTRACT

This study examined emergency transport times during an earthquake in Sapporo, a city of 1.97 million, considering road closures due to high liquefaction risk or severe building damage ($\geq 20\%$). Using geographic information system and public data, transport routes and delays were analyzed. Significant delays, up to 101 minutes, were concentrated in the northeastern part of the city, while other areas saw minimal impact. The findings suggest that closed and semi-closed roads, as well as the location and function of triage posts, affect transport efficiency. To reduce delays and improve survival rates for seriously injured individuals, it is necessary to deploy medical personnel in ambulances for on-site triage and enhance coordination with disaster base hospitals outside the city.

These strategies can help optimize emergency transport routes and ensure more timely care in future seismic events.

KEYWORDS

GIS, Closed roads, Emergency transport times, Triage

INTRODUCTION

Japan is one of the most earthquake-prone countries in the world. Between 2011 and 2020, 17.9% of earthquakes of magnitude (M) 6 or greater occurred around Japan.¹ Damage caused by earthquakes can include the collapse of houses and bridges, fires, liquefaction, and tsunamis, leading to road closures and paralysis of the transportation network.² During the Great Hanshin-Awaji Earthquake (1995, M7.3), traffic congestion occurred because of collapsed houses and private cars evacuating to safer locations, significantly delaying the arrival of fire engines and ambulances to disaster sites and hospitals.³ The Noto Peninsula Earthquake (2024, M7.6) caused widespread landslips, isolating many communities and delaying the delivery of relief supplies and infrastructure restoration.^{4,5} Preventing deaths and serious illnesses due to delays in emergency transportation is an important challenge that needs to be solved to minimize human casualties.

Geographic information systems (GISs) have been commonly used for disaster prevention and simulations. During disaster preparation and response, they can serve as an integrated focal point for a comprehensive preparation and response system or as a portable on-site source of spatial information. Following a disaster, they are essential for damage assessment, reconstruction support, and public education.⁶ Several methods for evaluating access to emergency medical care using a GIS have been proposed. One study considered the collapse of roads and reduced travel speeds due to flooding in Dhaka City, examining access to critical facilities such as hospitals, emergency medical services, and evacuation centres.⁷ Based on the basic information obtained from a field survey, they proposed an optimal route model representing the travel time on a road network under congested conditions during an emergency. They elucidated areas where emergency transportation was vulnerable in the event of a disaster based on the emergency response time of fire stations and medical institutions and distances from evacuation shelters.⁸ Focusing on the impact of slums and traffic congestion, another

study assessed the geographic conditions that make it difficult for urban-dwelling individuals with low income to access emergency medical care while considering traffic volume fluctuations. Combining unique data on emergency medical service locations, traffic dynamics, and informal settlement boundaries may account for realistic traffic conditions and their changes over time.⁹ Another group elucidated the factors behind delays in emergency medical care in evacuation zones following the Fukushima Daiichi Nuclear Power Plant accident; they also investigated the impact on emergency medical services in the study area before and after the evacuation orders for surrounding areas were lifted and evaluated the on-site emergency transport time using parameters that were not affected by road conditions or distance.¹⁰

Currently, earthquake disaster scenarios prepared by the Cabinet Office of Japan¹¹ anticipate large earthquakes, including the Nankai Trough Earthquake, which is expected to occur directly beneath the capital, as well as an ocean trench earthquake near the Japan and Kuril Trenches. A trench-type earthquake occurring around the Japan Trench or the Kuril Trench within the next 30 years is possible. If an earthquake occurred along the Kuril Trench, it is estimated that a seismic intensity of 7 would be felt in the towns of Erimo and Akkeshi in Hokkaido, and a 28-m tsunami would occur in the towns of Erimo and Kushiro in Hokkaido. Sapporo, the capital of Hokkaido, is the northernmost city in Japan, with a population of 1,973,395 and a population density of 1,760 people/km.^{12,13} It is divided into ten administrative districts. Sapporo City's fourth earthquake damage estimate¹⁴ assumed an earthquake caused by five faults. In the event of an earthquake along the Tsukisamu Fault, which would cause the most damage, liquefaction would likely occur in one-third of the city. Damage to buildings is estimated at 7,799 being destroyed and 32,264 being partially destroyed; human casualties are estimated at 363 deaths with 2,156 people being seriously injured.

