Urban Mobility during Heavy Snowfall, Analyzed by Mobile Spatial Statistics Data

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Abstract: In this study, we propose a general method for quantitatively capturing urban daily mobility based on the Mobile Spatial Statistics data including residential location information by Docomo Insight Marketing Co. Ltd. We propose a method for setting up aggregation zones that can ensure calculation accuracy while aggregating a large amount of the hourly population data by mesh and residential municipalities. In the proposed method, the distance traveled and time used for travels can be easily calculated. By applying the method to the Sapporo Metropolitan area and showed impact of the heavy snowfall disaster in Sapporo in early February 2022.

Keywords: mobility, commuting flow, Mobile Spatial Statistics, disaster, snowfall

1. INTRODUCTION

(1) Research background and purpose
In Japan, where natural disasters occur frequently, quantitatively understanding the extent to which urban activities and functions have declined after the disaster and the recovery speed of functions will be important in improving resilience.

In this research, we develop a method of quantification of urban mobility. At that time, we capture the amount of one-dimensional movement along the distance from the central business district (CBD). As expressed in many urban economic models, various social and economic activities in cities are located according to the distance from the CBD, taking into account demand and land prices. We believe that it is possible to understand the activity level of a city based on one-dimensional distance, since people move by changing their distance from the CBD.

In recent years, large-scale data based on mobile phone location information has become available as a method to understand the urban mobility, replacing traditional questionnaire surveys and cross-sectional traffic counted figures at roads and railway stations. As an example of analyzing population distribution during disasters, Okumura (2015) used the increase and decrease in population distribution obtained from mobile phone GPS location data to understand the recovery process of urban functions in Sendai City, degraded by the Great East Japan Earthquake in 2011. Yamaguchi et al. (2017) attempted to quantify the impact of the Kumamoto Earthquake using GPS location information data categorized into main base (home) stays, sub-base stays, other stays, and movements. In this way, there are studies that attempt to extract the recovery process of urban functions from changes in population distribution in urban areas, but no method has been developed to quantitatively understand mobility, such as distance traveled or time used for travels.

(2) Characteristics of the data used

In this study, we use Mobile Spatial Statistics provided by Docomo Insight Marketing. Docomo's mobile phone network periodically identifies mobile phones located in coverage area of each radio antenna. Mobile Spatial Statistics use this system to aggregate the number of mobile phones and estimate the population by taking into account the penetration rate of Docomo in each region, and estimate the population on an hourly basis for 500m meshes. Note that the estimation targets the population aged 15 to 79, excluding those aged 80 and over, who have a low penetration rate, and those aged 14 and under who cannot sign up for a mobile phone contract.

This study uses hourly population estimate data by date, hour, mesh, and residential municipality. Due to the nature of Mobile Spatial Statistics, a concealment process is performed to the meshes with small population value. Additionally, if a mobile phone is turned off or is moving between meshes and is not detected to have stayed in any mesh for more than 15 minutes, the location of the device will not be identified and will become a missing value. This causes the problem that the total resident population within the target metropolitan area varies depending on the time of day, so the ratio of the total resident population for each time period based on the maximum value of the total resident population for each day is calculated. We will calculate the correction value by dividing the original data by this correction factor and use it in the analysis below.

2. METHODOLOGY

2.1 Target Metropolitan Area and Measurement Origin

Mobile Spatial Statistics data is an estimate of the hourly resident population for each mesh, and does not itself represent movement. After setting up spatially continuous zones, we consider that increases and decreases in the existing population in adjacent zones occur due to movement across the boundaries between those zones, and then calculate the amount of movement backwards. If we consider a circular area of 100km from CBD, it will include a maximum of approximately 125,000 meshes, so the data size of the resident population by mesh will be enormous and difficult to handle. Therefore, it is necessary to set aggregation zones properly so that quantitative indicators such as the number of people and distance of one-dimensional movement can be accurately grasped while compressing the data size.

For the municipalities listed in the definition of metropolitan areas in the National Census, we will calculate meshes whose center points are within 100 km from the measurement origin described below. We set one measurement origin for measuring urban movement in a one-dimensional manner. Here, in order to prevent movement toward the CBD from being dismissed as a circular direction, we use the center of gravity position, which is weighted by the day-night population difference, as the measurement origin. Note that this origin is only a reference for measuring distance, and does not mean that this point is the destination of all the travelers. **Figure 1** shows the location of measurement origin in Sapporo City.

