Thermal Mapping Analysis for Effective Road Heating Equipment Installation

K. Hatamoto
Research and Development Division, Hanshin Expressway Research Institute for Advance Technology, Japan
keigo-hatamoto@hit.or.jp
K. Horikoshi & S. Kume
Kobe Management and Conservation Department, Hanshin Expressway Co., Ltd., Japan
koichi-horikoshi@hanshin-exp.co.jp, kume-shoichi@hanshin-exp.co.jp

ABSTRACT

This report presents a thermal mapping analysis conducted on the Kita-Kobe Route of the Hanshin Expressway to identify areas particularly prone to freezing. The study aims to address issues related to road freezing and the frequent use of deicing agents by identifying the most effective locations for installing road heating systems. Over two winter periods in 2021 and 2022, a study was conducted using three vehicles to collect road surface temperature and infrared radiation data. A total of 54 measurement sessions were conducted.

The main results identified the top 10% of locations with the lowest pavement surface temperatures as "cold spots." Specific conditions contributing to pavement surface freezing, such as bridge sections, areas permanently in the shade, and sections without roofs, were also identified. The majority of the high-frequency cold spots were concentrated in the eastern section of the route, with the total length of the most frequent cold spots being approximately 1.3 km. The reproducibility of the top locations was confirmed for each year. Comparison with feedback from snow removal crews generally matched the thermal mapping results, though there were some exceptions due to differences in snow depth distribution and solar radiation. These results will be used to prioritize the installation of road heating systems using carbon sheets. We have the potential to establish a system that can regularly conduct thermal mapping, integrate data with ICT-enabled spraying vehicles, and implement on-demand measures that allow for minimal spraying at necessary locations.

1. INTRODUCTION

The Hanshin Expressway is an urban expressway in the Kansai region of Japan. Among its routes, the Kita-Kobe Route experiences the lowest road surface temperatures, making it the most prone to freezing. Consequently, snow and ice alerts are issued frequently each year, and the repeated application of anti-icing agents has led to severe salt damage to the expressway's structures. On the other hand, snowfall is not particularly heavy, with closures due to snow accumulation occurring only seven times in the past 10 years. However, these closures often last for extended periods, causing significant disruption to drivers. This situation created a demand for snow and ice countermeasure equipment capable of both preventing freezing and melting snow.

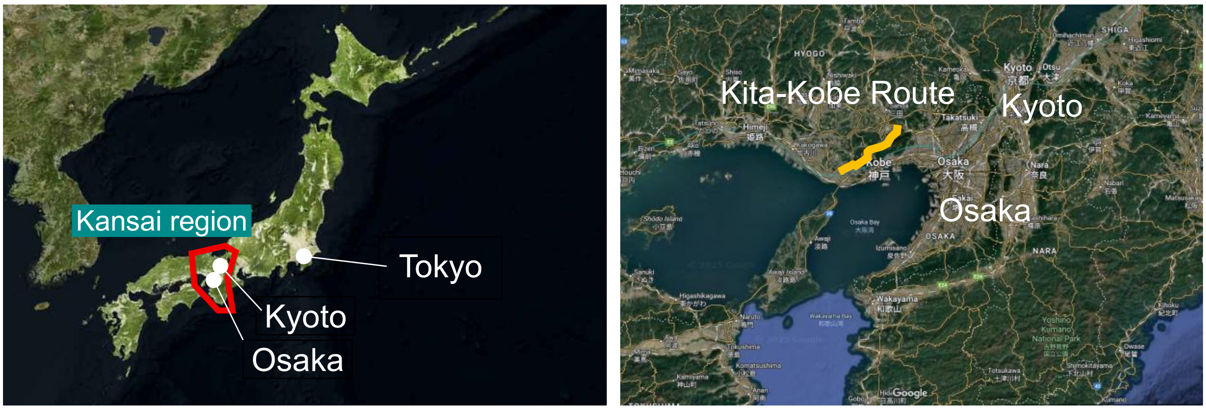


Figure-1 Location Map

Through validation experiments, road heating using carbon sheets was identified as the optimal equipment for both preventing road surface freezing and melting snow. Initially, we considered installing this system on steep, high-elevation ramps. However, equipping all ramps was not feasible from a cost perspective, necessitating a more selective approach to identify the most effective sections. Furthermore, on-site teams responsible for applying anti-icing agents suggested that many high-risk locations are also scattered along the main expressway line. This led us to conclude that a comprehensive plan for the entire Kita-Kobe Route was necessary. Therefore, we decided to conduct thermal mapping over a two-year period to survey the road surface temperature and identify the specific locations most prone to cooling and freezing.