Emergency medical services in Japan are provided via 119, and the ambulance that is available and closest to the scene of the emergency or that can arrive there the fastest will be dispatched. After carrying out necessary observations and emergency treatment at the scene, the ambulance crew selects a medical institution appropriate to the symptoms of the injured person. On the way from the scene to the hospital, emergency medical technicians provide first aid as part of pre-hospital care and transport the patient to the hospital.¹⁵ At least one emergency medical technician—who must have passed the national emergency medical technician examination and the firefighter recruitment examination—rides in an ambulance. They perform specific procedures, including

administering medicine, as pre-hospital care during transportation of injured or sick people from the scene of a disaster or traffic accident to a hospital. In the event of a disaster, they arrive at the scene first and carry out triage.^{16,17} The paramedic training course systematically teaches the knowledge and skills necessary for triage during disasters and trains students to respond appropriately at disaster sites.¹⁸

To improve survival rates during disasters, it is essential to shorten emergency transportation time. Establishing an efficient and robust emergency transport system for injured and sick individuals during an earthquake is important. This study took into account road closures due to liquefaction and collapsed houses and calculated emergency transport times in 10 administrative districts of Sapporo using GIS, and compared them with the city of Sapporo as a whole. The aim was to improve the survival rate of seriously injured people in the event of an earthquake caused by the Tsukisamu fault, which is expected to cause the most damage in Sapporo City, by proposing more efficient transport routes.

METHODS

EMERGENCY TRANSPORT ROUTE, MEANS, AND TIME

The transportation routes were mapped based on the Sapporo City Disaster Medical Relief Action Plan.¹⁹ Upon receiving a call for help, an ambulance departs from the fire station and arrives at the disaster site to transport the injured person to a triage post. A triage post refers to an area in which triage is carried out. Triage posts are located within the health centre. There is one health centre in each administrative district, with a total of ten in the city. They are set up during disasters and are not normally set up here. Triage posts provide triage and first aid to injured patients transported from the disaster site. If the injury is deemed serious at triage, the patient is transferred to a core hospital. The term “core hospital” refers to a hospital designated by the mayor of Sapporo as one that provides the medical care necessary to treat seriously injured or ill patients, such as emergency surgery.²⁰ There are 16 core hospitals in Sapporo City. Chuo administrative district has the most, with four. Higashi, Atsubetsu, Toyohira, and Nishi administrative districts each have two. Kita, Shiroishi, Minami, and Teine administrative districts each have one²¹. However, if someone is deemed seriously injured at a disaster site, they are directly transported to a core hospital without going through a triage post. Because of this, two transport routes were created: one that went through the triage post and one that did not. This analysis did not take into account the severity of injury, so the transport of patients who died or had minor injuries was not included in the analysis.

The analysis focused only on the time it took for seriously injured patients to be transported. Emergency transport time was defined as the time from the call for help to the arrival of a seriously injured person at the core hospital. The time required for an ambulance to depart from the fire station was set to 1 min²², and the time required for triage was set to 30 s²³. Given the lack of detailed information regarding the triage process, only a standardized duration of 30 s was incorporated to represent the triage time. Triage is the process of determining the priorities for medical treatment so that injured or sick people receive appropriate treatment and transportation²⁴, and was conducted under the Simple Triage and Rapid Treatment (START) Act.

DATA SOURCE

ArcGIS Pro3.1 (Esri, Redlands, USA) and Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) were used for analysis. Data are represented in Table 1.