2.2 Establishment of Basic Zones

Zones are delineated based on the distance from the measurement origin, with movement across these zones being treated as one-dimensional movement of people. Let the width of each

Figure 1. Measurement origin in Sapporo City

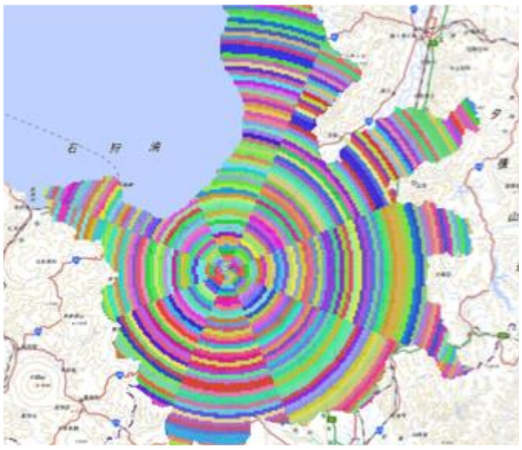

Figure 2. Basic zones in Sapporo Metropolitan Area

distance zone be denoted as k km. If k is set to a small value, close to the mesh size of 500 m, the accuracy may be compromised, as some movements approaching the measurement origin may be inaccurately classified as movements to the outer zone. Conversely, if k is set to an excessively large value, the proportion of actual movements that are overlooked will increase, leading to an underestimation of movement. Thus, it is essential to strike a balance between the variability of calculation results and the computational load.

In this study, we have chosen $k = 1$ km. The target metropolitan area is divided into distance zones emanating from the measurement origin in eight directions, establishing basic zones that integrate the mesh into partially circular zones with the zone adjacent to the measurement origin and fan-shaped configuration. **Figure 2** shows the basic zones that divide the Sapporo Metropolitan Area into distance zones of 1 km and eight directions.

2.3 Residential Dependent Zone System

To effectively capture the trips originating from each residential municipality, a zone system has been developed that corresponds to each residential municipality, building upon the foundational basic zones previously established.

1) A computational domain is established to monitor the movements toward the city center for each residential municipality. Specifically, basic zones that are located in the same direction as the residential municipality and are closer to the measurement origin are designated as the “inward direction domain”. Conversely, basic zones positioned in the opposite direction to the residential municipality are classified as the “opposite direction domain.”

2) In both the inward direction domain and the opposite direction domain, basic zones that are equidistant from the measurement origin are collectively referred to as aggregation zones. These aggregation zones are then numbered according to their respective distances.

It is important to note that the aforementioned zone system is defined for each residential municipality, which implies that the same basic zone may be categorized into different measurement zones depending on the specific residential municipality.

2.4 Capturing Inward Movements

Consequently, the zone system constructed in this manner consists of zones that are continuously ordered along the direction of movement. Movers departing from each residential municipality toward the city center enter the computational domain starting from the zone with the highest number, subsequently progressing toward aggregation zones with progressively smaller numbers. Movers whose destination is located within the intermediate aggregation zone concludes his/her movement at that zone. Additionally, movers whose destinations is situated in the opposite direction domain first traverse the aggregation zone closest to the measurement origin, which has the smallest number, before transitioning into the opposite direction zone and moving toward aggregation zones that are farther from the origin.

The numbering of the opposite direction zones is established to begin at -1 and continue as negative numbers, corresponding to the distances subtracted from the origin. This arrangement allows for the morning commute toward the city center to be interpreted as the movements toward aggregation zones with smaller numbers, whereby the difference in zone numbers represents the distance traveled.

2.5 Quantification of Movements

The following relationship holds true for all zones within the zone system: at any given time, the total population present in any downstream zones with a smaller zone number is equal to the cumulative number of individuals who have passed through that zone up to that specific time. From these temporal variations, it is possible to calculate the hourly passing population and the average passage time of individuals. The average inflow time into the calculation area is determined by obtaining the entry time and the number of commuters into the zone system, followed by averaging these values.