Thermal mapping is an approach in road freezing countermeasures that allows for a linear understanding of the road surface's temperature characteristics to find potentially freeze-prone locations. With thermal mapping, an entire route can be measured within nearly the same timeframe, which minimizes discrepancies caused by time lags. By simultaneously measuring infrared radiation (the presence or absence of radiative cooling), the method provides data that excludes weather-induced variations, making it possible to compare various locations under nearly identical conditions. The objective is to specifically identify the most hazardous, high-priority locations along the route, leading to more efficient snow and ice countermeasures.

2. INTRODUCTIOOBSERVATION METHOD AND PERIOD

2.1. Observation Equipment

For the thermal mapping, we mounted sensors, including a radiation thermometer and recording devices, onto a vehicle as shown in Figure-2, and conducted observations while driving the actual routes.

Figure-2 Sensor Mounting Position

Covering the entire Kita-Kobe Route—including the mainline (both directions) and all ramps—with a single vehicle would take over four hours, making the data susceptible to changes in road surface temperature over time. To address this, the route was divided into sections, and three vehicles were deployed simultaneously, allowing the entire survey to be completed in about one hour. The raw data was recorded at 0.2-second intervals, which corresponds to a data point approximately every 3.3 meters when traveling at 60 km/h.

2.2. Number of Observations

Observations were conducted during the winters of 2021 and 2022, with 24 observation runs in 2021 and 30 in 2022, for a total of 54 runs. Observations were scheduled three times a day at 1:30, 3:30, and 5:30. If any part of the data from a single run was incomplete, all data from that entire run was excluded from the analysis.

2.3. Cold Spots

For each observation run, the data from the entire route was sorted by road surface temperature from lowest to highest. The top 10% of these locations were defined as "cold spots," representing areas particularly susceptible to freezing or lingering snow. We then counted the number of times each location was classified as a cold spot across all runs.

The decision to define cold spots as the top 10% was based on an analysis of the rate of change (the slope of the graph) in temperature between ranked data points. As shown in Figure-3, this rate of change tended to decrease around the top 5% mark. However, the temperature differences around this 5% boundary were small, meaning that minor temperature fluctuations between observation runs could easily alter a location's rank. To account for this and ensure no critical locations were missed, we decided to use a more conservative range, doubling the data volume to the top 10%. The specific procedure for extraction is as follows.