CONSTRUCTION OF BASE MAPS AND CLOSED ROADS

Sapporo City's administrative districts and road networks were identified, and hospitals, fire stations, and health centers were overlaid on the map. Based on the 4th earthquake damage estimate, "areas with a high probability of liquefaction" and "areas with a rate of total house destruction $\geq 20\%$ " were extracted in a 100 m $\times$ 100 m mesh; roads in areas where the two overlapped were designated as closed roads. Closed roads and roads sandwiched between closed roads were considered impassable. In addition, if an area appeared where a road was closed, it was connected to a road that was not closed. Traffic congestion was assumed to be caused by detouring closed roads, and the area in which traffic congestion would occur was set within a 200 m radius of the closed road (referred to as semi-closed roads). Based on the method of Hagita et al.²⁵, we assumed that travel time on semi-closed roads would be ten times longer than normal. In this analysis, five scenarios were considered. The first scenario was a normal scenario, in which there were no closed or semi-closed roads and patients were transported directly from the disaster site to the core hospital. The second scenario was one in which there were closed roads but no semi-closed roads or triage posts. The third scenario was one in which there were closed roads but no semi-closed roads, and patients were transported via triage posts. The fourth scenario was one in which there were closed and semi-closed roads but patients were not transported via triage posts. The fifth scenario was one in which there were closed or semi-closed roads and patients were transported via triage posts.

RESULTS

The average transport time, standard deviation, and range for Sapporo city and each administrative district are shown in Table 2. The average transport time in Sapporo under normal circumstances was 10.84 min. The standard deviation was 4.85. The minimum was 2.12 and the maximum was 54.73, giving a range of 52.61. When closed roads, semi-closed roads, and triage conditions were added, the average transport time ranged from 11.03 to 18.41 min. The largest increase in transport time was observed when closed roads, semi-closed roads, and triage were included, increasing by approximately 7 min compared with normal conditions. Next, a comparison was made with normal times in 10 administrative districts. In the scenario where there were closed roads, no semi-closed roads, and no triage posts, Shiroishi ward saw the longest transport times, with the difference from normal times being as much as eight minutes (Figure 1). In the scenario where there were closed roads, no semi-closed roads, and patients were sent via triage posts, the transport time was longest in Higashi Ward, with the difference from normal times being as much as 20 minutes (Figure 2). In the scenario where there were closed and semi-closed roads and no triage posts were used, areas in Higashi Ward where transport times were more than 30 minutes longer than normal were concentrated. The maximum extension time was approximately 85 minutes (Figure 3). In the scenario with closed and semi-closed roads and triage posts, areas where transport times were more than 30 minutes longer than normal were concentrated in Higashi Ward. Transport times were also longer by 15 minutes or more in most areas of Higashi Ward. The maximum extension time was approximately 101 minutes. There were also areas in Kita Ward where transport times were longer by 15 minutes or more (Figure 4).

LIMITATIONS

In the present study, emergency transport times were calculated by assuming that an unlimited number of ambulances could be dispatched immediately after a rescue call. However, in reality, the number of ambulances is limited, and they may not be dispatched immediately. It is necessary to consider whether ambulances should be limited to their areas of operation within each fire station or whether they should be stationed mainly in areas where major damage is expected. Although the triage time was set at 30 seconds for all cases, it is possible that this may vary depending on factors such as the severity of injuries, the number of seriously injured people, and the manpower at the triage post. Therefore, there is a possibility that the transport time may

be longer if the transport route goes through the triage post. If an earthquake occurs in winter, road closures due to accumulated snow can delay emergency transportation. As the extent and severity of congestion are expected to increase, the emergency transport times in this study are likely to be underestimated. In addition, survival rates may be reduced in winter because of the cold weather. Considering snowfall during winter, emergency transport times are expected to be different. This study focused on the time required for emergency transport; however, an analysis focusing on the number of seriously injured people is important. This analysis also did not consider the ability of each hospital to accept patients, which should be assessed in the future.