Each zone's population comprises effective residents (individuals whose destination is the respective zone) and movers (individuals enroute to zones further away). The temporal variations in the effective resident population of each zone allow for the calculation of the arrival times of effective residents at their intended destinations. To determine the average destination arrival time for the entire calculation area, the earliest and latest arrival times of effective residents are identified, and the intermediate values are averaged to obtain the overall mean.

By utilizing the average inflow time into the calculation area and the average destination arrival time, it becomes feasible to calculate the travel time from the moment of entry into the calculation area to the arrival at the intended zone.

3. COMMUTING IN THE SAPPORO METROPOLITAN AREA DURING HEAVY SNOWFALL

3.1 Overview of the Heavy Snowfall in February 2022

A record-breaking heavy snowfall occurred from February 5 (Saturday) to February 6 (Sunday) in 2022, centered around Sapporo City, resulting in significant transportation disruptions. The period from January 31 (Monday) to February 4 (Friday) is designated as the week preceding the heavy snowfall, while the period from February 7 (Monday) to February 10 (Thursday) is referred to as the week of the heavy snowfall.

This study aims to quantitatively assess the decline and recovery processes of transportation functions by municipality of residence, shown in **Figure 3**. As examples, zone system for Ebetsu City and Kitahiroshima City are shown in **Figure 4** and **Figure 5**, respectively.

Figure 3. Four municipalities around Sapporo City

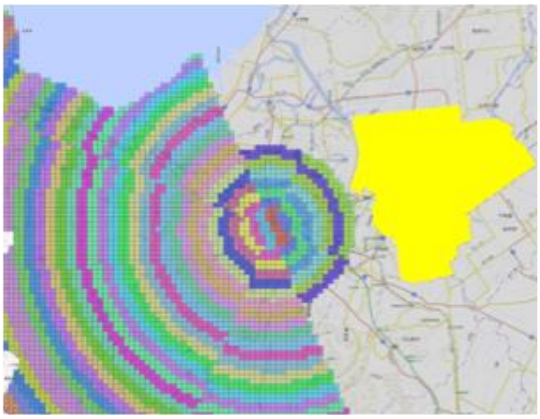

Figure 4. Zone system for Ebetsu City

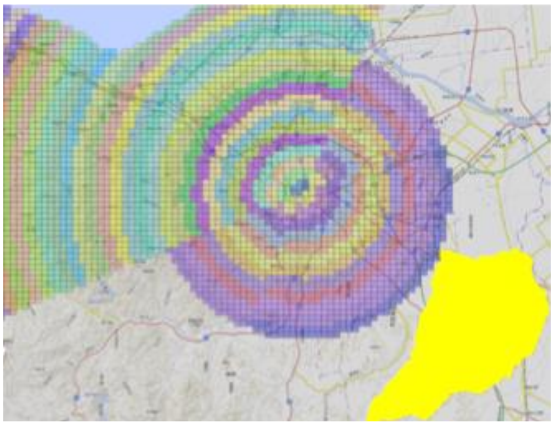

Figure 5. Zone system for Kitahiroshima City

3.2 Comparison of Commuting Transportation by Modes

Ebetsu City, located to the northeast of Sapporo City, is served by the JR Hakodate Line. The utilization rate of railways as a means of commuting purpose to other municipalities is 38%, the highest within the metropolitan area. Due to the heavy snowfall, the JR Hakodate Line was suspended from noon on February 6 (Sunday) until 6 PM on February 9 (Wednesday), with services resuming for morning commutes on February 10 (Thursday).

Kitahiroshima City, situated to the southeast of Sapporo City, is served by the JR Chitose Line. The railway utilization rate for commuting purpose to other municipalities is 30.1% indicating a slightly lower railway utilization rate compared to Ebetsu City, while the automobile utilization rate stands at 56.6%. The JR Chitose Line experienced a suspension from noon on February 6 (Sunday) until 6 AM on February 9 (Wednesday), with services available for morning commutes beginning on February 9 (Wednesday).

Ishikari City, located to the north of Sapporo City, has no railway service within its jurisdiction, and the automobile utilization rate for commuting purpose to other municipalities is 63%, the highest in the metropolitan area excluding Sapporo City.