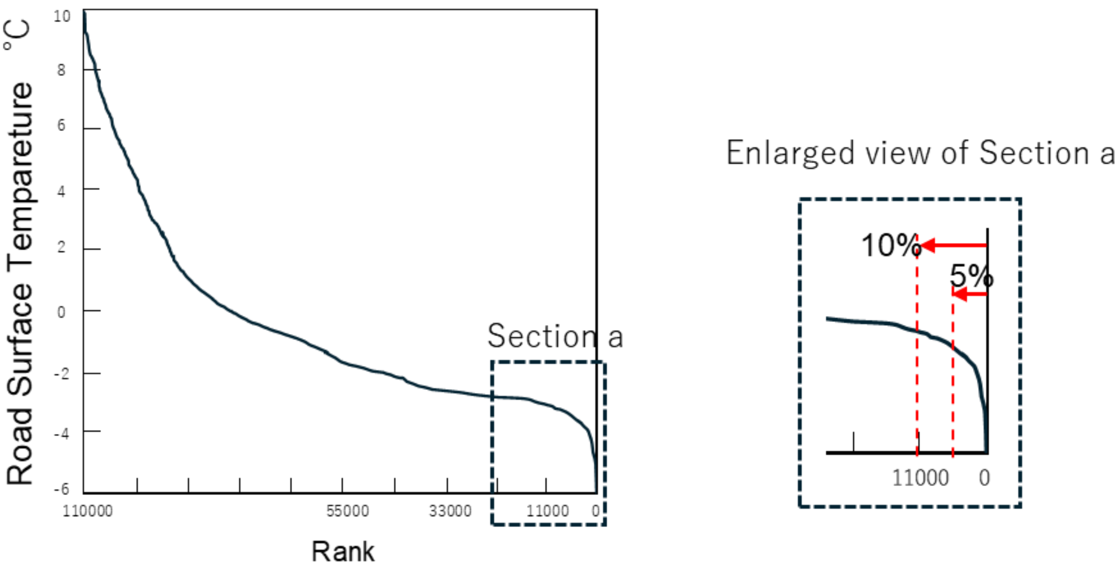


Figure-3 relationship between Road Surface Temperature and Rank

2.4. Analysis Method

2.4.1 *Organizing the Original Data*

As the driving routes for each observation area resulted in some overlapping data, the original data was first segmented by route (e.g., eastbound mainline, westbound mainline, individual ramps) and organized to ensure there was only one data point for each unique location.

2.4.2 *Correcting Data to Standard Coordinates*

Because the observations were made from moving vehicles, the exact measurement locations were not identical for each run. Therefore, we used linear interpolation between the measured data points to estimate the road surface temperature at standardized coordinate positions. This process resulted in a dataset with a uniform 1-meter interval for each location, enabling direct comparison of data across different runs.

2.4.3 *Extracting Cold Spots*

The cold spots (the top 10% of locations) were extracted and compiled into a table. With the total length of the Kita-Kobe Route, including the mainline and ramps, being approximately 110 km, the top 10% corresponds to a total length of 11 km.

2.4.4 *Tallying Cold Spot Frequency*

All the individual cold spot tables were aggregated to calculate the total number of times each 1-meter section of the route appeared as a cold spot (i.e., ranked in the top 10%) across all observation runs.

3. COLD SPOT EXTRACTION RESULTS

3.1. Aggregated Results from All Observation Runs

Figure-4 shows the cold spot extraction results, color-coded on a continuous scale based on the frequency of occurrence. Colored sections indicate locations that were classified as a cold spot at least once, with cooler colors (e.g., blue) signifying a higher frequency. The results confirmed that cold spot occurrences were infrequent in the western area and were concentrated in the eastern area, which has a relatively higher elevation.