DISCUSSION

IMPACT OF CLOSED ROADS, SEMI-CLOSED ROADS, AND TRIAGE POSTS

This analysis showed that emergency transportation times were longer in areas with closed and semi-closed roads. In an actual situation, it is possible that roads may be blocked that are different from those assumed in this study. This could lead to situations where ambulances get stuck or have to make U-turns. We believe that by using drones to evaluate roads and determine the transportation route, it is possible to shorten the transportation time.²⁶ In addition, differences in emergency transport times were observed depending on whether the patient first visited a triage post. Passing through triage posts was delayed by more than 30 min compared to normal times in areas where roads were closed or semi-closed. In Higashi administrative districts, delays were more than 15 min longer than usual, reaching up to 101 min. The delays may be because there are no health centres in that area, meaning ambulances must cross areas where roads are closed or semi-closed to reach health centres. If disaster victims in such areas could be transported directly to hospitals without going through triage posts, emergency transport times would be shortened, leading to improved survival rates. However, without triage, hospitals accepting patients are forced to treat all patients, from those with minor injuries to those with serious injuries, meaning that they can become overwhelmed. By having doctors and nurses triage patients inside the ambulance and transporting them to the appropriate hospital, the time spent at the triage post can be reduced. In Sweden, triage in emergency medical care is performed by registered nurses and specialist nurses.²⁷

All patients should be transported promptly to medical care because longer prehospital times may increase the risk of poor functional outcomes. Poor functional outcome increase by 6% for every 10-minute delay from the time of injury to medical care, and a delay of more than 50 minutes predicts poor outcomes.²⁸ With the goal of avoiding

passing through triage posts, it is expected that overall transport times will be shortened by having nurses and other medical personnel complete triage within the ambulance.

OPTIMAL DEPLOYMENT OF AMBULANCE VEHICLES

Fire stations surrounded by closed roads or that are near closed and semi-closed roads are expected to experience difficulty dispatching emergency vehicles and fire engines in the event of a disaster. Moreover, there is the risk that they will take longer to reach the affected area. Dispatching ambulances and fire trucks within and outside cities can support local emergency response activities. For emergency vehicles and fire engines to arrive quickly at a disaster scene, avoiding being caught in traffic jams is important. Furthermore, it is necessary to thoroughly inform residents not to use their own cars for evacuation, confirmation of safety, commuting, etc.²⁹ In addition, it is necessary to consider devices and measures to reduce the use of private vehicles and to place restrictions on their use based on the time elapsed since an earthquake.³⁰ Additionally, it is important to promote earthquake resistance measures for emergency transportation roads to ensure emergency vehicles can pass quickly after a disaster.^{31,32} Immediately after a disaster strikes, it is necessary to inform citizens that traffic restrictions will be enforced to prioritise the transportation of personnel and supplies necessary to save lives, prevent the spread of the disaster, and transport injured people.³³

MAINTAINING HOSPITAL FUNCTIONS

Like fire stations, core hospitals surrounded by closed roads or located near closed or semi-closed roads may not be accessible to ambulances. Hospitals may be damaged by an earthquake and cease functioning. If a hospital's functions are paralysed, seriously injured patients will have to be transported to other core hospitals, which could result in longer emergency transport times and exceedance of hospital capacity. If a large number of seriously injured people cannot be treated within a city, they must be quickly transported to disaster base hospitals outside the city. However, land transport can be affected if roads are closed; in these cases, air transport by medical helicopters is also an option.³⁴ However, it is necessary to select a hospital with advanced capabilities to accommodate a medical helicopter or air transport base for seriously injured patients.

CONCLUSIONS

In this study, in order to improve the survival rate of seriously injured people, emergency transport times were calculated and compared for the entire city of Sapporo and 10 administrative districts in the event of an earthquake caused by the Tsukisamu

fault in Sapporo. As a result, many blocked and semi-blocked roads occurred in Higashi administrative districts, which extended transport times. When transporting via triage posts, transport times were extended not only in Higashi administrative districts but also in Kita administrative districts. This result indicates that road blockages due to liquefaction and collapsed houses are highly likely to extend emergency transport times.

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List of Figure Captions

Figure1: Figure1 showed the difference in transport times for scenarios with closed roads, no semi-closed roads, and no triage posts.