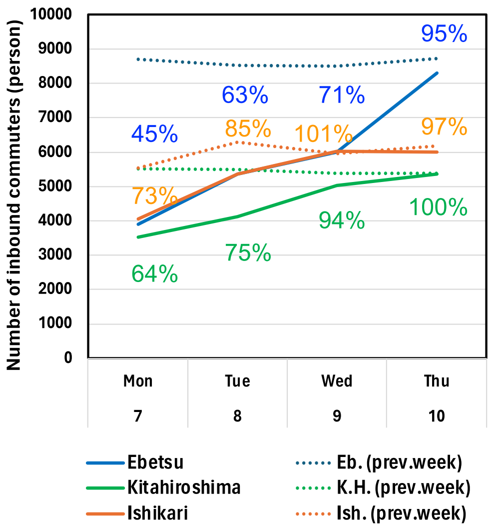

Figure 6. Number of inbound commuters from the three cities

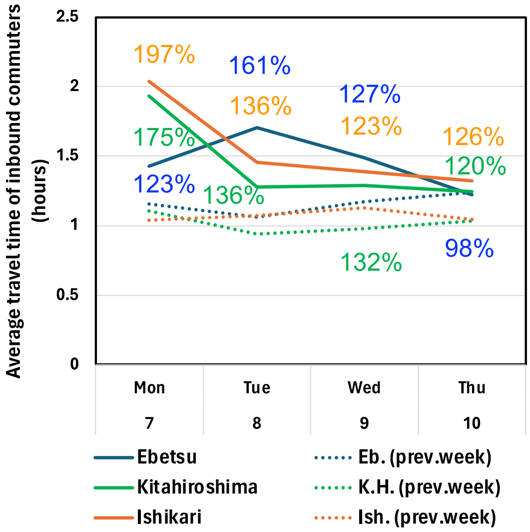

Figure 7. Average travel time of inbound commuters from the three cities

The following analysis compares the number of inbound commuters traveling towards Sapporo, as well as the average morning travel times for the three cities with varying railway utilization rates, focusing on the weekdays from Monday to Thursday during the week preceding the heavy snowfall and the week of the heavy snowfall.

Figure 6 illustrates the trends in the number of inbound commuters traveling towards Sapporo from Ebetsu City, Kitahiroshima City, and Ishikari City. In the week preceding the heavy snowfall, the differences in daily figures were minimal for each city, with approximately 8,500, 6,000, and 5,500 individuals, respectively. An examination of the reduction rates during the week of the heavy snowfall reveals that in Ebetsu City, the number decreased by 45% on February 7 (Monday) and subsequently recovered to 71% on February 9 (Wednesday), reaching 95% by February 10 (Thursday). In Kitahiroshima City, the decline was 64% on February 7 (Monday), but following the resumption of railway services, the number rebounded to 94% on February 9 (Wednesday) and returned to 100% of the previous week's level on February 10 (Thursday). Ishikari City experienced a reduction of 73% on February 7 (Monday), with a full recovery to the previous week's levels by February 9 (Wednesday).

Thus, it can be inferred that the recovery timing for inbound commuters was quickest in Ishikari City, where the rate of automobile utilization is high, while Ebetsu City and Kitahiroshima City experienced delays in recovery, constrained by the timing of the resumption of railway operations.

Figure 7 presents the trends in the average morning travel time for inbound commuters heading towards Sapporo from the three cities. During the week preceding the heavy snowfall, there were no significant differences in travel time on weekdays, with Ebetsu City and Ishikari City averaging approximately 1.1 hours, while Kitahiroshima City averaged about 1.0 hour. Changes in travel time during the week of the heavy snowfall reveals that in Ebetsu City, the travel time surged to 123% on February 7 (Monday) and increased further to 161% on February 8 (Tuesday). Subsequently, travel time decreased, returning to 98% of the previous week by February 10 (Thursday) when the railway services were restored. In Kitahiroshima City, travel time experienced a sharp increase, reaching 175% on February 7 (Monday). Although there was a gradual reduction in travel time after February 8 (Tuesday), they remained at 120% of the previous week on February 10 (Thursday), indicating a prolonged period of extended travel