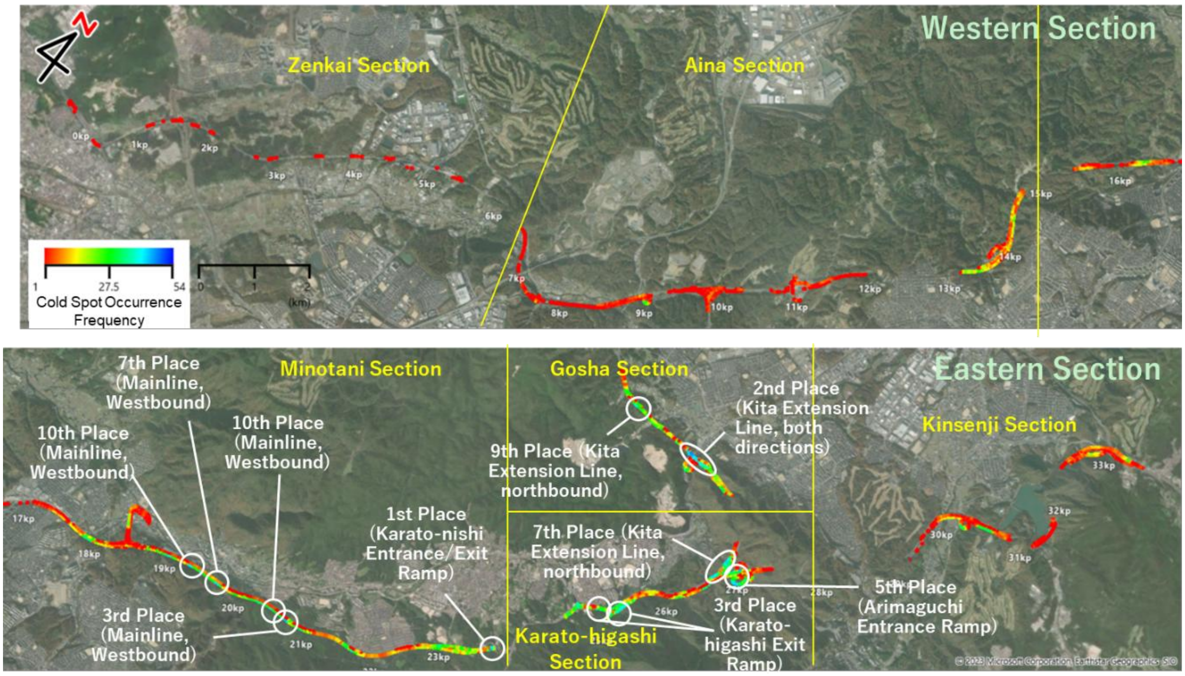


Figure-4 Frequency of Cold Spot Occurrences on the Kita-Kobe Route

Further investigation into the locations with a high frequency of cold spots revealed they commonly share the following conditions:

- Bridge sections
- Sections shaded during the daytime
- Open sections with no overhead structures, which are susceptible to radiative cooling

Next, Table-1 lists the locations with the highest frequency of cold spot occurrences in descending order. It details the locations that were classified as cold spots in 40 or more of the 54 total observation runs, along with the length of these sections. In calculating the section lengths—a task performed with the selection of sites for snow and ice countermeasure installation in mind—we consolidated points into lines wherever possible. If locations with 40 or more occurrences were within 20 meters of each other, the intermittent gaps were included to calculate a total continuous length.

Table-1 Cold Spot Occurrence Frequency and Section Length on the Kita-Kobe Route

Rank	Section Name	Section Length	Number of Cold Spot Occurrences
1	Karato-nishi Entrance	**40m (50m)**	40-49 times
	Karato-nishi Exit Ramp	**20m (30m)**	40-43 times
2	Kita Extension Line Southbound **2.54kp~2.23kp**	**250m (320m)**	40-48 times
	Kita Extension Line Northbound **2.57kp~2.29kp**	**220m (330m)**	40-46 times
3	Karato-higashi Exit Ramp (near exit)	**40m (140m)**	40-46 times
	Karato-higashi Exit Ramp (near mainline)	**85m (205m)**	40-42 times
3	Mainline Westbound **20.83kp~20.76kp**	**70m (100m)**	40-46 times
5	Arimaguchi Exit Ramp (near mainline)	**75m (200m)**	40-45 times
5	Arimaguchi Entrance Ramp (near mainline)	**70m (125m)**	40-45 times
	Arimaguchi Entrance Ramp (loop section)	**75m (180m)**	40-45 times
7	Mainline Westbound **19.81kp~19.77kp**	**40m (120m)**	40-44 times
7	Kita Extension Line Northbound **0.88kp~0.53kp**	**160m (310m)**	40-44 times
9	Kita Extension Line Northbound **3.45kp~3.43kp**	**20m (100m)**	40-43 times
10	Mainline Westbound **19.42kp~19.36kp**	**60m (100m)**	40-42 times
10	Mainline Westbound **20.56kp~20.55kp**	**10m (110m)**	40-42 times
	Total : 1235m	**Total : 1235m (2420m)**	

The total length of the sections identified as cold spots 40 or more times using this method was approximately 1.3 km. The length shown in parentheses in the table represents an extended range that includes surrounding areas where cold spots occurred 30 or more times, indicating a wider high-frequency zone. Although the structural type is not specified in the table, most of the sections with 40+ occurrences were on bridges; the remaining locations were in areas that receive minimal solar radiation.