Figure2: Figure2 showed the difference in transport times for scenarios with closed roads, without semi-closed roads, and via triage posts.

Figure3: Figure3 showed the difference in transport times for a scenario with closed and semi-closed roads and without passing through the triage posts.

Figure4: Figure4 showed the difference in transport times for a scenario with closed and semi-closed roads and passing through the triage posts.

Table1. Data used in the analysis

Data	Data Source
Road information	Road Network Hokkaido Version 2018 (Geotechnologies Corporation [formerly Increment P Corporation], Tokyo, Japan) ³⁵
Seismic intensity distribution	Sapporo City's fourth earthquake damage estimate ¹⁴
Liquefaction Hazard Level	Sapporo City's fourth earthquake damage estimate ¹⁴
Rate of total house destruction	Sapporo City's fourth earthquake damage estimate ¹⁴
Administrative district data	National census ³⁶
Hospital	National Land Information Download Site ³⁷
Fire station	National Land Information Download Site ³⁸
Health center	Sapporo City (2023) ³⁹

Table 2. Average delivery time (top), range (middle), standard deviation (bottom)

Area	No closed roads(min)	Closed roads(min)			
	No triage (normal conditions)	No semi-closed roads		Semi-closed roads	
		No triage	Triage	No triage	Triage
Chuo	6.99	7.00	13.32	7.21	13.68
	2.78-20.45	2.78-20.45	7.72-25.92	2.78-20.45	7.72-25.92
	2.03	2.03	2.96	2.30	3.16
Kita	13.09	13.43	18.93	16.97	25.56
	2.12-28.09	2.12-28.70	7.56-39.13	2.12-44.11	9.18-55.09
	4.80	4.80	7.01	7.26	8.63
Higashi	8.43	9.07	16.72	16.49	31.57
	2.35-19.58	2.77-20.45	6.32-32.54	3.30-94.81	6.32-110.09
	2.71	2.88	5.51	12.48	14.86
Shiroishi	10.19	10.91	16.41	12.49	17.92
	3.87-16.70	3.87-18.72	10.55-28.52	3.87-31.45	10.55-39.26
	2.92	3.29	3.24	5.19	5.12
Toyohira	9.44	9.45	13.89	9.55	13.99
	3.20-27.38	3.20-27.38	9.50-31.86	3.20-27.38	9.50-34.26
	3.22	3.23	3.13	3.35	3.29
Minami	17.38	17.38	20.56	17.38	20.57
	6.38-54.73	6.38-54.73	6.91-55.23	6.38-54.73	6.91-55.23
	9.09	9.09	7.51	9.09	7.50
Nishi	8.89	9.01	13.39	10.04	14.29
	3.48-22.14	3.48-22.14	8.15-27.61	3.48-38.70	8.15-39.78
	2.64	2.75	3.49	4.72	4.90
Atsubetsu	9.15	9.17	12.85	9.90	13.61
	3.33-17.28	3.33-18.12	4.92-21.41	3.33-33.93	4.92-36.22
	2.92	2.95	2.99	4.12	4.23
Teine	10.38	10.38	12.18	10.38	12.18
	5.06-29.00	5.06-29.00	6.30-30.23	5.06-29.00	6.31-30.23
	3.35	3.35	3.47	3.35	3.47
Kiyota	14.47	14.48	20.48	14.69	20.69
	4.91-36.80	4.91-36.80	12.05-42.13	4.91-36.80	12.05-42.13
	3.92	3.92	3.23	4.06	3.45
Sapporo City	10.84	11.03	15.87	12.51	18.41
	2.12-54.73	2.12-54.73	4.92-55.23	2.12-94.81	4.92-110.09
	4.85	4.89	5.55	8.15	10.77

Figure 1. shows the difference in transport times for scenarios with closed roads, no semi-closed roads, and no triage posts.