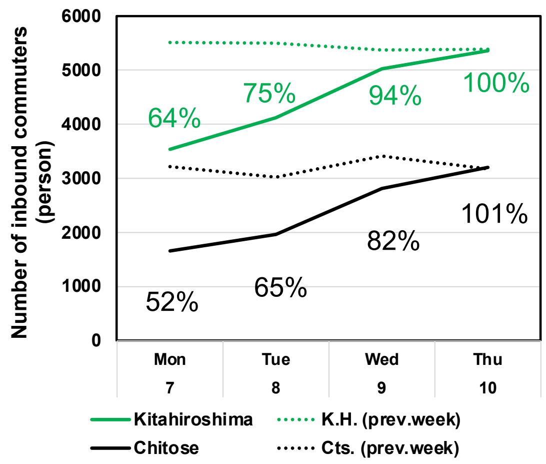

Figure 8. Number of inbound commuters from Kitahiroshima and Chitose

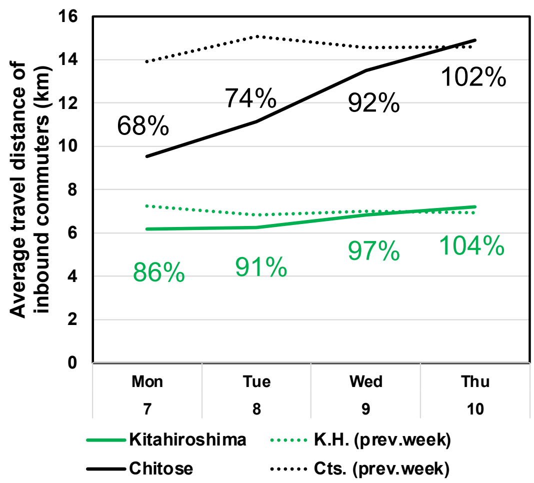

Figure 9. Average travel distance of inbound commuters from Kitahiroshima and Chitose

time. In Ishikari City, travel time on February 7 (Monday) nearly doubled, reaching 197% compared to the previous week. Although there was a notable decrease beginning the following day, travel time remained elevated at 126% of the previous week by February 10 (Thursday).

The observed fluctuations indicate that Ebetsu City, characterized by a high railway utilization rate, exhibits travel time that require a considerable recovery period; however, once restored, the railway is capable of providing regular services. Conversely, in Kitahiroshima City, the recovery timeline for commuters and students aligned with the resumption of railway operations; nonetheless, the increase in travel time persisted throughout the duration of the disruption. This phenomenon can be attributed to a higher proportion of automobile users in Kitahiroshima City compared to Ebetsu City, leading to prolonged road functionality degradation and resultant traffic congestion. Furthermore, Ishikari City, which lacks railway services and has a high reliance on automobiles, experienced a relatively minor decline in the number of commuters and students, coupled with a swift recovery. However, the average travel time did not return to the levels observed in the preceding week. This discrepancy suggests that while road recovery occurred rapidly and vehicular passage was feasible, the functionality of the roads remained compromised due to the enduring impact of snow, thereby affecting overall travel time.

3.3 Comparison of Commuting Transportation by Distance

Kitahiroshima City and Chitose City are situated to the southeast of Sapporo City, both served by the JR Chitose Line. The distances to the Downtown Sapporo are approximately 11 km and 27 km, respectively. In the following analysis, we will compare the number of inbound commuters towards Sapporo from these two cities, as well as the average travel distance (the mean distance per individual) and average travel time, focusing on the trends observed on weekdays before and after the heavy snowfall.

Figure 8 illustrates the trends in the number of inbound commuters towards Sapporo from both Kitahiroshima City and Chitose City. In the week preceding the heavy snowfall, Kitahiroshima City had approximately 5,500 individuals commuting or attending school in Sapporo, as indicated in Figure 6, while Chitose City recorded around 3,200. Both cities exhibited minimal daily fluctuations. Upon examining the reduction rates during the week of

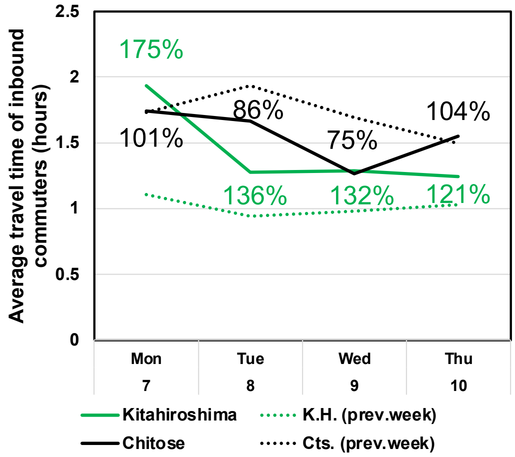

Figure 10. Average travel time of inbound commuters from Kitahiroshima and Chitose