3.2. Reproducibility of Results Over Two Years

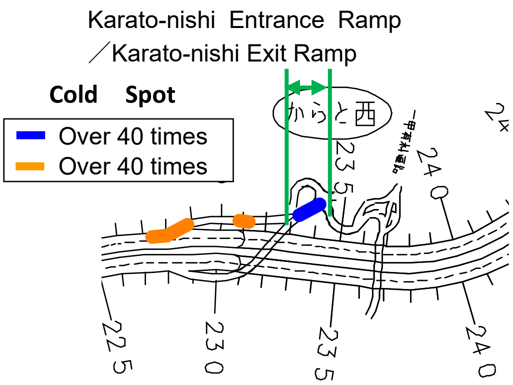
We compared the thermal mapping results from the two years (2021 and 2022) to verify the reproducibility of the highest-ranking cold spot locations. The locations that ranked in the top 5 in the combined results also ranked highly in the analysis of each individual year, confirming reproducibility for these key spots. However, for locations with lower ranks, reproducibility was not confirmed within the top 10 of each respective year's results. Nevertheless, the general trend of top locations being concentrated around the Karato-higashi and Goshha interchanges demonstrated sufficient reproducibility.

Table-2 Cold Spot Occurrence Frequency Over Two Years

Section Name	Overall Rank	2022 Rank	2021 Rank
Karato-nishi Entrance Ramp／Karato-nishi Exit Ramp	1	2	2
Kita Extension Line Southbound 2.54kp - 2.23kp／Kita-Kobe Northbound 2.57kp - 2.29kp	2	1	6
Karato-higashi Exit Ramp (near exit)／Karato-higashi Exit Ramp (near mainline)	3	2	2
Mainline Westbound 20.83kp - 20.76kp	3	4	6
Arimaguchi Exit Ramp (near mainline)	5	4	1
Arimaguchi Entrance Ramp (near mainline)／Arimaguchi Entrance Ramp (loop section)	5	-	1
Mainline Westbound 19.81kp - 19.77kp	7	-	6
Kita Extension Line Northbound 0.88kp - 0.53kp	7	-	4
Kita Extension Line Northbound 3.45kp - 3.43kp	9	6	-
Mainline Westbound 19.42kp - 19.36kp／Mainline Westbound 20.56kp - 20.55kp	10	7	-
Karato-higashi Entrance Ramp	-	7	-
Gosha Entrance Ramp／Gosha Exit Ramp	-	-	4
Nishinomiya-Yamaguchi-Minami Entrance Ramp	-	-	9
Mainline Westbound 19.7kp - 19.3kp	-	-	9
Minotani JCT Westbound Exit Ramp	-	-	9

3.3. Comparison with Interview Results from Snow Removal Personnel

Following a road closure on the Kita-Kobe Route due to snowfall from January 24 to 26, 2023, we interviewed the snow removal personnel involved. We asked them to identify locations where snow remained the longest and where road icing was observed. The results of this interview were then compared with the cold spots extracted from the thermal mapping data, as shown in Figures 5 through 9.



Not mentioned in the interviews

Figure-5 Comparison of Cold Spots (left) and Interview Results (right) at Karato-nishi

While the extraction results based on cold spot frequency were generally consistent with the interview results, some discrepancies were observed. For instance, the Karato-nishi entrance/exit ramp (Figure-5), which had the highest cold spot frequency, was not pointed out during the interviews. Similarly, the loop section of the Arimaguchi entrance ramp had a high number of cold spot occurrences but no reports of lingering snow or ice. One possible explanation for these inconsistencies is that snowfall depth is not always uniform even in adjacent areas, as it can be influenced by local topography and wind direction.

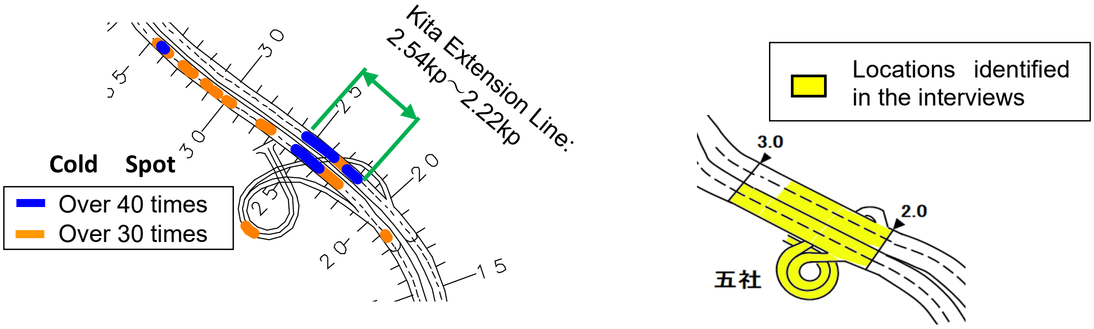


Figure-6 Comparison of Cold Spots (left) and Interview Results (right) near the 2.54 kp mark on the Kita Extension Line