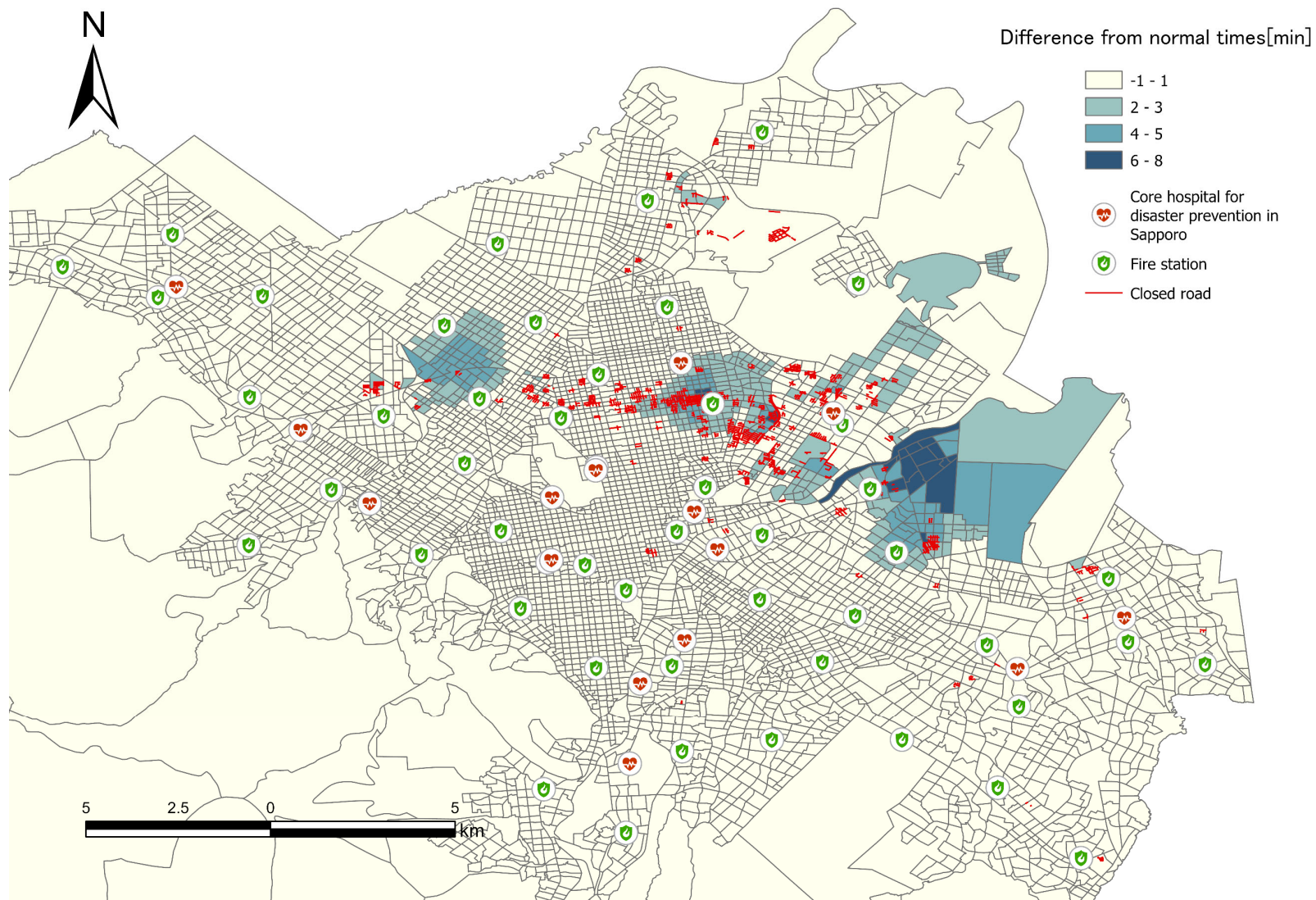


Figure 2. shows the difference in transport times for scenarios with closed roads, without semi-closed roads, and via triage posts.