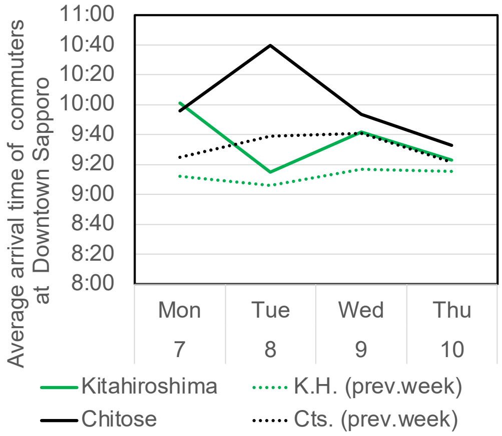

Figure 11. Average arrival time at Downtown Sapporo from Kitahiroshima and Chitose

the heavy snowfall, it is noted that Kitahiroshima City experienced a decline to 64% on February 7 (Monday); however, following the restoration of railway services, the numbers rebounded to 94% on February 9 (Wednesday) and returned to 100% of the previous week's levels by February 10 (Thursday). In contrast, Chitose City saw a decrease to 52% on February 7 (Monday), followed by a gradual recovery, also reaching pre-disruption levels by February 10 (Thursday). While the reduction rates in Chitose City were slightly greater on each day compared to Kitahiroshima City, the patterns and timing of recovery were notably similar.

Figure 9 presents the trends in average travel distances of inbound commuters from Kitahiroshima City and Chitose City. In the week preceding the heavy snowfall, the average travel distances were approximately 7.0 km and 14.5 km, respectively, with no significant daily variations observed. During the week of the heavy snowfall, a noticeable decline in travel distance was recorded; specifically, Kitahiroshima City experienced a reduction of 1 km on February 7 (Monday), but subsequently rebounded to the previous week's levels by February 9 (Wednesday) following the restoration of railway services. In contrast, Chitose City exhibited a more pronounced decrease of 4.4 km on February 7 (Monday), with a gradual recovery that reached the previous week's levels by February 10 (Thursday). These observations suggest that in Chitose City, which is situated farther from the Downtown Sapporo, a larger proportion of individuals may have chosen to forgo long-distance travel to the Downtown Sapporo compared to those in Kitahiroshima City.

Figure 10 illustrates the trends in average travel time of inbound commuters from Kitahiroshima City and Chitose City. In the week preceding the heavy snowfall, Chitose City experienced travel times fluctuating between 1.5 and 1.9 hours, which were significantly longer than the approximately 1.0 hour required in Kitahiroshima City. The impact of the heavy snowfall is particularly evident in Kitahiroshima City, where, as previously mentioned, travel time surged to 175% of the normal level on February 7 (Monday). Although a reduction was observed following this peak, travel time remained at 120% of the previous week's levels by February 10 (Thursday). In contrast, Chitose City exhibited travel times on February 7 (Monday) and February 10 (Thursday) that were nearly equivalent to those recorded in the prior week, while the average travel times on February 8 (Tuesday) and February 9 (Wednesday) were shorter than those in the week preceding the snowfall. This phenomenon is likely attributable to a decrease in the proportion of long-distance commuters targeting the Downtown Sapporo, who may have opted to forego their commutes due to the adverse weather conditions.

Next, we will examine the arrival of commuters in Downtown Sapporo (Chuo Ward).