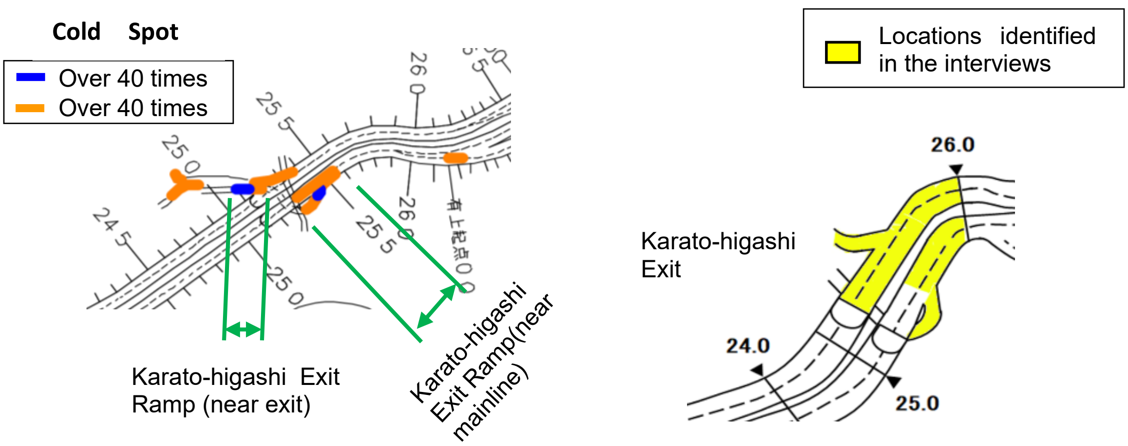


Figure-7 Comparison of Cold Spots (left) and Interview Results (right) at the Karato-higashi Exit

In the section around the 19.4–20.8 kp mark of the mainline (Figure-8), only the eastbound lane ranked high in cold spot frequency, whereas the interview results indicated lingering snow or ice on the westbound lane as well. This discrepancy is likely due to the influence of daytime solar radiation. As mentioned in section (1),being in the shade is one of the conditions that contributes to lower road surface temperatures. The topography in this section features a slope on the south side of the road, which shades the eastbound lane during the day.

Since the thermal mapping was primarily conducted on clear days, the westbound lane, which received sunlight, registered a lower cold spot frequency. In contrast, the shaded eastbound lane showed a higher frequency, resulting in a difference between the lanes in our data. However, on rainy or snowy days, neither lane receives thermal energy from the sun. Given that other conditions such as elevation and road structure are identical for both lanes, the westbound lane is also susceptible to temperature drops under these circumstances. The interviews were conducted during a snowfall event, so it is presumed they reflect the on-site conditions where snow cover prevented both lanes from receiving sunlight, leading to the potential for lingering snow and ice on the westbound lane as well.

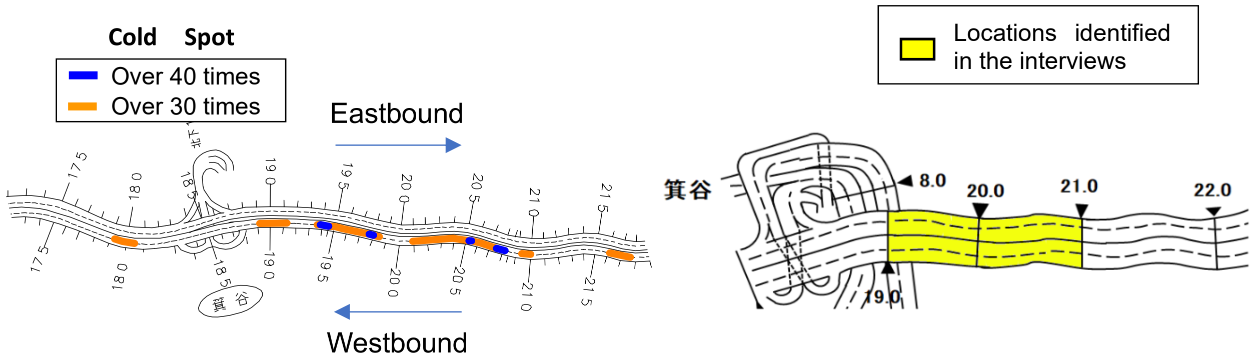


Figure-8 Comparison of Cold Spots (top) and Interview Results (bottom) on the Mainline, Westbound (19.4–20.8 kp)