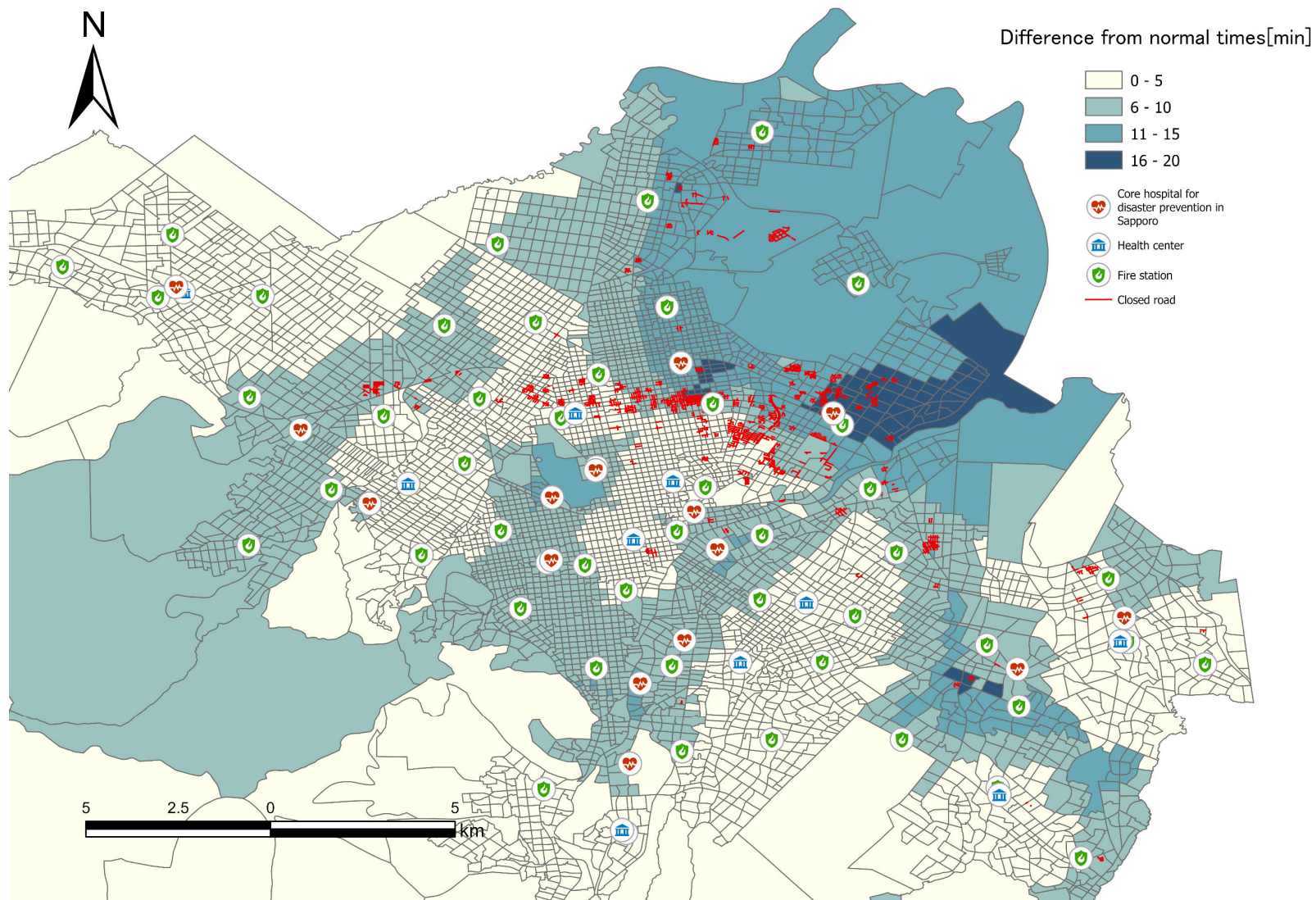


Figure 3. shows the difference in transport times for a scenario with closed and semi-closed roads and without passing through the triage posts.