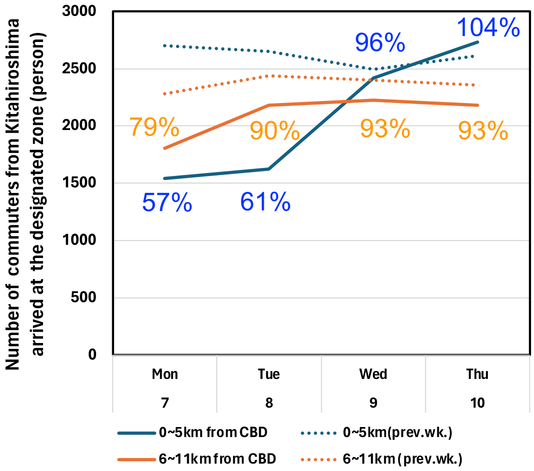

Figure 12. Number of inbound commuters from Kitahiroshima categorized by target area

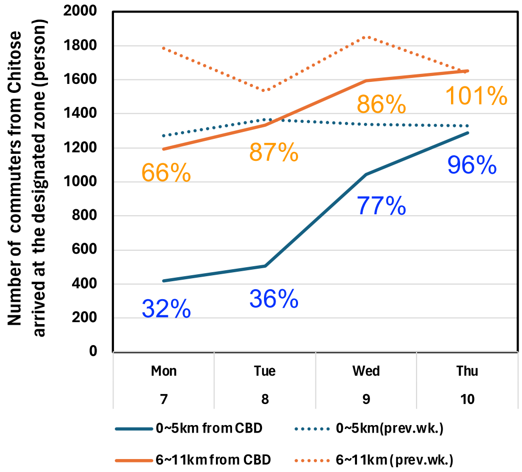

Figure 13. Number of inbound commuters from Chitose categorized by target area

Figure 11 depicts the trends in average arrival time of commuters from both Kitahiroshima City and Chitose City within these zones. In the week preceding the heavy snowfall, the average arrival time for commuters from Kitahiroshima City ranged between 9:10 and 9:20, while those from Chitose City arrived between 9:20 and 9:40, exhibiting minimal daily variations. An analysis of the changes in arrival time during the week of the heavy snowfall reveals that commuters from Kitahiroshima City experienced a delay of approximately 50 minutes on February 7 (Monday). However, on February 8 (Tuesday), their arrival times improved significantly, with the difference from the previous week narrowing to within 10 minutes. Although there was a slight delay on February 9 (Wednesday), arrival times returned to levels consistent with the previous week by February 10 (Thursday). Conversely, commuters from Chitose City faced an approximate delay of 30 minutes on February 7 (Monday), which further extended to 10:40 on February 8 (Tuesday). By February 9 (Wednesday), the difference from the previous week had diminished to around 10 minutes, and by February 10 (Thursday), the arrival times had nearly returned to the previous week's level.

Figures 12 and **13** illustrate the trends in the number of arrivals for commuters residing in Kitahiroshima City and Chitose City, respectively, categorized by the target area's proximity to the central urban area. The data is divided into two segments based on the distance from the measurement origin. In both cities, a significant decline in the number of arrivals was observed on February 7 (Monday) and February 8 (Tuesday) during the week of the heavy snowfall, with destinations closer to the city center experiencing a more pronounced decrease. Notably, the decline in Kitahiroshima City was somewhat less severe than that observed in Chitose City. Furthermore, it is evident that on February 9 (Wednesday), following the restoration of railway services, there was a rapid recovery in the number of arrivals at destinations located near the city center.

Based on the observed fluctuations, it is evident that the decline in the number of commuters towards Sapporo due to the heavy snowfall was significantly more pronounced in Chitose City, which is located farther from the city center. Notably, it was determined that long-distance commuters, particularly those traveling to the central area of Sapporo, opted to discontinue their journeys during this period. Typically, Chitose City experiences longer travel time for inbound commuting compared to Kitahiroshima City. However, during the heavy snowfall, the phenomenon of average travel time reversing occurred, as the cessation of travel by long-distance commuters resulted in a relative reduction in average travel times for those remaining on the route.

4. CONCLUSION

This study focuses on the critical role of commuting and educational transport in maintaining the level of economic activity within urban areas and proposes a quantification method to assess this function. Utilizing the proposed methodology, we quantitatively analyzed the decline in commuting and educational transport functions in the Sapporo Metropolitan area during the heavy snowfall event in February 2022, as well as the subsequent recovery process. The results indicate that variations in the modal share of transportation for commuting and education, as well as differences in distance from the city center, significantly influenced both the impact of the snowfall and the recovery trajectory.

It is recommended that future research continue to build upon this analysis by examining additional metropolitan areas and other types of disasters or events.

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