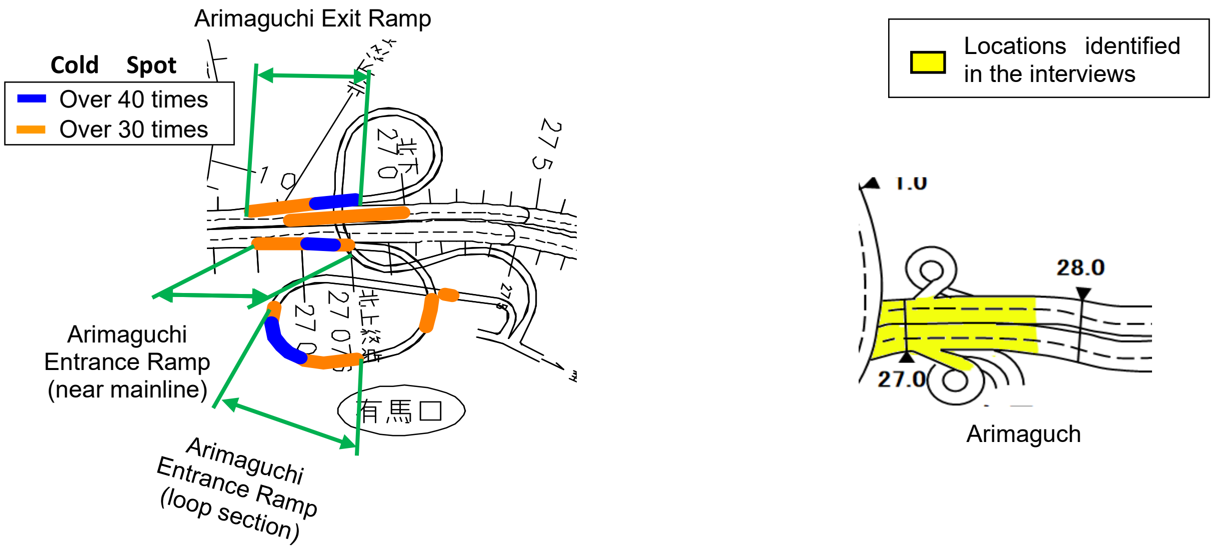


Figure-9 Comparison of Cold Spots (left) and Interview Results (right) at Arimaguchi

4. CONCLUSION

In this study, we created a thermal map of the Kita-Kobe Route and extracted cold spots from it, successfully identifying the locations most prone to significant drops in road surface temperature. A comparison of two years of observation data confirmed the reproducibility of the highest-ranking cold spot locations. Furthermore, by comparing our analysis with interviews conducted with snow removal personnel, we confirmed a general consistency between the thermal mapping results and the actual locations where lingering snow and ice occur.

The Hanshin Expressway is located in a relatively temperate region of Japan. Although the Kita-Kobe Route is the coldest section of this expressway system, it is not frequently impacted by heavy snowfall. Nevertheless, the frequent application of anti-icing agents to prevent freezing is required. The overall human and financial costs of snow and ice countermeasures are substantial, encompassing staff standby duties and construction schedule adjustments dependent on weather forecasts. Moreover, concerns regarding the corrosion of road structures caused by these anti-icing agents remain an unresolved issue.

By advancing these studies further, if a system for conducting thermal mapping on a routine basis can be established, it could potentially be linked with data from ICT-equipped spreader vehicles. This would open up the possibility of realizing on-demand countermeasures, where a minimum amount of anti-icing agent is applied only to the necessary locations. We will continue to closely monitor the challenges faced on-site and proceed with studies that are aligned with real-world needs.