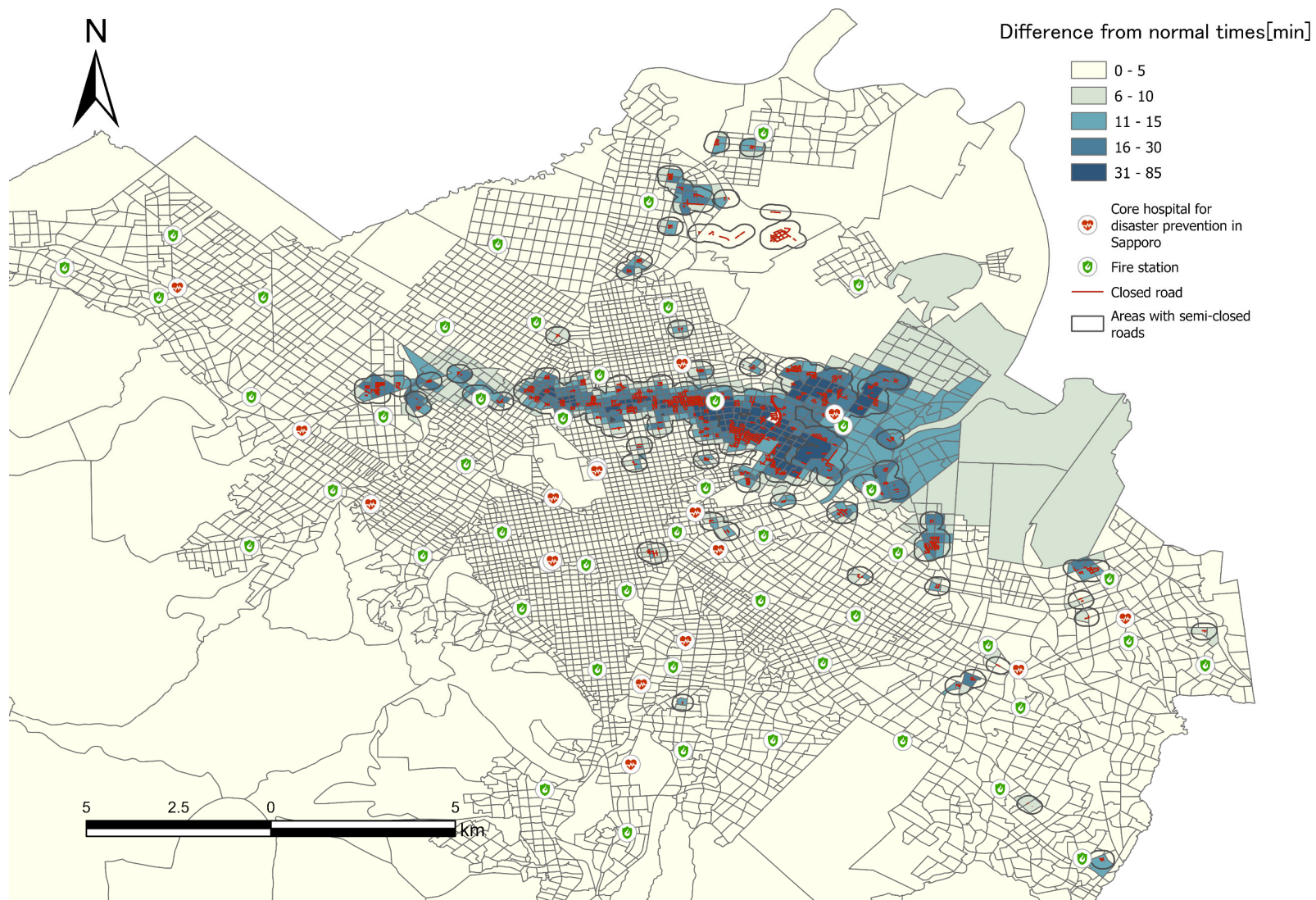


Figure 4. shows the difference in transport times for a scenario with closed and semi-closed roads and passing through the triage posts.

